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A Tube Viscometer for Slurry Investigations

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SUMMARY An improved design of tube viscometer suitable for investigating settling slurries is described, and the use of an inverted "U" tube configuration is justified. Some minor problems are discussed with emphasis on the dependence of results on tube diameter.

1 INTRODUCTION

With the increasing acceptance of slurry pipelines as a means of long distance transport for coal and minerals there is a developing need for means of assessing the suitability of a pipeline for a particular application. Knowledge of the laminar flow behaviour of the slurry is almost essential to the design of solids pipeline facilities. A number of techniques may be used to determine this behaviour, but a survey of previous work on slurry viscometry has shown that the most suitable approach is to use a vertical tube viscometer (Tuft, 1977). This form of instrument is chosen because of its wide range of attainable shear rates, (as opposed to rotational viscometers) and its insensitivity to settling problems with coarse slurries (which will settle out in horizontal tubes). On these grounds a new form of vertical tube viscometer has been evolved at M.D. Research Co. The instrument is intended to be particularly suitable for settling slurries, and was designed with a view to both fundamental studies and practical pipeline design.

2 DESCRIPTION OF THE VISCOMETER

The viscometer is shown schematically in Fig. 1. The tubes are an inverted 'U' shape, and consist of lengths of cold-drawn stainless steel joined by various fittings of precisely the same bore as the tubes themselves. A rubber pinch valve at the top of the pressure-tight perspex tank connects the short inlet section to a long piece of straight tube ending in a relatively sharp 180° bend machined in perspex. From this bend a third tube of similar length returns to the level of the tank and is positioned over a collecting hopper.

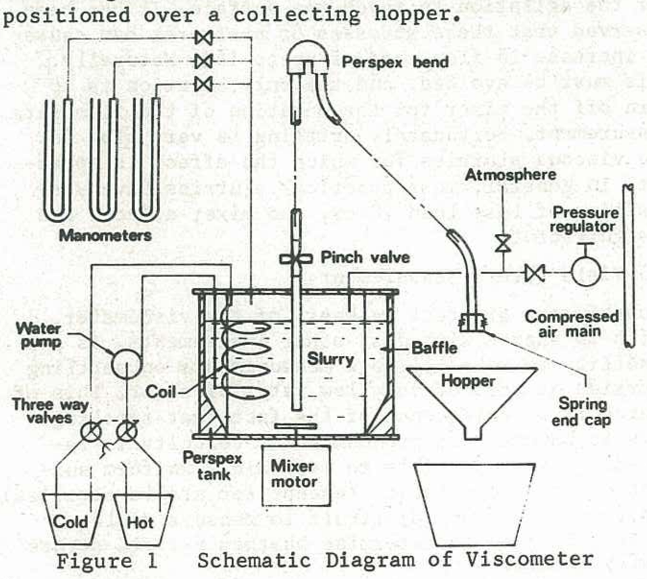

Figure 1 Schematic Diagram of Viscometer

The inverted 'U' tube configuration was chosen for three reasons:

i) To virtually eliminate static head.
ii) To permit long tubes to be used without separating the ends by an impractical height.
iii) To allow a downward flow at the tube outlet.

Reasons (i) and (ii) greatly increase sensitivity of pressure measurements at low flow rates and large tube diameters (for coarse slurries), and reasons (ii) and (iii) are significant operational conveniences. Tube diameters range from 2.3 mm to 15.8 mm, and total lengths range from 3m to 6m.

Flow is induced by compressed air, the pressure of which is controlled by a precision regulator and measured on one of three 1.8m manometers containing mercury, tetrabromoethane or ethyl alcohol. Flow is stopped by both the pinch valve, which also prevents solids from settling back into the tank and increaseing the concentration, and a sprung end cap at the outlet, which prevents low viscosity fluids from trickling out of large diameter tubes.

To measure the flow rate slurry issuing from the tube is caught in a measuring cylinder while a stopwatch records the time taken to obtain the sample. The full cylinder is also weighed, whence the slurry density and concentration can be calculated. A scale on the side of the transparent reservoir permits measurement of the slurry level so that the static head can be found.

Temperature, measured to within 0.1°C with a resistance thermometer, is controlled by manually switching a small pump to pass hot or cold water through a copper coil in the reservoir. A simple mixing impeller in the bottom of the tank helps maintain uniform temperature and concentration.

