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S. K. KAWATRA [a] & A. K. BAKSHI [a]

[a] Department of Metallurgical and Materials Engineering, Michigan Technological University, Houghton, MI, 49931

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On-Line Viscometry in Particulate Processing

S. K. KAWATRA and A. K. BAKSHI

Department of Metallurgical and Materials Engineering, Michigan Technological University, Houghton, MI 49931

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On-line viscometry of suspensions is very difficult compared to viscometry of pure liquids. The problem arises because of the unstable nature of the suspensions, particularly when coarse and fast settling particulates are present. Several attempts have been made in the past in which special mixing chambers have been designed to maintain slurry homogeneity while measuring viscosity. However, the credibility of these instruments are questioned by many authors, as quite often the same systems measure different rheological behavior for similar suspensions. In most of the designs suggested in the past, solving one of the problems of suspension viscometry introduces new problems. For example, agitation can keep the solids suspended, but it can also seriously affect the sensitivity of the viscometer. In this article the problems involved with three different types of viscometers (rotational, capillary, and vibrational), which have been used for measuring viscosity of suspensions, are discussed.

BACKGROUND

Unlike non-particulate fluids, rheological measurements of particulate fluids (suspensions) are very difficult. Since a suspension is a multi-phase system, its rheology depends upon the properties of both the liquid and the solids which constitute the suspension. During rheological measurement, the stability of the suspension must be maintained, so that the properties of the suspension will not change while they are being measured. Suspension stability is influenced by several interdependent parameters, such as: (i) Settling velocity of the particles, which depends upon the liquid viscosity, particle size, and particle density; and (ii) Coagulation and flocculation, which depend upon the surface properties of the particles, which in turn are influenced by the chemistry of the carrier liquid. Other parameters, such as particle concentration and particle packing, also influence interparticle interaction, and hence the rheology. The forces arising from all these parameters affect the movement of the fluid, and changes in these will change the rheology of the suspension. Unfortunately, most of the viscometers available to-day are not capable of keeping up with these complex mechanisms of suspension rheology.

Nevertheless, the importance of suspension rheology is widely felt in various industries. In the food industry, more and more attention is given to rheological properties to utilize modern technology for food production, handling, storage, and

quality improvement[1]. In injection molding (ceramic and metal casting) lower viscosities are needed to facilitate mixing, transportation, and enhance solids loading (to reduce shrinkage during sintering)[2]. In paint manufacturing, optimum rheology is needed for quality control. Similarly in the coal and mineral industries, a complete knowledge of rheology is necessary for optimum grinding[3–5,38,39] and efficient separations[6,7,40]. Slurry rheology is also important in the emerging coal slurry utilization technologies. A suitable yield value is needed to store the slurry without allowing the solids to settle, while lower viscosities are needed at intermediate and high shear rates for easier transportation and better atomization[8,9]. Similarly, examples of the importance of slurry rheology can be seen in many other industries, such as in paper and pulp making, waste treatment, cement manufacturing, and so on. Therefore, the need for a suitable rheometer for process control in these industry is always felt. The search for such an instrument was reported as early as 1940[10] and researchers are still working towards it in the 1990's[11–13]. This shows that until today a satisfactory on-line rheometer for suspensions has not been developed. In this article, a survey of viscometry systems for particulate fluids is provided. Since measurement of coarse suspensions is more difficult than measurement of suspensions containing submicron particles, emphasis is given to research work conducted on systems containing coarse, fast settling particles. Three different types of viscometers, the rotational type, the capillary type, and the vibrational type, are discussed whose use have been reported widely for suspensions.

ROTATIONAL VISCOMETERS

Operating Principle

Because of their control over shear rate, rotational viscometers are widely used among researchers. Most rotational viscometers used for suspensions are of the co-axial cylinder type. A line diagram of a simple co-axial cylinder viscometer is given in Figure 1. In this type of viscometer, the fluid is placed in the gap between two concentric cylinders for measurement. Then one of the cylinders is rotated by a motor at a particular r.p.m. while the other is kept stationary, and the torque required to rotate the cylinder is measured. As the viscosity of the fluid increases, the drag force on the surface of the rotating cylinder increases. This in turn increases the torque reading, from which viscosity of the fluid is determined.

Thus the only parameters which are measured by the instrument are the torque (T) and angular velocity (Ω) of the rotating cylinder. Then shear stress is calculated from torque, and shear rate is calculated from angular velocity. Viscosity is calculated by taking the ratio of shear stress and shear rate. The rheological type of the fluid is determined based on the variation of shear stress as a function of shear rate, as shown in Figure 2. A Newtonian fluid has the same viscosity at all shear rates, while the viscosity of a non-Newtonian fluid varies as the shear rate changes. Unless proper equations are used to calculate shear stress and shear rates from torque and angular velocity, an incorrect value of fluid viscosity will result. Calculation of shear stress from torque is straightforward and can be expressed by the following equation, which is valid for both Newtonian and non-Newtonian fluids:

$$\tau = T/(2\pi r^2 L) \qquad (1)$$

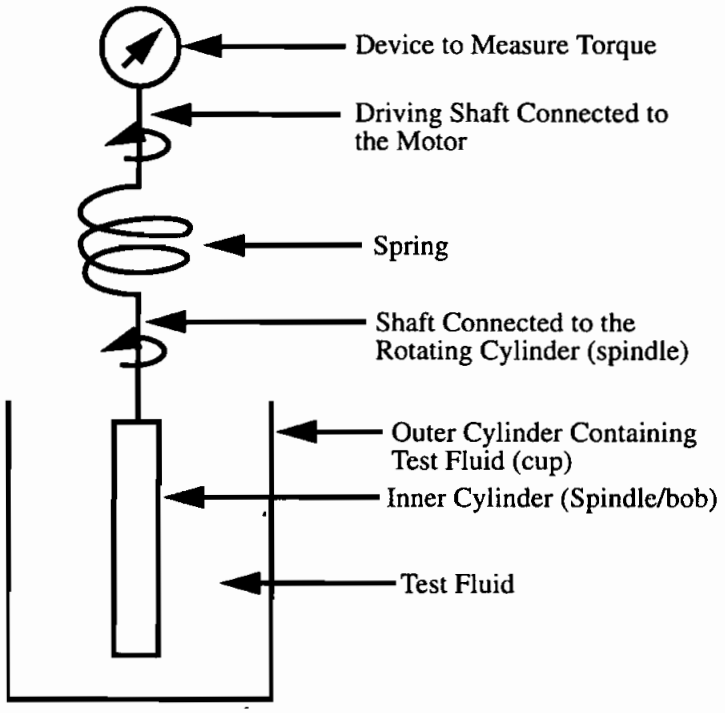

FIGURE 1 Line diagram showing the mechanism of a typical co-axial cylinder viscometer. The change in torque due to the drag force of the fluid on the rotating surface of the cylinder is the measure of viscosity.

Where, τ = shear stress
r = radial distance of the fluid from the axis of the inner cylinder
T = torque
L = length of the inner cylinder.

From this, it can be seen that the shear stress in the viscometer is not a constant, but decreases as one moves from the wall of the inner cylinder to the wall of the outer cylinder.

Calculation of the shear rate from the angular velocity is more complex, and depends upon both the type of fluid and the gap between the two cylinders. For Newtonian fluids:

$$\tau = \eta\gamma \tag{2}$$

Where, τ = shear stress
$\dot{\gamma}$ = shear rate
η = viscosity

From this flow model it can be shown that[15],

$$\dot{\gamma} = [2R_2^2/(R_2^2-R_1^2)]\Omega \tag{3}$$

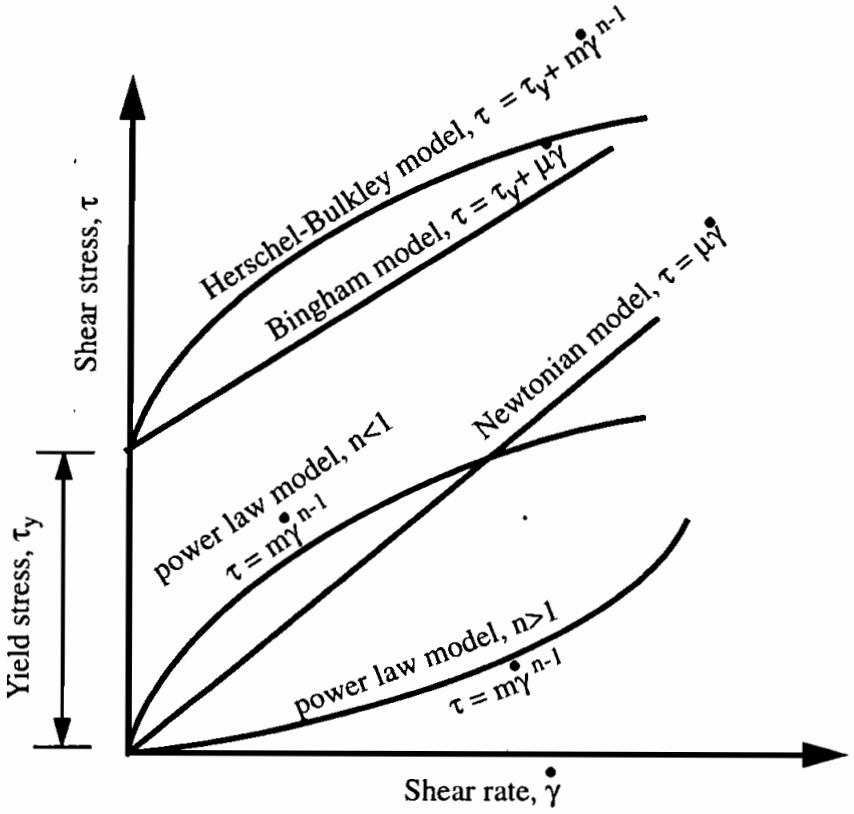

FIGURE 2 Flow curve models reported for suspensions.

where, $\dot{\gamma}$ = shear rate at the surface of the inner cylinder
R_1 = radius of the inner cylinder
R_2 = radius of the outer cylinder
Ω = angular velocity of the inner cylinder.

