Rheological characterisation of highly concentrated mineral suspensions using an ultrasonic velocity profiler

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In this research, Ultrasonic Velocity Profiling (UVP), combined with pressure difference (PD) measurement, is experimentally evaluated for the in-line rheological characterisation of different concentrations of opaque non–Newtonian mineral slurries. A unique tube viscometer was designed and constructed. It consisted of four pipes, one of stainless steel and three of PVC, linked to an in-line mass-flow meter and equipped with two different ranges of pressure transducers on each pipe. The stainless steel pipe, with an inner diameter of 16 mm, was equipped with a specially designed flow adapter for in-line rheological characterisation using the UVP-PD method. The three PVC pipes with internal diameters of 9 mm, 13 mm and 16 mm served as a tube viscometer for in-line rheological characterisation of the mineral suspensions. Results determined by the UVP-PD method were compared with results obtained by off-line rheometry and in-line tube viscometry. The agreement between the UVP-PD method, tube viscometry and conventional rheometry was found to be good (within 15 %) for all of the highly concentrated mineral suspensions investigated over a given range of shear rates. This method has been found to have significant potential for the development of new in-line rheometer technology for process control within the mining industry.

Keywords: ultrasound, UVP-PD method, tube viscometry, non-Newtonian, rheology.

1 INTRODUCTION

The rheological behaviour of non-Newtonian, highly concentrated and opaque fluids used in industry have so far been analysed using commercially available instruments, such as conventional rotational rheometers and tube viscometers. Certain authors believe that tube viscometers are best suited for this specific application as they are geometrically similar to a pipeline [1]. However, tube viscometry is time-consuming and design engineers do not have the luxury of unlimited time to entertain the diversities of experimental research [1-2]. The development and adaptation of the UVP-PD technique has given engineers and scientists in the mining engineering field a new tool to investigate the industrial flow process behaviour of these fluids [3-9]. This method was successfully tested on a wide variety of industrial and model suspensions in the food industry [6-9]. It has been shown that ultrasonic propagation through these complex mineral suspensions is indeed possible [10-12]. The main objective of this paper is to evaluate the capabilities of the UVP-PD technique for rheological characterisation of different concentrations of opaque non–Newtonian slurries.

2 LITERATURE STUDY

2.1 UVP-PD technique

Takeda [3] developed a new ultrasonic velocity profile method for mechanical measurements of fluids in physics and engineering. It uses pulsed ultrasonic echography together with the detection of the instantaneous Doppler shift frequency. This method was originally developed in medical engineering to measure blood flow by means of Doppler sonography during the 1960's [13]. A detailed description and working principle of the UVP monitor can be found in Jensen [14] and Met-Flow SA [15]. The UVP-PD set-up and method was developed in Erlangen, Germany by Steger and Muller [4-5]. This concept is based on the Ultrasound Pulsed Echo Doppler Velocity Profile technique (UVP), in combination with a pressure difference method (PD). Ouriev [6] further developed the in-line ultrasound-based rheometer, which was further modified and optimised by Birkhofer and Wiklund [7-9].

2.2 Tube viscometry

A tube viscometer is in essence a small diameter pipeline and therefore geometrically similar to a pipe [2]. The test fluid flows at a measured flow rate through the tube and the pressure drop ΔP is measured between two fixed points L m apart in the pipe. The relationship between the wall shear stress τ_w and the volumetric flow rate Q and the shear stress τ is as follows [16]:

$$\frac{Q}{\pi R^3} = \frac{8V}{D}\frac{1}{\tau_w^3}\int_0^{\tau_w} \tau^2 f(\tau)\,d\tau\,, \qquad (1)$$

where $\tau_w = \frac{R}{2}\left(-\frac{\Delta P}{L}\right)$ and $\left(-\frac{\Delta P}{L}\right)$ is equal to the pressure drop per unit length of tube. The shear stress at any radius *r* is:

$$\tau = \frac{r}{2}\left(-\frac{\Delta P}{L}\right). \tag{2}$$

A plot of 8*V/D* vs τ_w will give a unique line for a given material for all values of *R* and $\left(-\frac{\Delta P}{L}\right)$ in laminar flow. This also provides confirmation of the assumption that the time dependent properties of the fluids tested are not significant. The problem with tube viscometry is that 8*V/D* is not the true shear rate but the wall shear rate for a Newtonian fluid, therefore this "pseudo" shear rate has to be transformed to the true shear rate at the wall, $\dot{\gamma}_w$, by using the Rabinowitsch-Mooney transformation procedure for tube viscometer data [16].

