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SLURRY PIPE FLOW MEASUREMENTS USING TOMOGRAPHIC ULTRASONIC VELOCIMETRY AND DENSITOMETRY

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ABSTRACT

This paper presents the preliminary results for demonstration of a new approach for measurement of the velocity profile in a heterogeneous slurry pipe flow. This technique is based on simultaneous tomographic pulse-echo ultrasonic flow velocity and time-of-flight speed of sound measurements. Reconstruction of the velocity distribution is based on the measured local speed of sound, which depends on the local slurry concentration. To show the feasibility in applying this technique, we have carried out controlled experiments in the laboratory with known fluids and flow conditions. The two fluids tested were a viscous Newtonian fluid, propylene glycol, and a non-Newtonian fluid, Carbopol 980. The flow conditions tested were fully-developed laminar pipe flow. The velocity measurements were validated against both LDV measurements and theoretical predictions. The speed of sound results were shown to produce reproducible measurements and consistent with existing data. Obtaining an accurate velocity profile is our first milestone for developing an on-line, real-time rheometer for measurements in dense slurries flowing within pipelines.

INTRODUCTION

Rheological characterization of solid-liquid dispersions are commonly performed using off-line measurement devices. This approach has been under critical scrutiny since once a sample is withdrawn from the process stream its rheological properties will begin to change. Most often, the fluids to be characterized have rheologies that intimately depend on the flow field. This dependence is especially true for colloidal suspensions in which size and fractal dimensions of the clusters or aggregates depend strongly on the environment under which they exist. Many of these fluids exhibit shear-dependent viscosity, in the form of shear thinning or shear-thickening behavior (Smith et al. 1997), requiring determination of their viscosity at various shear-rates which correspond to the range of shear rates observed in the flow field. Off-line measurements can hardly reproduce the same conditions which exist in a real flow field such as shear induced migration of solid particles (Leighton and Acrivos, 1987). Further, given that the material in the pipeline may not be homogeneous, it will be difficult to obtain a representative sample for off-line measurements.

Existing real-time on-line process monitoring rheometers monitor the properties of a side stream of material (Dealy and Wissbrun, 1990). The steady shear viscosity is measured at a single shear rate (or flow rate). To obtain viscosity at various shear rates, either the flow rate in the side stream is controlled by an auxiliary pump or several parallel or serial side streams at different flow velocities are produced. For example, the current capillary viscometry technology uses an auxiliary pumping capacity and by cascading a series of capillary tubes, which limits the number of data points to the number of tubes, provides multiple-point viscosity measurements.

The target of the ultrasonic measurements is the local shear rate as determined from the measured local velocity in the pipe. This may be achieved by using an ultrasonic reflection-mode (pulse-echo) Doppler velocity mapping system. The principle of operation of the system is as follows: Ultrasonic transmission time-of-flight measurements can be used to determine the integrated line-of-sight acoustic velocity in the fluid. If the fluid

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contains scattering particles, then a coherent reflection system can be used to measure the Doppler frequency shift caused by the fluid flow. The magnitude of the Doppler shift can be used to determine the fluid velocity. Applying a sequence of range gates to the Doppler measurements allows determination of the fluid velocity profile along the line-of-sight of the ultrasonic transducer. If the acoustic velocity is uniform across the cross-section of the pipe, and is axisymmetric then this range-gated ultrasonic Doppler data can provide accurate measurement of the fluid velocity profile.

This approach has previously been implemented to the measurement of velocity distribution in uniform and homogenous fluids (Brunn et al. 1993, Vorwerk et al. 1994). However, in pipes involving flow of complex fluids of unknown or varying properties, both the fluid velocity profile and the acoustic velocity are expected to be nonuniform across the cross-section of the pipe. The time-of-flight acoustic transmission measurement will be in error if the fluid velocity is not taken into account, and the reflection Doppler measurement will be in error if the acoustic velocity profile is not known. This will cause a distortion of the fluid velocity profile measured by the ultrasonic Doppler system, since the Doppler shift is proportional to the acoustic velocity and the range gate mapping assumes a uniform acoustic velocity across the pipe.

In this paper, we explain a technique based on tomographic measurement of the speed of sound and fluid velocity in the pipe. Our objective is to obtain a more accurate profile of velocity within flow fields where the speed of sound can change within the cross-section of the pipe. This profile is obtained by reconstruction of the velocity profile from the local speed of sound measurement simultaneously with the flow velocity. Since this is work in progress, we present the results obtained here to date and defer further results of our work in the future papers.

PRINCIPLES OF OPERATION

Ultrasonic Doppler velocimetry (UDV) relies on measurement of the Doppler frequency shift of moving tracer particles, or scatterers, within a pipe flow. Using a short ultrasonic pulse system, the cross-sectional velocity profile can be obtained from the Doppler shift at each point in range. The Doppler frequency shift is given by

$$f_D = \frac{2v}{c} f \qquad (1)$$

where v is the particle velocity, c is the speed of sound in the fluid, and f is the ultrasonic frequency. For example, the Doppler shift for a particle moving with velocity of 1 m/sec in water with speed of sound equal to 1500 m/sec, and an ultrasonic frequency of 5 MHz is 6.67 kHz.