The following measurements are required at each of about ten different flow rates for a full laminar flow test in one tube size: applied pressure, volume of sample, time to collect sample, weight of sample, mean slurry level in tank during flow measurement, temperature. Together with some instrument constants this data is used to calculate points on a graph of shear stress versus apparent shear rate, $8V/D$ (V = mean velocity, D = tube diameter).

This form of presenting the result is chosen because it displays the maximum information in a simple manner, permits characterisation of the slurry's flow behaviour, and provides greatest flexibility for further analysis and interpretation. The rate quantity $8V/D$ is preferred to the true shear rate (the two are equal only for Newtonian fluids) because it is a simple quantity directly related to pipe flow applications, and because its calculation does not involve unreliable techniques such as graphical differentiation of experimental data.

3 EFFECT OF TUBE CURVATURE

An obvious disadvantage of the U-shape of the tubes concerns the effect of the tube curvature on the pressure drop. Ito (1969), among others, gives an equation for the increase in friction factor due to secondary (non-axial) flow when a Newtonian fluid flows through a curved tube.

Using this relationship it can be shown fairly simply that the additional pressure drop due to curvature in the U-tube is minimised if:

i) The radius of curvature is very large (e.g. over 1m), which would result in a tube of impractical dimensions.
ii) The curved section is very short relative to the total length of tube i.e. very small radius of curvature of about three times the tube diameter.

The second alternative is clearly preferable; although it means a very large friction factor in the bend for large tubes at high Reynolds No. (an increase by a factor of up to 3) the length over which the high friction factor acts is so short relative to the total length of tube that the maximum error is only a few percent at worst, and rarely more than 1%. This is an acceptable level of error, (except at the high end) relative to the accuracy of the whole system, so the effects of curvature can usually be safely ignored.

Further, since most slurries possess a yield stress it could be expected that the curvature-induced secondary flows which cause the additional head losses would be somewhat damped, and thus the effects of curvature would be even less than for Newtonian fluids.

The very gentle bends in the downward-flow tube, which are grossly exaggerated in Fig. 1, also have no effect. These curves are only sufficient to provide a couple of centimetres lateral displacement, and have huge radii in excess of 30m.

4 CALIBRATION

The operation of the viscometer was checked with Newtonian fluids whose viscosity could be measured independently. Each tube was tested with at least two aqueous glycerol solutions of widely differing viscosity (e.g. 5cP and 50cP). The viscosities of the solutions were also measured (at the same temperature) with a Brookfield LVT rotational viscometer, which served as a calibration "standard". The accuracy of the Brookfield is itself limited (at worst a few percent) but was quite adequate for the present purpose.

Figure 2 shows fairly typical results, with turbulance occuring in the low-viscosity fluid at high shear rates (Re $\approx$2000 at 8V/D$\approx$1600 sec^{-1}). The excellent agreement between rotational and tube viscometers is evident. Markedly poorer results were sometimes obtained from low-viscosity fluids in larger tubes, where bad scatter occurred at low shear rates (due to inaccuracy in measuring low pressures) and slight non-linearity, or apparent dilatancy, occurred at high Reynolds Numbers (due to curvature effects becoming significant). However, such combinations of low viscosity and large tubes would be used rarely since more suitable tubes would be available. Thus except for infrequent occasions when Reynolds Number exceeds 1000 the accuracy of the viscometer is high; above Re = 1000 results must interpreted with care.

5 SOME OPERATIONAL PROBLEMS

During the development, commissioning and use of the viscometer various difficulties arose, some of which could not be solved once and for all but can be considered as minor limitations of the instrument. The most significant of these difficulties are worth brief discussion.

