In-line ultrasonic device for flow and rheology measurements of complex fluids

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Ultrasound pulsed Doppler velocimetry imaging has been implemented to study the flow and rheological properties of complex fluids undergoing steady pressure driven tube flow. The rheological measurements are based on the principles of velocimeter-based rheometry. The shear rate is determined as a function of radius by differentiating the velocity profile and the conservation of linear momentum theory provides a relation between shear stress and radius that is independent of the constitutive relation. The fluids studied include Microcrystallinecellulose gel, Xanthan gum solution, modified and unmodified starch gels, fruit concentrates, diced particles in fruit juice, hardwood and softwood fiber suspensions, and a polymer melt. A comparison of results with those of conventional rheometers showed that this method has the potential to be used as a process rheometer as it provides shear viscosity data over a wide range of shear rates with a single measurement. The shear rate limitations were investigated and a design curve was generated to predict the deviation of the shear viscosity from the rotational rheometers at low shear rates.

Keywords: Ultrasonics, rheology, viscosity, in-line viscometer, rheometry, shear dependent, complex fluids

1 INTRODUCTION

Many materials are conveyed within a process facility by means of pumping and flow in a circular pipe. From a conceptual standpoint, such a flow offers an excellent opportunity for rheological measurement. In pipe flow, the velocity profile for a fluid that shows shear thinning behavior deviates dramatically from that found for a Newtonian fluid, which is characterized by a single shear viscosity. This difference can be exploited experimentally to determine the shear viscosity at each radial position. From an experimental standpoint, the question we address is what measurements must be made and how to make those measurements in order to ascertain the shear viscosity variation in the pipe. Our goal is to obtain spatially resolved data and to show that from a single set of such data, the viscosity of a complex fluid can be obtained over the range of shear rates in the pipe. This hypothesis is enabled by the capability to measure the velocity and the pressure drop simultaneously. The velocity is used to determine the shear rates and the pressure drop allows the variation of the local value of shear stress. The measurements can be obtained in a standard process flow, without the need for additional pumping capacity or inducing flow in a side stream. We call this approach "pointwise" viscosity measurements. The shear rates are obtained from non-invasive flow measurements, ultrasonic pulsed Doppler veloccimetry (UPDV), while the stress distribution can be readily calculated using standard transducers for pressure drop measurements. Therefore, this method can potentially be employed as an in-line or on-line viscosity probe for process control purposes to improve both process efficiency and end product quality.

2 THEORY

The theoretical basis for pointwise rheological measurements rests with the traditional theory of viscometric flows [1,2]. Such flows are kinematically equivalent to unidirectional steady simple shearing flow between two parallel plates. For a general complex liquid, three functions are necessary to completely describe the properties of the material: two normal stress functions, N_1 and N_2 and one shear stress function, σ. All three of these depend upon the shear rate. In general, the functional form of this dependency is not known *a priori*. However, there are many accepted models that can be used to approximate the behavior, such as the power-law model.

Viscometric flows used for measurements include well-known flows such as flow in a narrow gap concentric cylinder device and between a small angle cone and a flat plate. In both of these cases, the flows established in these devices approximate almost exactly simple shearing flow. There are other viscometric flows in which the shear rate is not constant throughout, these include the wide gap concentric cylinder flow and flow in a circular pipe.

Viscometric flow theories describe how to extract material properties from macroscopic measurements, that are integrated quantities such

as the torque or volume flow rate. For example, in pipe flow, the standard measurements are the volume flow rate and the pressure drop. The fundamental difference with <u>pointwise</u> measurements is that the local characteristics of the flows are exploited. Here, we focus on one such example, steady, pressure driven flow through a tube of circular cross section. The standard assumptions are made, namely that the flow is uni-directional and axisymmetric, with the axial component of velocity depending upon the radius only. The conservation of mass is satisfied exactly and the z-component of the conservation of linear momentum reduces to

$$\frac{dr\sigma(r)}{dr} = r\frac{dP}{dz} \tag{1}$$

where P is the pressure and r is the radial coordinate. The pressure gradient is assumed to be constant and is characterized by a pressure drop, ΔP over a length L. Along with the requirement that the stress cannot be singular at r=0, this allows Eqn. (1) to be integrated as