Quite often, Newtonian solutions of known viscosity are used to calibrate the torque scale of the viscometer to determine viscosity of non-Newtonian fluids. This is not correct because with different flow models different expression for shear rate will be obtained. For example, for a non-Newtonian fluid that obeys the power law (see Figure 2), the shear rate is given by the following equation:

$$\dot{\gamma} = 2\Omega/n[1-(R_2/R_1)^{-2/n}] \quad (4)$$

where, $\dot{\gamma}$ = shear rate at the surface of the inner cylinder
R_1 = radius of the inner cylinder
R_2= radius of the outer cylinder
Ω = angular velocity of the inner cylinder
n = flow index, from the power law equation.

From equations 3 and 4 it is seen that unless the appropriate equation is used to calculate shear rates of a particular fluid the viscosity measured by the viscometer will be wrong.

The measurement of the viscosity of a fluid with unknown flow behavior can be greatly simplified by using a coaxial cylinder viscometer whose annular gap is very narrow. If this gap is less than 1% of the diameter of the inner cylinder, then the velocity gradient of the fluid inside the annular gap will very closely approximate linearity for fluids of all types (Newtonian as well as non-Newtonian). In this case, the equation of the shear stress can be written as[15]:

$$\tau = T/(2\pi R_a^2 L) \tag{5}$$

Where, τ = shear stress at all points in the gap
R_a = average radial distance of the fluid from the axis of the inner cylinder
T = torque
L = length of the inner cylinder.
and the equation for shear rate can be simplified to[15]:

$$\dot{\gamma} = [R_a\Omega/(R_2-R_1)] \tag{6}$$

where, $\dot{\gamma}$ = shear rate at all points in the gap

From these values of shear stress and shear rates, flow curves of unknown fluid types can be determined.

While the narrow-gap coaxial-cylinder viscometers work well for liquids, they are unfortunately not suitable for coarse suspensions. This is because the narrow gap is prone to jamming and plugging by solid particles.

Critical Discussion of the Rotational Viscometers

Constant shear operation Rotational viscometers can be operated at a steady shear rate for a long time. This helps in taking precise measurements of viscosity at any particular shear rate, especially at low shear rates where yield stress can be calculated. By changing the rpm of the rotating spindle (or cylinder), the shear rate can be changed, thus a flow curve for non-Newtonian fluids can be determined with these instruments.

Wall slip The equations for shear stress and shear rates described in Equations 1 through 6 are derived under the assumption that the velocity of the fluid at the surface of each cylinder is the same as the velocity of the cylinder surface. This is the no slip condition or shear-flow condition. However, quite often slip occurs at the wall, and correct viscosity of a suspension cannot be obtained by using standard formulas. One of the reasons for such slippage in suspensions is believed to be migration of particles away from the cylinder wall[15,27]. This leaves a dilute suspension at the wall compared to the bulk of the fluids. This is often termed "apparent slippage," and it must be addressed while measuring suspension rheology. Corrections for slippage can be obtained experimentally by varying spindle dimensions, or theoretically by using correction factors suggested by various authors[15,37]. Some investigators have used cylinders with roughened surfaces (e.g., by cutting grooves on the surface) to avoid wall slip[16].

End effects Ideally the length of the cylinder in a co-axial cylinder viscometer should be infinite, to eliminate end effects. End effects are seen, because the fluid below the inner cylinder (and above the inner cylinder if it is submerged) will exert an additional torque on the spindle that is not included in Equations 1 through 6. End corrections are further complicated when different spindle shapes are used, such as the design shown in Figure 3(b) which has been used for eliminating solids build up on top of the spindle[11–13,20]. By changing this geometry, the direction of the velocity gradients will no longer be radially outwards at the ends. In some high precision laboratory viscometers, the bottom surface of the inner cylinder is made cup shaped to trap a layer of air below it, and so minimize the end effects. Also, by keeping the top surface of the inner cylinder above the fluid, torque exerted by the fluid on this surface can be eliminated. However, both these options cannot be practical in a flowing slurry line, and so cannot be used in on-line instruments. As far as end effects are concerned, the double gap design shown in Figure 3(c) is most suitable for suspensions, because it minimizes the end surfaces of the spindle.

Sensitivity Rotational viscometers are very sensitive and any disturbances associated with sample flow will offset the torque reading. In order to avoid settling of solids, many researchers have suggested top to bottom flow of slurry in the annular space. This arrangement will work if the flow is strictly vertical and has no component acting in the r (radial to spindle) or θ (tangential to spindle) directions. Otherwise the change in torque experienced by the spindle will not be solely from the molecular forces (shear) within the fluid, but will be supplemented by the fluid flow (see Figure 4). This also changes the shear rate experienced at the surface of the spindle because the flow interferes with its rotation[11,12].