2.3 Rheological characterisation

The equation for the Herschel-Bulkley model is as follows:

$$\tau = \tau_y + K(\dot{\gamma})^n, \tag{3}$$

where *K*, *n* and τ_y are three empirical curve-fitting parameters and are known as the fluid consistency index, the flow behaviour index and the yield stress respectively [16]. Eqs. 2 and 3 can be combined and integrated to give the radial velocity profile:

$$v = \left(\frac{n}{(1+n)}\right)\left(\frac{\Delta P}{2LK}\right)^{\frac{1}{n}} \cdots$$

$$\left(\left(R - R_{plug}\right)^{1+\frac{1}{n}} - \left(r - R_{plug}\right)^{1+\frac{1}{n}}\right), \tag{4}$$

where $R_{plug} = \frac{2L\tau_y}{\Delta P}$ is the plug radius [9]. It will be noted that the Herschel-Bulkley model can easily be modified to describe the power-law and Bingham plastic models.

3 EXPERIMENTAL PROCEDURES

3.1 UVP-PD setup

The schematic layout of the experimental UVP-PD flow loop is shown in Fig. 1. A special flow adapter for repeatable and stable positioning of ultrasound transducers was designed and manufactured. The flow adapter cell was designed for simultaneous measurements of velocity profiles and velocity of sound in-line. More information on this particular design of flow adapter and transducer setup can be found in Birkhofer [7] and Wiklund [8]. Ultrasound transducers (TN and TX-line, Imasonic, France) together with the latest UVP instrument (UVP-Duo-MX, Met-Flow SA, Lausanne, Switzerland) were used for velocity profile measurements. Special software was developed in MATLAB® to fit theoretical velocity profiles to experimental data and determine rheological parameters.

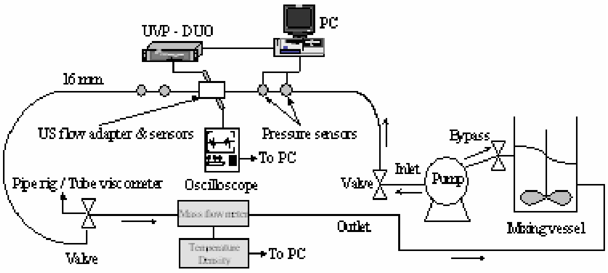

Figure 1: Schematic illustration of the UVP-PD flow loop

The experimental UVP-PD flow loop forms part of a specially designed tube viscometer.

3.2 Tube viscometer

A unique portable pipe rig was constructed at the IMST and is described in detail by Kotzé [17]. The pipe rig consisted of a progressive cavity positive displacement pump with variable speed drive which fed through a damper to minimize pump pulsations to three PVC tubes and one stainless steel pipe. Three PVC tubes were used as an in-line pipe viscometer. The stainless steel pipe (16 mm) was used to measure rheological parameters in-line by using the UVP-PD method. The PVC tubes were in parallel and had 16, 9 and 13 mm inner diameters respectively. All of the pipes were linked to an in-line mass-flow meter (Danfoss, Cape Town, South Africa), which also measures fluid temperature and density. The mixing tank had a capacity of 250 l and was fitted with an electrically driven mixer that ran continuously during tests. Differential pressure was measured by two high range (0-10 bar) and low range (0-1 bar) point pressure transducers (S-11, WIKA, Cape Town, South Africa).