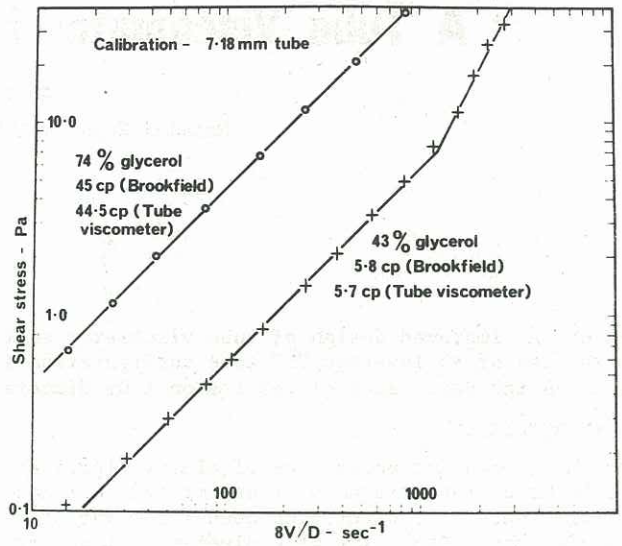

Figure 2 Typical Calibration results

5.1 Tube Hydrophobicity

Early attempts at the glycerol calibration discussed previously produced results which varied in a random and unreproducible manner. The trouble was eventually traced to an oiliness or hydrophobic state of the as-delivered steel tubing. It was hypothesised that the fluid would fail to wet part of the tube wall and consequently formed bubbles which altered the tube's effective diameter. Presumably a different pattern of bubbles occurred each time the tube was filled, hence the lack of repeatability. Following treatment of the tubes with a degreasing agent (trichlorethylene) and a wetting agent (sodium silicate solution) the problem diaappeared and the successful calibrations mentioned earlier were achieved.

5.2 Mixer Effects

The mixer in the viscometer is essential to ensure a uniform distribution of solids throughout the slurry. However, under some conditions of strong agitation the mixer can have an effect on flow rate. If the tank is nearly full with a slurry of over 100 cP viscosity, large stresses must be generated by the impeller at the bottom of the tank in order for the agitation to reach the surface. It has been observed that these stresses or pressures can cause an increase in flow rate of up to 15%. Naturally this must be avoided, and the only solution is to turn off the mixer for the duration of the flow rate measurement. Fortunately settling is very slow in the viscous slurries for which the effect is apparent. In general, most practical slurries have viscosities of less than 20 cP, and mixer effects are insignificant.

5.3 Yield Stress Measurement

Probably the greatest weakness of the viscometer, which is shared with most other instruments, is its inability to make reliable measurements on settling slurries at zero or very low rates of shear. This of course is a consequence of the fact that settling effects become more pronounced as velocity is reduced. It is impossible to maintain a uniform suspension at zero velocity (except for stable slurries) and thus it is very difficult to measure yield stress, or even to determine whether a yield stress really exists.

The problem is compounded by the fact that extrapolation of a shear stress-8V/D graph to zero 8V/D is frequently impractical. It is common at low shear rates for the experimental curve to be almost asymptotic to the stress axis, whence extrapolation becomes very hazardous - any value down to zero is possible. Standard procedure, unless there is a specific reason for doing otherwise, is to ignore the true yield stress and assume a Bingham plastic model. An artificial yield stress can then be obtained by regression.

The fact that a particular slurry does possess a yield stress can be shown by other means (e.g. observation of pouring behaviour) but does nothing to quantify it. On occasions attempts have been made to measure the true yield stress by observing whether or not flow stops when the pressure is abruptly reduced to a value estimated to be near that of incipient flow. In this way the tube is still full of homogeneous suspension when the measurement is taken. However, this is a rather tedious trial and error method and is still not very accurate - variations of 30% are common.

5.4 Particle Size

There is obviously an upper limit to the size of particles which can pass through any given tube. This limit is considerably smaller than the tube diameter (by a factor of 2 or 3) because a number of particles can interact to bridge across the tube and block it. Pseudo-homogeneous flow could not really be said to occur with particles of this size anyway. As a consequence it is necessary to test coarse slurries in large diameter tubes, with a resulting loss of precision due to higher Reynolds Number and low pressure drop. Particle size effects are also often blamed for the anomalous behaviour best described as a diameter effect.

6 THE DIAMETER EFFECT

For a pure homogeneous liquid in laminar flow through a tube a plot of shear stress versus 8V/D should correlate data from viscometer tubes of all diameters. This can be shown theoretically (e.g. Skelland, 1967) after making the assumptions of no slip at the tube wall, and no time dependence. For almost all slurries so far tested in the viscometer this has not been the case, as shown by Figure 3 which is a typical example of the results obtained.

