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INLINE ULTRASONIC RHEOMETRY OF A NON-NEWTONIAN WASTE SIMULANT

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INTRODUCTION

The viscosity of a Hanford waste stream is potentially an indicator of its composition, including solids load, and of how well it has been mixed. Viscosity could be a useful control variable that might indicate the need for heating or dilution, for example. However, traditional off-line measurements are slow and samples can be difficult to take. Pausing processing to take samples disrupts and slows down production schedules and so, if viscosity measurements are necessary, requires increased capacity in the whole process. An alternative viscosity measurement that does not require sampling and that is fast would be more useful than traditional techniques.

In this work, rheological measurements of a waste simulant were made without taking samples. A viscometric flow was created within the transport pipeline itself and shear stress and shear rate were recovered from relations valid for developed steady state laminar flow in a long horizontal pipe[1],

$$\tau = \frac{\Delta P}{2L} r \tag{1}$$

$$\dot{\gamma} = -\frac{d\mathrm{v}}{dr} \tag{2}$$

viscosity being the ratio of shear stress to shear rate, τ/γ. In equation (1) the local shear stress is shown to be a linear function of the distance from the centerline of the pipe r, the proportionality constant being half the pressure drop per unit length of pipe. A simple measurement of pressure drop was performed to determine the shear stress profile in the measurement volume. In equation (2) the local shear rate is given by the local velocity gradient. In this work we determined the velocity gradient from flow profiles measured by pulsed Doppler ultrasonic velocimetry. The velocimeter determined the Doppler frequency shift of a backscattered ultrasonic signal as a function of the range of a scattering particle from the transducer.

MATERIALS AND METHODS

The waste simulant used was a 1.8 weight percent mixture of RD Laponite (Rockwood Specialties Inc.) in tap water, prepared according to the manufacturer's directions. The fluid was seeded with glass beads ("Ballotini Impact Beads, AH-Spec" from PQ Corporation, with diameters between 45 and 90 microns) to a concentration of 0.05-vol. percent. The beads served to scatter the ultrasound pulses back to the transducer. The beads did not settle or migrate.

The ultrasonic transducer was mounted in a long, straight, level section of 2-inch nominal ID plastic pipe, as previously discussed[2]. The transducer was positioned approximately 100-pipe diameters downstream of disturbances, so that the flow in front of it could be treated as fully developed. The pressure drop per unit length was measured in the straight section using a pair of flush mounted diaphragm pressure transducers (GP:50 model 280-C-PE-2-FS-GJ, 0-2 psig range). The pressure transducers were positioned approximately 3.69m apart. The large diaphragms of the transducers were placed tangential to the inner diameter of the pipe, to eliminate errors that would result from blocked pressure ports. The simulant was circulated with a progressive cavity pump with a variable speed drive. A surge bottle was installed downstream of the pump to dampen pressure fluctuations.

The ultrasonic transducer layout remained as previously discussed[2]. A single ultrasonic transducer (XACTEX model IM-HP-1/4-5 XIM 1055-27) was inserted into a port in a PVC block that was inclined at an angle of 45 degrees with respect to the centerline of the block. The block was then inserted in the pipe loop. The block had been bored out to match the ID of the upstream pipe to within 0.005 inches, taking care to keep the pipe and block concentric. The transducer was positioned in the port so that one edge of its face was flush with the inside wall of the block.