$$\sigma(r) = -\frac{\Delta P}{2L}r \tag{2}$$

Here, $\Delta P = P_2 - P_1$, where P_2 is the pressure downstream of P_1 and $\Delta P < 0$. Equation (2) shows that the local shear stress in a tube is determined by the pressure drop. Recalling the definition of the shear rate, Eqn. (2), it is seen that both the shear stress and the shear rate are functions of radius. To obtain the shear stress as a function of shear rate, in principle we can solve for the radius as a function of the shear rate and substitute this into the shear expression for the shear stress versus radius. From an experimental standpoint, we measure w(r) in order to calculate the radial depdedence of the shear rate, $\dot{\gamma}(r)$, and, then, at each value of r, determine the shear stress from Eqn. (2). The shear stress versus shear rate is obtained by choosing different radial positions and finding each corresponding value. The shear viscosity, $\eta(\dot{\gamma})$, is defined through

$$\sigma(\dot{\gamma}) = \eta(\dot{\gamma})\dot{\gamma} \tag{3}$$

and can obtained by dividing $\sigma(\dot{\gamma})$ by $\dot{\gamma}$.

The power of this technique is twofold. First, the

viscosity can be measured over a wide range of shear rates. At the tube center, symmetry considerations require that the velocity gradient be zero and hence the shear rate. The shear rate increases as r increases until reaching a maximum at the tube wall. On a theoretical basis alone, the viscosity variation with shear rate can be determined from very low shear rates, theoretically zero, to a maximum shear rate at the wall, $\dot{\gamma}_w$, The corresponding variation of the viscosity was described above for the power-law model where it was shown that over the tube radius, the viscosity can vary by several orders of magnitude. The wall shear rate can be found using the Weissenberg-Rabinowitsch equation

$$\dot{\gamma}_w = \frac{Q}{\pi R^3}\left(3 + \frac{d\ln Q}{d\ln(\Delta P)}\right) \tag{4}$$

where R is the tube radius and Q is the volume flow rate. Since Eqn. (4) requires the measurement of Q for different ΔP, an estimate can be obtained by

$$\frac{d\ln Q}{d\ln(\Delta P)} = 1$$

assuming that fluid is Newtonian with and

$$\dot{\gamma}_w = \frac{4Q}{\pi R^3} \tag{5}$$

The second important feature of this technique is that it is independent of the constitutive relation of the material. This is a direct reflection of its rigorous foundation in viscometric flow theory.

In addition to the measurement of the viscosity, this technique also allows the yield stress to be estimated. For a typical yield stress type material, there is a critical shear stress below which the material does not deform and above which it flows. In pipe flow, the shear stress is linear with radius, being zero at the center and a maximum at the wall. Hence, the material would be expected to yield at some intermediate position, where the stress exceeds the yield stress. The difficulty with this method is in the determination of the point at which yielding occurs and, indeed, whether the material is appropriately modeled as having a yield stress or is better considered as having a highly shear thinning viscosity. For example, if a fluid could be modeled as a power law material with an exponent of 0.25, the velocity profile from $\frac{r}{R} = 0$ to $\frac{r}{R} = 0.4$ varies

by 1%. From a purely experimental standpoint data showing such an effect could either be interpreted through a low power-law exponent or through a yield stress. The latter interpretation can result in robust estimates of this difficult to measure parameter.

As we shall see, the limitation on this technique stems from two related sources. First, the velocity data must be differentiated at each radial position to obtain the local shear rate. If the velocity data are not sufficiently smooth, large errors can result. Secondly, near the tube center, the velocity gradient is nearly zero. The precision of the measurement is particularly critical to obtain meaningful data in this region.

3 EXPERIMENTAL

The velocity measurement was performed by emitting multiple ultrasound pulses through the pipe and recording the echo, which was scattered from the particles in the fluid. After demodulation and low pass filter, the signals were stored and analyzed in a desktop computer. The position was calculated from time of flight of the sound wave and the velocity was calculated using the Doppler shift frequency effect, in which a wave scattered from a moving particle is subject to a frequency shift proportional to the velocity of that particle.

Signal analysis was carried out using a fast Fourier transform program and velocity profiles were monitored. The average velocity values used in velocity profiles were calculated by power weighted averaging. Each velocity profile was plotted by averaging of eight consecutive velocity profiles to increase accuracy.

Two types of flow loops were used. One was primarily for suspensions of foodstuffs and materials which generally could be easily pumped. This flow loop consisted of a 53.2mm internal diameter acrylic tube, a positive- displacement pump and two pressure transducers. To provide steady fully developed laminar flow conditions, the ultrasound probe was placed 5 m from the loop bend and the ratio of the length between pressure transducers to tube diameter was 67.