Solids settling and centrifuging The most difficult suspensions for viscometers to deal with are those which contain fast settling particles. The solids settle during measurement, which not only destroys the homogeneity of the sample but also interferes with spindle

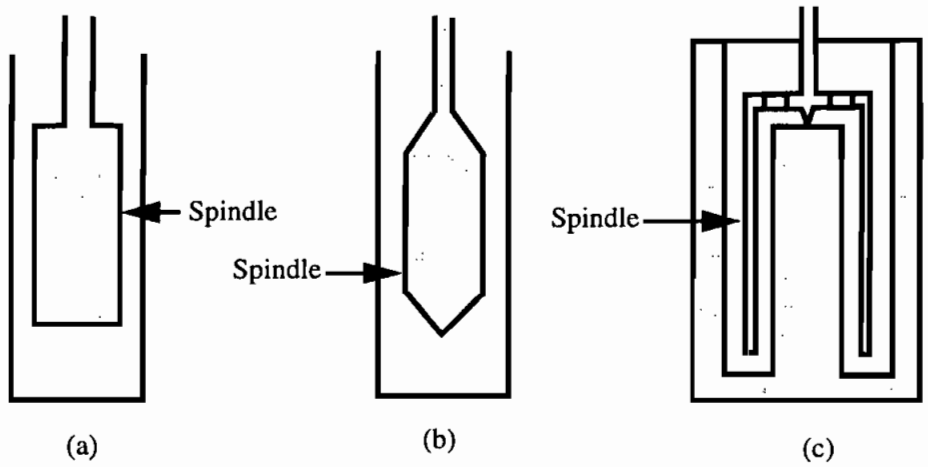

FIGURE 3 Different spindle designs adopted for suspension use.

Control of shear rate is the strongest point of rotational viscometers. This helps in measuring the rheology of non-Newtonian fluids, specially at low and medium shear rates. However, at higher shear rates (above 300 sec^{-1}) rotational viscometers are not suitable for suspensions because high rotational speed of the spindle produces a centrifugal force that segregates the solids.

The annular gap between the cylinders must be at least 10 times larger than the largest particle in the suspension to avoid solids plugging. The sample must also be screened to remove any oversize and tramp material. Other problems which must be considered for rotational viscometers are wall slip and end effects.

CAPILLARY VISCOMETER

Operating Principle

In a capillary viscometer the fluid is passed through a tube under pressure. By measuring the flow rate and pressure drop across the tube shear stress and shear rate can be calculated. Although capillary viscometers are normally designed for Newtonian fluids, they are also extensively used for non-Newtonian fluids. These viscometers provide a simple and inexpensive method for rheological measurement, and when suitable for an application, capillary viscometers are more precise than rotational viscometers[15]. Specifically, these viscometers operate better at higher shear rates[22] which are common in many processing and manufacturing units.

For a fluid flowing through a tube (Figure 12) the shear stress at the wall can be calculated from the pressure difference across the tube by using the following formula:

$$\tau = R(P_1 - P_2)/(2L) \tag{7}$$

Where, τ = shear stress at the wall
P_1 = Pressure at the entry of the tube
P_2 = Pressure at the exit of the tube
L = Length of the tube
R = radius of the tube.

Shear rate at the wall for Newtonian fluids can be calculated by measuring the flow rate, Q through the tube by applying the following formula:

$$\dot{\gamma} = 32Q/\pi R^3 \tag{8}$$

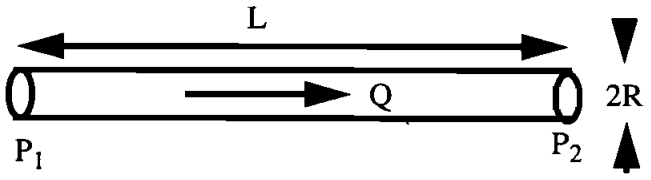

FIGURE 12 Line diagram of a capillary tube.

Where, $\dot{\gamma}$ = shear rate at the wall
Q = flow rate

Thus by using the measured pressure difference across the tube and the flow rate through the tube, shear stress, shear rate, and viscosity can be calculated. Equation 8 is derived from the Newtonian flow model. Therefore, for such fluids Equation 8 gives the true shear rate of the fluid. For non-Newtonian fluids the shear rate obtained from Equation 8 is called the apparent shear rate. True shear rate of non-Newtonian fluids can be obtained from $32Q/\pi R^3$(Equation 8) by the following formula which is derived by Metzner and Reed[23] after modifying the Rabinowitsch[24] equation:

$$\dot{\gamma} = (3n' + 1/4n'). (32Q/\pi R^3) \tag{9}$$

Where, $\dot{\gamma}$ = shear rate at the wall
n′ = flow index given by the following formula

$$n' = \frac{d\log (\Delta P/4L)}{d\log (4Q/\pi R^3)} \tag{10}$$

Where, n′= flow index
ΔP = pressure difference across the tube = $P_1 - P_2$

n′ can be determined graphically by plotting $\Delta P/4L$ vs. $32Q/\pi R^3$ on a log-log scale and measuring the slope of the resulting line. Equations 9 and 10 are valid for fluids with or without yield stress[23].