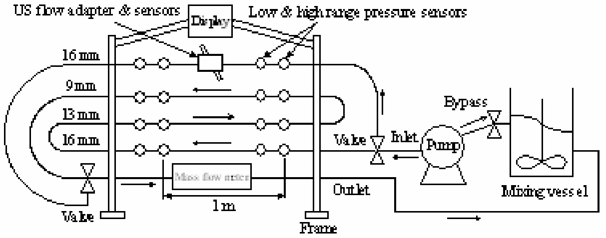

Figure 2: Pipe rig layout

All the outputs of the pressure transducers and the mass-flow meter were connected to a data acquisition unit (µDAQ, Eagle Technologies, Cape Town, South Africa) linked to a personal computer (PC). The schematic layout of the above is shown in Fig. 2.

3.3 Rotary Viscometer

Rheological parameters were also obtained from flow curves measured with a Paar Physica MCR300 rheometer equipped with an air bearing. The cup and roughened bob geometry was used for testing.

3.4 Materials tested

Two model mineral suspensions were tested namely bentonite (Protea Chemicals, Cape Town, South Africa) and kaolin (Serina Kaolin, Cape Town, South Africa). Water was selected for calibration purposes. Bentonite 7 % w/w with a d_{85} of about 25 µm was selected as the Bingham plastic model fluid. The yield pseudoplastic mineral suspension selected was kaolin clay 12 % v/v with a d_{85} of about 35 µm.

4 RESULTS AND DISCUSSIONS

4.1 Bentonite 7 % w/w

An experimental velocity profile along the pipe diameter for bentonite 7 % w/w (density ρ = 1044 kg/m^3, velocity of sound c = 1560 m/s) measured by the in-line UVP-PD method is shown in Fig. 3. These are represented by the theoretical profile obtained by fitting the experimental data and pressure drop using the Bingham plastic model. The flow is laminar, since the value of the Reynolds number is equal to 742 [18], validating the use of the theoretical point velocity distribution equations. The volumetric flow rate obtained from integration of the measured velocity profile equals 0.456 l/s and differs by 11 % when compared to the flow rate obtained from the mass-flow meter (0.411 l/s).

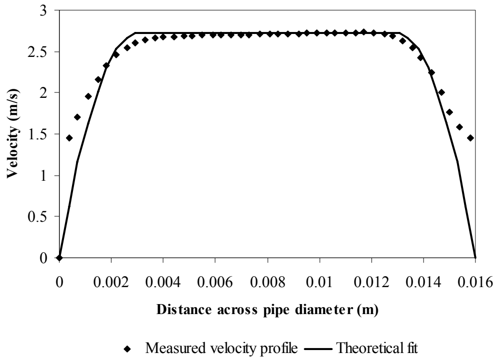

Figure 3: Experimental and theoretical velocity profile for bentonite 7 % w/w

Bentonite suspensions showed little attenuation and absorption of ultrasonic energy and thus the acoustic energy could penetrate across the whole pipe diameter. The end results or flow curves obtained from off-line conventional rheometry and in-line tube viscometry, as well as determined by the in-line UVP-PD rheometric method, are displayed in Fig. 4. Error curves are +/- 15 % error deviations from the UVP-PD flow curve. Results obtained from the tube viscometer and conventional rheometer show good agreement when compared with each other over the shear rate range. The UVP-PD method shows lower apparent viscosities when compared to those determined from the other two rheological methods. However, results show a 15 % agreement when apparent viscosities obtained from all three methods, are compared.

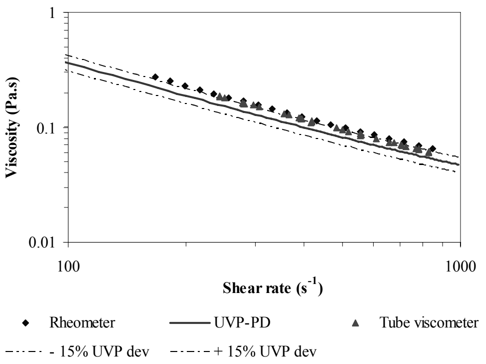

Figure 4: Variation with shear rate in viscosity for bentonite 7 % w/w

4.2 Kaolin 12 % v/v

Experimental and theoretical velocity profile for kaolin 12 % (density ρ = 1198 kg/m^3, velocity of sound c = 1555 m/s) is shown in Fig. 5. The flow is laminar (Reynolds number = 601) validating the use of theoretical Herschel-Bulkley models.