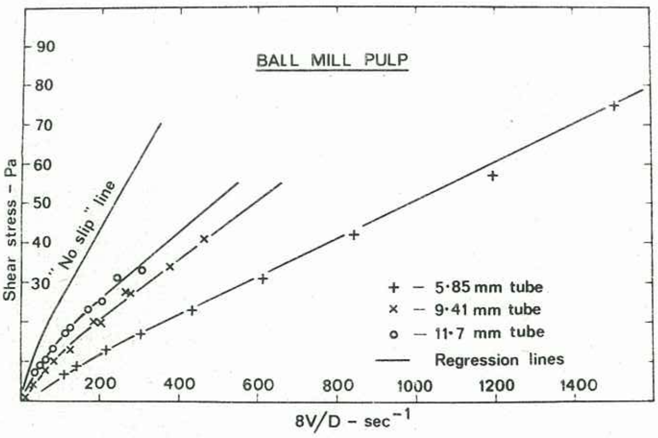

Figure 3 The Diameter Effect

At this stage the effect is not fully understood, although it is almost certainly a consequence of some sort of "slip" due to non-homogeneity at the tube wall. The other possible cause, time dependence or thixotropy, can be dismissed since it would also appear as a length effect, which is not the case. None of the three theories so far examined (Schofield & Scott Blair, 1930; Oldroyd, 1949; Jastrzebski, 1967) seem to apply consistently to all experimental data; in fact none of them were found to be applicable to the data from the present viscometer, although Cheng & Tookey (1969) have successfully used Jastrzebski's approach.

It is generally accepted that the effect increases with the particle size/tube diameter ratio (d/D), but the limits of this dependence are ill-defined. Shaheen (1971) found no diameter effect with a d/D of 0.02, yet the present work has shown a pronounced effect in similar sized tubes but with the much smaller d/D of only 0.003. Clearly other factors are involved. Work directed towards clarifying the situation is presently being carried out at M.D. Research Co., but in the meantime some method of obtaining meaningful results must be used, even if it is only crude.

Such a method consists basically of assuming a rheological model for the bulk of the slurry (e.g. Bingham plastic) and postulating a thin film of clear liquid (a "slip layer") adjacent to the tube wall. It is then straightforward to derive an expression for the flow rate as a function of the bulk slurry rheological parameters and the slip layer thickness and viscosity. A computer can be used to carry out a multiple non-linear regression to fit the experimental data from three or four tubes to this expression, and to produce values for the slip layer thickness and viscosity and the slurry properties.

Although effective, this is a purely empirical approach which does nothing to illuminate the mechanisms involved. It is also of somewhat limited value because it forces a complex situation to fit a very simple model, with some occasional peculiar results such as large random variations in the slip layer thickness. However, the fact that the regression value for the slip layer viscosity is always very close to the viscosity of water (within a few percent) indicates that the model has reasonable semblance to reality. The slip layer thickness is usually of the order of 10 μm.

Application of this method transforms the experimental points of Figure 3 into the lines shown, which represent the regression lines and the "no-slip" or "true" line for the slurry properties. This is an extremely viscous ball mill pulp (180 cP) in which the effect is very pronounced. For some slurries of very low concentration and viscosity (say less that 10 cP) the difference in viscosity between the "slip layer" and the bulk of the slurry is not usually enough for the increase in flow due to "slip" to be significant, but such slurries are only infrequently encountered.

7 CONCLUSIONS

The vertical U-tube viscometer described in this paper has been demonstrated to be a functional, versatile instrument, capable of accurately characterising non-Newtonian suspensions (including fast-settling slurries) of a wide range of properties over a wide range of shear rates. Its greatest weaknesses consist of the difficulty of obtaining a precise measurement of yield stress for settling slurries, and the obstacle imposed by the occurrence of a diameter effect. Neither of these weaknesses are severe, however, and they do little to limit the instrument's usefulness.

Its uses range from direct application to slurry pipe system design to fundamental investigations of suspension rheology. Pipe design applications include the direct prediction of laminar flow behaviour of stable slurries in full scale pipes; the prediction of laminar/turbulent transition for both stable and settling slurries; and the provision of an important fluid-property basis for such essential turbulent-flow parameters as Reynolds Number and Hedstrom Number. In addition a knowledge of the yield stress is important in determining settling behaviour. Fundamental research using the viscometer could, for example, be directed towards a study of surface chemical factors and their influence on suspension flow properties, including the diameter effect.

The U-tube viscometer is a functional instrument with a number of practical applications for both settling and stable slurries.

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