Necessary Conditions for Capillary Viscometers

The necessary conditions[25] (Bird *et al.*, 1960), which must be satisfied in a capillary viscometer measurements are:

a) Laminar flow (Reynolds number < 2100)
b) Constant fluid density
e) Steady flow
d) End effects are negligible
e) No slip between the wall and the fluid
f) The fluid must be incompressible.

Common Capillary Viscometer Types

Common capillary viscometers are either constant flow type or constant pressure type viscometers. Piston viscometers are examples of the constant flow type. In these viscometers, fluid is pushed through the tube by a piston moving at a constant speed. Thus the flow rate through the tube remains constant. By measuring the pressure difference across the tube, viscometric functions can be calculated. In constant pressure

capillary viscometers a constant pressure is applied at the entry of the tube and the flow rate is measured by collecting the fluid flowing through the tube[15].

Discussion of the Capillary Viscometers

Capillary viscometers have several advantages as listed below.

- Since the flow is continuous and the sample stays inside the tube for a very short time, solid settling inside the viscometer is not a problem. However, the suspension should be kept well mixed before it enters the tube. This is usually done in an agitated system immediately before the sample enters the tube[28,29].
- Capillary viscometers are suitable for making measurements at high shear rates, where industrial operations such as pumping and spraying are carried out.
- They are simple to construct, and if they can be suitably used with a given fluid, can generate more accurate data than a rotational viscometer.

Many of the problems encountered in rotational viscometer are also common in capillary viscometers. Some of the examples are listed below.

- Similar to rotational viscometers, the diameter of the capillary viscometer should be at least 10 times larger than the top particle size of the suspended particles. Therefore, the sample must be screened to remove unusually coarse material before it is allowed to pass through the tube.
- Slippage at the wall is still a problem with capillary viscometers. This is mainly because of particle migration away from the wall[15,21]. As a result, a more dilute fluid is left in contact with the wall. The presence of wall slip can be detected by comparing flow curves of the same sample generated by tubes of different diameters[27]. This problem is minimized by selecting tubes with larger diameters with respect to the top particle size in the suspension, or by using any of several suggested correction factors[15,37].
- End effects are noticed in capillary tube viscometers, because of pinching of the slurry stream at the entry and exit of the tube[21]. Therefore, flow profiles at the ends are different than in the rest of the tube. This problem is eliminated by using tubes with high length to diameter ratio (above 300).
- Tubes must be calibrated at suitable intervals to compensate for any diameter changes resulting from abrasion or scaling.

Despite these problems, capillary viscometers are widely used by many investigators[15,21,23,27,28].

Selected Designs

Examples of the use of capillary viscometers for suspensions are abundant in the literature. Antonini *et al.*[28] measured rheological properties of a coal water slurry with 70 wt% solids content by using different dimension tubes. Their apparatus consisted of a 10 liter reservoir equipped with interchangeable tubes of different lengths and diameters.

The slurry was agitated by a pneumatic stirrer. For each pressure applied, they measured the flow rates by continuously weighing the slurry flowing through the tubes. Then from pressure gradient and flowrate, they generated flow curves for the coal slurry samples.

Turian *et al.*[29] reported a new design of capillary viscometer for measuring shear stress, shear rate, and yield stress of suspensions. The main body of the instrument consisted of a stainless steel container to hold the sample. The solids were kept in suspension by stirring the sample in the container. They used different dimension stainless steel tubes (with diameters from 2.4 to 8.8 mm) which could be connected to the bottom of the container. The sample flowing through the capillary tube was collected by a bucket placed on top of a electronic balance. The whole system was covered by a water jacket to maintain a constant temperature. Flow rate through the tube was determined by the balance whose signal was recorded by a computer. Shear stress (τ) and shear rate $\dot{\gamma}$ were calculated from pressure drop ΔP and flow rate Q.

Turian *et al.* determined yield stress by extrapolating the shear stress-shear rate curve to a shear rate of zero. They used pulverized Pittsburgh Seam (No. 8) coal to make the measurements over a shear rate range of 1 to 10^4 sec^{-1}. They also determined the yield stress of the slurry by the vane method[30] to verify the result obtained from the capillary tube, and reported that the yield stresses obtained by both the methods were similar.

Another way of measuring viscosity of a slurry is to drain a measured volume of slurry from an overhead container through a capillary tube and to measure the time taken for the material to drain completely. The slurry is kept in suspension in the tank by constant stirring. This method was first tried by DeVaney and Shelton[10], later it was reported by other authors[7,26]. The model used by Schack *et al.*[26] is shown in Figure 13. The authors measured the viscosity by measuring the time required for 100 ml. of