The drive signal sent to the ultrasonic transducer consisted of a 5MHz carrier modulated by a pulse train. The pulses were short (5-20 cycles of the carrier wide), effectively sampling the Doppler waveform. The backscattered sound from each transmission was received, quadrature demodulated (outputting I and Q channels) and range-gated, using approximately 100 ranges across the width of the pipe. The results were saved for long sequences of pulses (of the order of 1024). A complex FFT of $I+iQ$ at a given range over the duration of the pulse sequence yielded a power spectrum that was usually peaked at the Doppler frequency. In this work the 50% point of the integrated power

spectrum was chosen as the Doppler frequency for a specified range. From this frequency the velocity at that range x was calculated using the usual relationship,

$$v(x) = \frac{c}{2\cos\theta}\frac{f_{Doppler}(x)}{f_{carrier}}, \tag{3}$$

where θ was the angle (in this case 45-degrees) of the ultrasonic beam off the pipe axis. Performing the FFT and estimating the Doppler frequency from the spectrum for every range across the width of the pipe yielded the velocity profile. The range data provided by the Doppler velocimeter were corrected for the distance along the beam axis from the center of the active piezo element (which sits behind a thin epoxy impedance matching layer and a small pocket of stagnant fluid) to the inner wall of the block. The origin of the coordinate system was then translated again from the inner wall to the centerline of the block and pipe.

Pulse repetition rates were chosen to be at least twice the expected maximum Doppler frequency to avoid aliasing. In this work the repetition rate was approximately 5kHz. The maximum velocity that could be measured at this rep rate was approximately 0.5m/sec. The duration of the entire pulse train was approximately 0.2 sec. With this duration the best possible velocity resolution was of the order of ± 1 mm/sec.

In this work 16 velocity profiles were obtained at each experimental condition. The shear rate profile was represented by a cubic spline

$$\dot{\gamma} = \sum_{j=0}^{N} \alpha_j \varphi_j(r/R) \tag{4}$$

where the φ_j are b-spline basis functions, r is the distance from the centerline and R is the radius of the pipe. Six basis functions were used (N=5), positioned at equally spaced knots from the centerline of the pipe to the wall. The integral of the shear rate was fit to the 16 velocity profiles to determine the spline parameters α_j. The data were weighted by the estimated scan-to-scan standard deviation of the velocity at each range and the normal equations (of least squares analysis) were modified to include a slight stiffening of second derivative of the spline at the interior knots to improve stability (the modifying terms introducing prior knowledge that the shape of a velocity profile is not too different from one for a fluid with a constant viscosity). With this inversion procedure differentiation was avoided and semi-empirical models of the viscosity were avoided.

RESULTS

Plotted as symbols in Fig. 1 are measured velocities versus distance from the centerline, at three different flow rates (the flow rates are approximate). Both axes have been divided by the radius of the pipe. The data were taken after steady state had been obtained in the flow loop. The profiles exhibit the central plug characteristic of shear thinning fluids. Also plotted are the fitted velocity profiles from the algorithm discussed

above. The shear rates versus position were recovered from the profiles using equation (4).