The second flow loop was used for polymer melts. This flow system consisted of 5.5 m long, 2.04 cm diameter acrylic tubing and 1.5 m long, 2.54 cm diameter stainless steel tubing and a gear pump. Stainless steel tubing was used at the exit of the pump to handle the high pressure in this section. The pressure drop was measured using two flush mounting pressure gauges P-1550 (Ametek, U.S. Gauge, PMT Products) that were placed 1 m apart.

All measurements were performed at room temperature and the temperature of the fluid was measured by a digital thermocouple in the storage tank. Two different flow rates studied were 4ml/sec and13ml/sec. It was not possible to increase the flow rate higher than 13ml/s due to the limitations of the flow system.

The ujltrasound probe was a 6.35 mm diameter piezo-electric transducer, which was clamped to the pipe wall with an angle of 45°.

From the velocity profiles of a fully developed laminar flow and simultaneous pressure drop measurements, shear rate and shear stress can be calculated, respectively [3].

4 RESULTS

Typical results for these experiments are shown in Figure 1. Here data are shown for the shear viscosity as a function of shear rate for various suspensions of tomato solids. The upper curve represents data for a 17% suspension, the middle curve, a 12.75% suspension and the bottom an 8.75% suspension. For the top and the bottom curves, the data were obtained from a single measurement of the velocity profiles. In each case, it is observed that data over nearly two decades of shear rate were measured. Also, over the entire shear rate range, the viscosity is strongly dependent upon the shear rate. The middle set of data contains two other features. First, there are two sets of UPDV data that were obtained at two different flow rates. The data are essentially indistinguishable. However, the data do access somewhat different ranges of shear rates. That is, the lower the value of the flow rate, the lower the range of shear rates that can be accessed during a UPDV experiment. Secondly, there are four data points represented by triangles. These data were obtained using a capillary viscometer and applying the standard formulas for calculating viscosity. Excellent agreement is found between the UPDV data and those obtained by the conventional method.

These results and similar studies on a wide range of fluids clearly demonstrates that usefulness of UPDV for viscosity measurements of complex fluids. For example, Fig. 2 shows velocity profiles obtained for paper pulp suspensions using UPDV. In this case, the velocity profiles are nearly constant over a most of the pipe. This can either indicate that the suspension is behaving as a power law fluid with a low power law exponent or it is behaving as a material with a yield stress. In the latter case, the yield stress can be associated with the radial position at which the velocity begins to decrease from its constant value. The yield stress measured

in this way is 13.6 ±3.1 Pa. An alternative means of determining the yield stress is with a vane viscometer. The value that we obtained for this same suspension was 10.3 ±2.6 Pa. The similarity between these two techniques is quite good. The yield stress itself is typically difficult to determine and there are very few studies that show agreement between the values obtained by different methods.
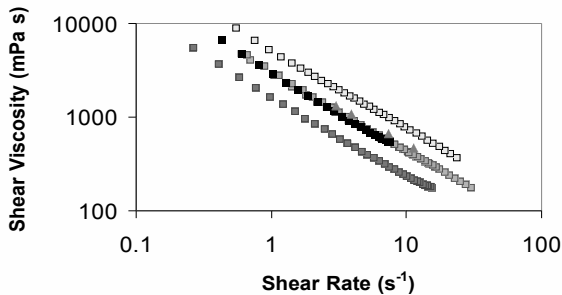

Figure 1. Shear viscosity versus shear rate for tomato suspensions obtained using UPDV (17%, top; 12.75%, middle; 8.75%, bottom; also shown by triangles are capillary data)
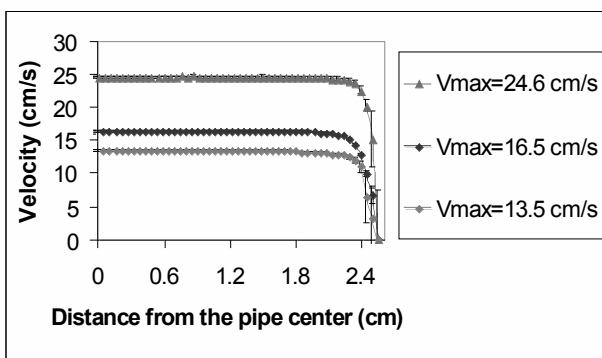

Figure 2. Velocity profiles for a pulp suspension measured by UPDV. The different profiles represent data obtained at different maximum velocities.

4 CITATIONS AND BIBLIOGRAPHY

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