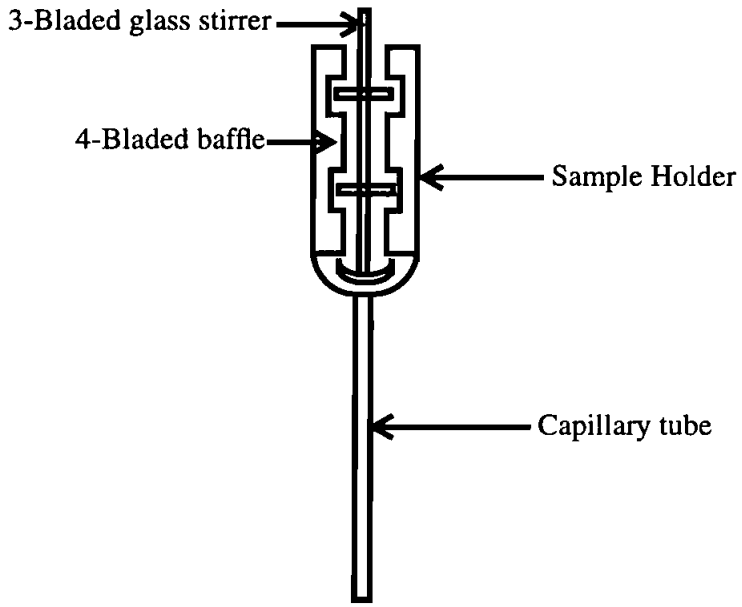

FIGURE 13 Diagram of consistometer chamber and capillary discharge tube used by Shack *et al.*, (from Schack *et al.*, 1957).

suspension to flow through the discharge tube. The major drawback of this instrument is that it does not determine whether the suspension is Newtonian or non-Newtonian. Also, it makes measurements at low shear rates, making it impossible to extrapolate to high shear rates (for hydrocyclone or pumping)[7].

Capillary viscometers are also used in plants to measure effective viscosity of fluids. This can be accomplished by measuring the pressure drop across a straight stretch of pipe. Shear stress and shear rate at the pipe wall can be calculated from pressure difference, flow rate and pipe dimensions. Apparent viscosity can be determined from the ratio of shear stress and shear rate at the wall. In this measurement, the fluid flow in the pipe must be laminar. In order for this method to work with suspensions, the suspension must be very stable (a high yield value), otherwise under laminar conditions a slow sedimentation process will take place at the bottom of the pipe[31].

Summary Compared to rotational viscometers, avoiding solids settling is relatively simpler in capillary viscometers, because the residence time of the sample inside the tube is very small. Measurements of non-Newtonian fluids can be made by changing different dimension tubes or by changing flow rates, which may not be an easy task in plants. For such measurements proper correction factors such as that suggested by Rabinowitsch[23,24] should be considered to obtain true viscosity of non-Newtonian fluids. As with rotational viscometers, wall slip and end effects must be considered while using capillary viscometers. Also, the sample must be pre-screened before allowing it to flow through the tube.

VIBRATING VISCOMETERS

Working Principle

Unlike rotational and capillary viscometers which are volume loading instruments, vibrating or oscillating viscometers are surface loading instruments, because they react only to a thin layer of fluid adjacent to the probe. The probe or sensor of the viscometer can be spherical (Figure 14), rod or plate shaped, or like a fork which vibrates in the fluid. The sinusoidal shear wave from the immersed probe is damped by the fluid, and

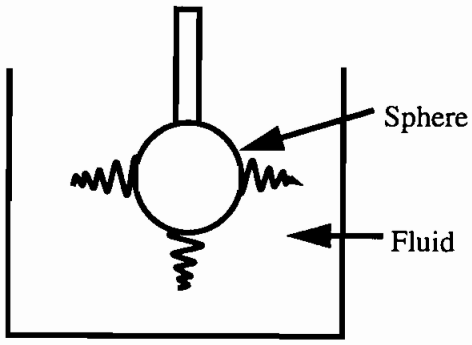

FIGURE 14 Vibrating sphere viscometer. The probe oscillates in the fluid, and the power required to maintain a constant amplitude of oscillation is the measure of viscosity.

the damping is a function of the product of the viscosity and the density of the fluid. Usually the probe is oscillated at a constant amplitude and the force or power required to maintain this amplitude is measured. Rachman[33] derived the following formula for a vibrating rod viscometer to determine viscosity.

$$\eta = R_0^2/A^2\omega_0\rho[F_0x_{00}\omega_{00}/F_{00}x_0\omega_{00})-1]^2 \quad (11)$$

where, η = viscosity of the liquid
ρ = density of the fluid
ω_0 = resonant frequency
ω_{00} = free resonant frequency
x_0 = amplitude at resonance
x_{00} = amplitude in vacuum
F_0 = force at resonance
F_{00} = force required to maintain x_{00}
A = area of the surface in contact with the fluid
R_0 = transducer loss in the vacuum.

Thus by measuring the force F_0 which is required to maintain a constant amplitude x_0, and knowing the density ρ of the fluid one can measure the viscosity η. The remainder of the terms in Equation 13 will be constants for a particular instrument.

Discussion of the Vibrating Viscometers

Some of the advantages of vibrating viscometers over rotational and capillary viscometers are:

- Since the gap of fluid between the sensor and the container wall does not affect the reading, suspensions with coarse particles can be tested without the danger of plugging.
- Unlike rotational viscometers, oscillating viscometers are not affected by minor turbulences associated with slurry flow. Therefore, forces associated with slurry flow (see Figure 4) will not affect its readings.