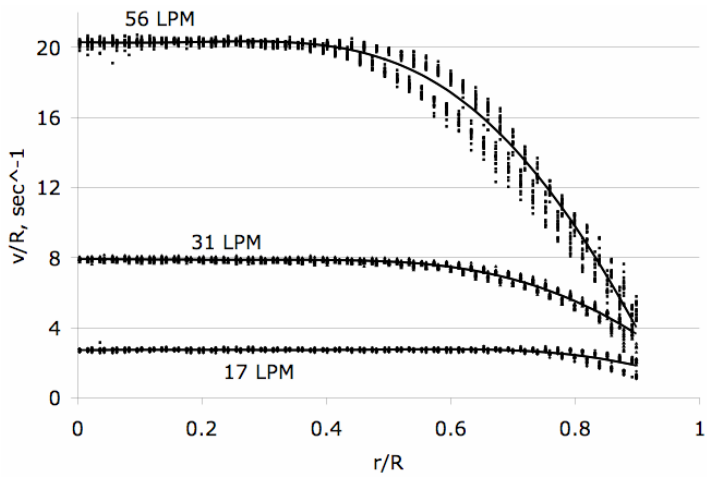

Figure 1

The velocity data were weighted during fitting by the scan-to-scan standard deviations. An example plot of the standard deviations versus distance from the transducer face is given in Fig. 2. Data were more scattered near the walls, the scatter being greatest near the far wall. It is hypothesized that the increased scatter resulted from a reduction in the peak amplitude of the spectrum near the walls caused by velocity gradient broadening.[3] Near the walls the velocity gradient was large and the width of the beam samples a broad range of velocities leading to a reduction in peak spectral amplitude. The effect was less near the transducer face as the pocket of stagnant fluid in front of it introduced a free slip surface. The broadening was small away from the walls because the velocity gradient was small in the central plug. The fitted velocity profile curve lies closer to the near wall data than the far wall, because the former were more heavily weighted. Measured velocities near the far wall tended to be lower than those close to the near wall, at the same distance from the centerline. Measured far wall velocities tend to be biased slightly low, as the velocity gradient broadening shifts the 50% point of the integrated spectrum to frequencies below those present along the beam axis.

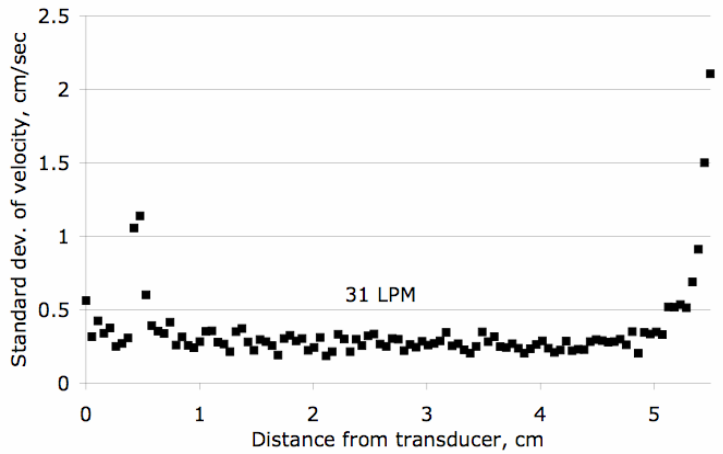

Figure 2

Plotted in Fig. 3 are rheograms for the simulant, obtained at the three different flow rates and steady state. The fluid exhibited an effective yield stress at all three flows. Uncertainty in the slope of the velocity profile in the central plug exists however, because of the scatter in the data. This uncertainty resulted in a corresponding uncertainty in the shear rate at small shear rates.

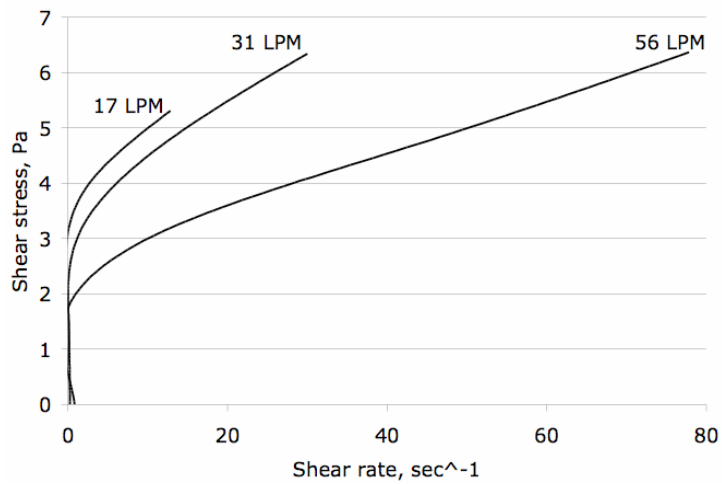

Figure 3

CONCLUSIONS

The method presented in this paper provides shear viscosities of a fluid over the whole range of shear rates present in a pipe flow. The method is non-invasive, does not interrupt the process and can provide continuous output. It is a true inversion of the pipe flow profile, with only minimal assumptions about the mathematical properties of the shear rate and the kinematics of pipe flow and no assumed physical model of the rheology.

The presentation will discuss factors that influence the performance of the instrument.

ACKNOWLEDGEMENT
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