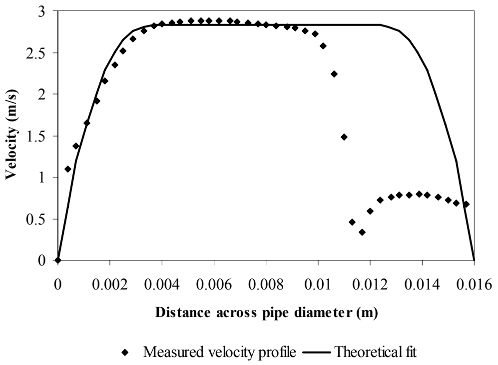

Figure 5: Experimental and theoretical velocity profile for kaolin 12 % v/v

The volumetric flow rate determined by integration is equal to 0.471 l/s and differs by 7 % when compared to the measured flow rate (0.44 l/s). Kaolin mineral suspensions attenuated the ultrasonic energy significantly more than when compared to bentonite suspensions. The effect of ultrasonic attenuation on velocity profile measurements can be observed in Fig. 5. Here the experimental profile starts to distort after the pipe radius (8 mm). In this case the penetration depth was significantly reduced due to ultrasonic attenuation. However, only half of the velocity profile is required for obtaining rheological parameters. The attenuation and absorption of ultrasound energy increased as the solids concentrations of the kaolin mineral suspensions increased and was also observed by Chen et al. [12] and Kotzé [17]. Fig. 6 shows the summary of rheological results obtained from three different methods. Results are in good agreement (within 15 %) with each other across the whole shear rate region (100 to 1000 s^{-1}).

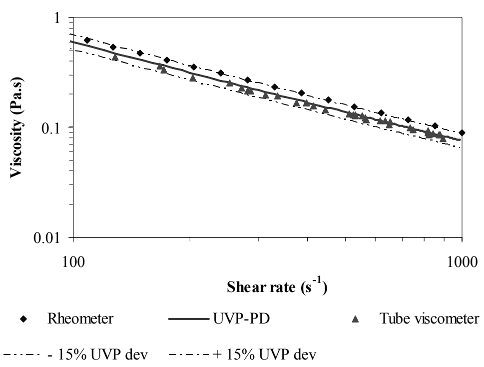

Figure 5: Variation with shear rate in viscosity for kaolin 12 % v/v

Tab. 1 shows mathematically determined rheological parameters from curve fitting for the above model mineral suspensions.

Table 1: Rheological parameters obtained from three different methods for bentonite and kaolin

Fluid	Parameters	UVP-PD	Tube viscometer	Rheo-meter
Bentonite 7 %	*K* (Pa.s)	0.0116	0.0089	0.0145
	n	1	1	1
	τ_y (Pa)	35.15	43.14	42.86
Kaolin 12 %	*K* (Pa.s)	1.32	0.62	3.52
	n	0.43	0.57	0.36
	τ_y (Pa)	49.94	46.15	47.30

5 CONCLUSIONS

The capabilities of the UVP-PD technique for the rheological characterisation of different concentrations of non-Newtonian slurries have been evaluated. Results were found to be in good agreement (within 15 %) when compared with those obtained by off-line rheometry and in-line tube viscometry. The UVP-PD rheometric method can be used effectively for in-line rheological characterisation of highly concentrated mineral suspensions and has been found to have significant potential for the development of new in-line rheometers for process control within the mining and minerals industry.

ACKNOWLEDGEMENT

The National Research Foundation of South Africa (NRF) and the Cape Peninsula University of Technology (CPUT) for funding.

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