The major disadvantage of this type of instrument is that the operator does not have any control over the shear rate. It is also difficult to measure the true viscosity of non-Newtonian fluid whose viscosity changes with shear rate. The shear rate $\dot{\gamma}$ will be a sinusoidal function of time. For a spherical probe, its peak value will be maximum at the equator and will be smaller by a factor cos ϕ at a sphere latitude of ϕ. Perry[34] derived the following equation for determining the maximum shear rate for the vibrating sphere viscometers:

$$\dot{\gamma} = k(\rho/\eta)^{1/2} \quad (12)$$

where, $\dot{\gamma}$ = maximum shear are
k = an instrument constant

From this equation we see that the maximum shear rate decreases as viscosity of the fluid increases. For a Newtonian fluid viscosity η is a constant, so maximum shear rate will remain constant. However, for viscoelastic fluids, the viscosity varies with shear rate, and computation of shear rate becomes complicated. Some investigators have suggested measuring the amplitude of vibration[33] and oscillating frequency as a means of measuring the apparent viscosity of viscoelastic fluids (non-Newtonian fluids)[35]. However, the reasoning provided for such measurements apply only to limited polymeric fluids, and the method does not work for suspensions[33,34].

Vibrating viscometers are sensitive to vibrations from supporting structures32,35. Unless precautions are taken to dampen these vibrations the instrument will pick up erroneous signals.

Selected Designs of Vibrating Viscometers

Vibrating rod viscometer for viscosity measurement Rachman[34] reported an assessment of vibrating viscometers in slurries. He utilized a vibrating plate transducer and a flexurally vibrating rod transducer in his research. However, for the suspension studies (with quartz slurries) only the flexurally vibrating rod transducer was used. In his initial experiment with 0.065 volume fraction solids in the slurry, Rachman experienced difficulty in measuring the viscosity because the solids settled quickly. In subsequent tests, the slurry was stirred vigorously by a motor driven pump to keep the solids in suspension. Then the stirrer was stopped and after 15 seconds, measurements were taken with the viscometer. In this way the investigator assumed that the slurry would have been in a similar state when each reading was taken. Similar measurements were taken with quartz-water slurries at 0.24 and 0.36 volume fraction solids. By changing the amplitude of vibration and transducer loading they showed that the denser slurries showed non-Newtonian flow whereas the dilute slurry with 0.065 volume fraction solids had Newtonian flow. However because of uncertain results, Rachman suggested use of this method only if no other simpler viscometer is obtained for measuring non-Newtonian slurry rheology.

Vibrating sphere viscometer for viscosity measurement Kawatra *et al.*[32] used a vibrating sphere viscometer manufactured by Nametre Co. along with a gravity flow sample presentation vessel as shown in Figure 15. Because of the basic design of the spherical oscillating probe (which oscillates at a high frequency and low amplitude rather than rotate in a single direction) and its durable construction, the flow of the slurry did not influence its reading. The solids settling problem was also eliminated because of the gravity flow arrangement of the slurry around the probe. Using this system Kawatra *et al.* were able to continuously measure viscosity of silica slurry at varying concentrations and temperatures in the feed line of a hydrocyclone.

However, the major difficulty in this type of instrument is that the operator has no control over the shear rate. The shear rate is a function of viscosity, higher in low viscosity fluids and lower in high viscosity fluids. Since most of the suspensions at higher solids contents show non-Newtonian flow their viscosity is highly dependent on shear rate. Thus for such suspensions, no logical conclusion can be drawn from viscosity measurements by these instruments unless they operate at the same shear rate as the process itself. Another problem with this type of instrument is that if the fluid velocity is very low, solids tend to settle in small layers over the top of the sphere (Figure 16)

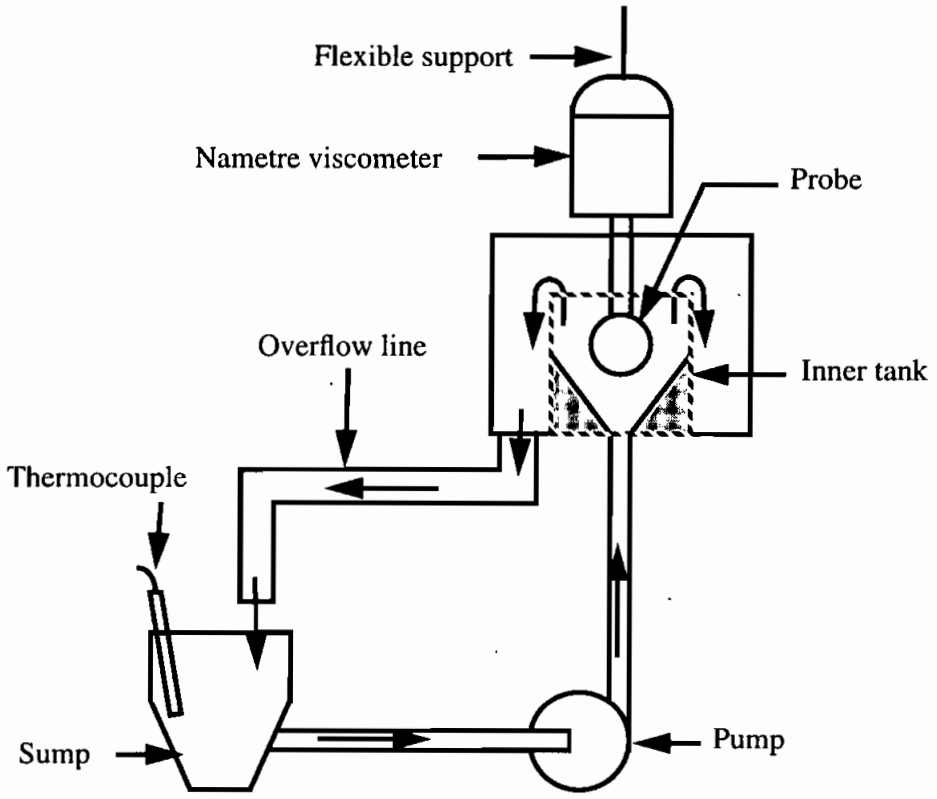

FIGURE 15 Nametre viscometer set-up. Sample is circulated through the system by a pump to keep the solids in suspension.

resulting in higher readings. These instruments are also affected by vibration from their surroundings, and special design is required to isolate from vibration. However, due to their ability to work in hostile plant environment, so far they are the most suitable instrument for making on-line viscosity measurements of Newtonian mineral slurries. The slurry used by Kawatra *et al.*[32] was Newtonian and therefore, good correlation could be established between the viscosity measured by this instrument and the hydrocyclone performance.

Vibrating sphere viscometer for distinguishing Newtonian and non-Newtonian suspensions Recently Kawatra and Bakshi[36] reported a system for classifying Newtonian and non-Newtonian suspensions in slurry streams. They used a vibrating sphere viscometer to measure apparent viscosity of slurries at high shear rates and a rotational viscometer to measure apparent viscosity of the same slurry at low shear rates. Since the shear rates were widely different, comparison of the apparent viscosities from the vibrating viscometer and the rotational viscometer allowed classification of the suspensions as either Newtonian or non-Newtonian flow types.

Summary The main advantages of vibrating viscometers over rotational and capillary

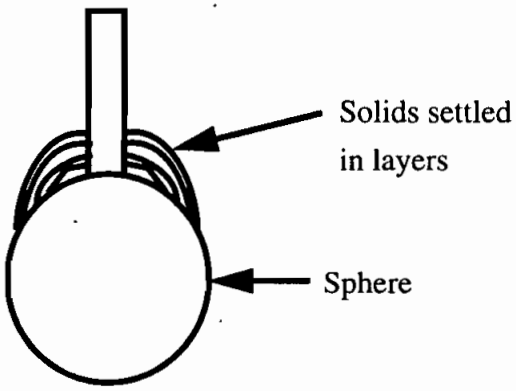

FIGURE 16 Vibrating sphere viscometer showing layers of solids settling on top of the sphere when the fluid velocity passing the spherical probe is small.

viscometers are, (i) these are less sensitive to plant disturbances, (ii) plugging is less of a problem, because these are surface loading instruments and the gap between the sensor and the container wall can be kept as large as required.

Vibrating viscometers still require some sort of agitation system to avoid solids settling. Since these viscometers are highly sensitive to vibrations from surrounding structures, steps must be taken to damp these vibrations. The main disadvantage of these instruments is their poorly defined shear rates which makes them highly unsuitable for measuring true viscosity of non-Newtonian suspensions.

CONCLUSIONS

Rotational and capillary viscometers are the most common viscometers which have been tried for measuring suspension rheology. Rotational viscometers have better control over shear rate which is essential for measuring the full rheology of non-Newtonian fluids. However, these instruments are very sensitive to disturbances in slurry flow. Because of this, many of the special designs studied in this report had baffle arrangements to inhibit unwanted forces like swirling and turbulence in the region of the measuring device. In capillary rheometers this problem is felt to a lesser extent because of the shorter residence time of the suspension inside the tube. However, the sample must be thoroughly mixed prior to its entry into the tube. Plugging is more of a problem in capillary tubes than in rotational viscometers. Slip at the walls is another problem felt by both the capillary and the rotational viscometers. In vibrating viscometers both plugging and wall slip can be eliminated easily, because vibrating viscometers are surface loading and the gap between the sensor and the container wall does not affect the measurement. Also, the vibrating viscometer can tolerate slight disturbance from slurry flow and is rugged enough for on-line use in suspensions. The main disadvantage of a vibrating viscometer is its inability to operate in a steady shear, which makes it unsuitable for non-Newtonian fluids. Otherwise, for Newtonian suspensions and for operations where a relative viscosity is needed vibrating viscometers are best suited for on-line use.

Although in the past many authors have claimed success in measuring on-line

rheology of suspensions, their claims have been refuted later by other authors, because the instruments were not capable of repeating their performance. This shows that the particulate processing industry still needs a reliable viscometer which can work on-line under plant conditions.

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