In order to obtain good range resolution it is essential to transmit a short ultrasonic pulse. The range resolution is approximately equal to one-half of the spatial width of the pulse. For N sine-wave cycles of wavelength λ, the range resolution is approximately

$$\Delta_R = N \frac{\lambda}{2}. \qquad (2)$$

For example, 5 cycles of 5 MHz (0.3 mm wavelength) yields a range resolution of approximately 0.75 mm. Obtaining such high range resolution creates a problem for measurement of the Doppler shift which is on the order of kHz. A gated sine-wave of only a few cycles has a relatively wide frequency bandwidth B of approximately,

$$B = \frac{f}{N} \qquad (3)$$

which is 1 MHz for 5 cycles of a 5 MHz wave. The Doppler shift would need to be on the order of or larger than 1 MHz to be distinguishably measurable from the frequency spectrum of the echo returned from the particles. Doppler shifts this large would only be expected if the fluid velocity were on the same order as the speed of sound in the fluid. Velocities of interest in pipe flow problems are much lower than the speed of sound. While reducing the bandwidth would allow for good Doppler velocity resolution it would yield a poor range-resolution. To resolve this conflict, we have opted to transmit and receive multiple pulses, i.e. to observe the fluid over a much longer time interval and obtain a higher number of observations from each point in the flow field.

DATA COLLECTION SYSTEM

The data acquisition system consists of a series of ultrasonic Doppler transceivers, computer interface, analog-to-digital converter, and computer system. The transceiver generates a specified number of cycles (currently 5) of ultrasound, then amplifies and transmits them through the ultrasonic transducer.

The same transducer is used to receive the echoes from the fluid particles. The received signal is passed through a low noise amplifier chain with gain adjustable to 99 dB. After amplification the received signal is coherently down converted in frequency from 5 MHz to baseband (centered at DC). Frequency down-conversion allows a much smaller amount of data to be recorded by the A/D converter than would direct A/D sampling. Computer interface electronics generate the sampling clock pulses used by the A/D converter. This number of pulses is adjustable, as is the time delay to the first sample. After A/D conversion the data is stored on the computer systems disk-drive.

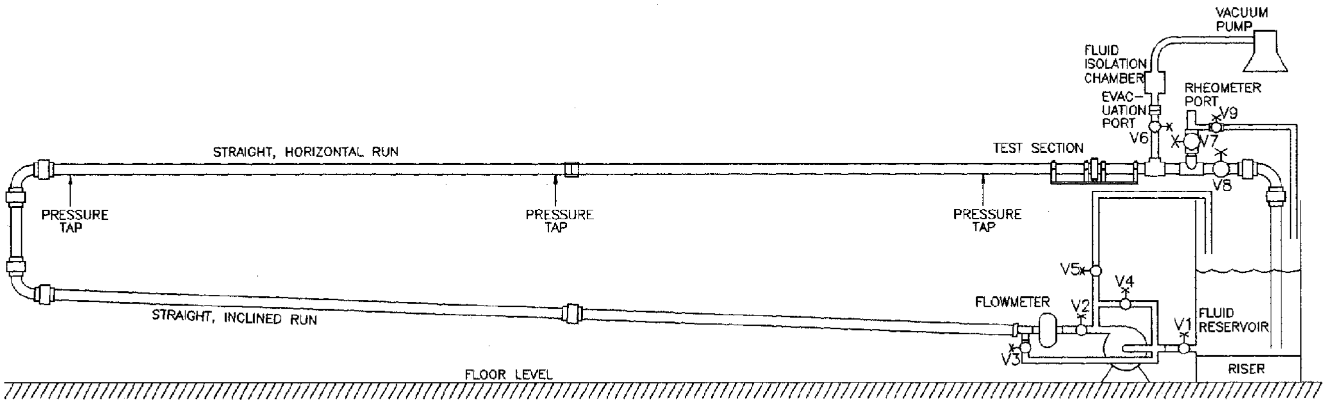


Figure 1. Pipe Flow Loop for Producing Laminar Fully-Developed Flow

APPARATUS AND PROCEDURE

A fully-developed flow in a circular pipe was generated using the hydraulic system shown in Figure 1. Flow was delivered to a 5.5 m long x 5 cm diameter (nominal) straight PVC pipe section. The ultrasonic transducer block was located far enough downstream such that the flow became fully-developed with no swirl or secondary flow before reaching the transducers. The flow rate in the pipe was measured using a positive displacement flowmeter.

A dual-beam arrangement LDV system working on the backscatter mode was used to verify what the velocity distribution in the pipe is for both Newtonian and non-Newtonian fluids. The probe volume dimensions were approximately 0.1 x 1 mm. The two beams were aligned along the axis of the pipe such that the pipe curvature was not an issue for the axial velocity measurements.

Figure 2 shows the orientation of the opposing transducers installed on the pipe. For velocity profile measurements, the ultrasonic signal was transmitted into the pipe and return signal was received by the same transducer (transceiver) and supplied to the data acquisition system. The processed signal was then converted into a velocity profile. For speed of sound measurements, the time-of-flight for the signal transmitted by one transducer to reach the receiving transducer was measured. To perform tomography, a grid of transducers was placed around the pipe. Figure 3 illustrates the orientation of the transducers and the transducer numbers. Two transducers were placed along each chord -- one for velocity measurement and the other for speed-of-sound measurement.

We used 50 μm silver-coated glass particles as tracers for both the LDV and UDV techniques. These particles were found to be very strong scatterers for both the LDV and UDV systems. Since we were exclusively operating in the laminar flow regime, we were not concerned with the dynamic response of the particles. Settling of particles was finite but not significant for the Newtonian case ($u_s/U<10^{-3}$), and almost non-existent for the non-Newtonian fluid which had a strongly shear-thinning behavior.

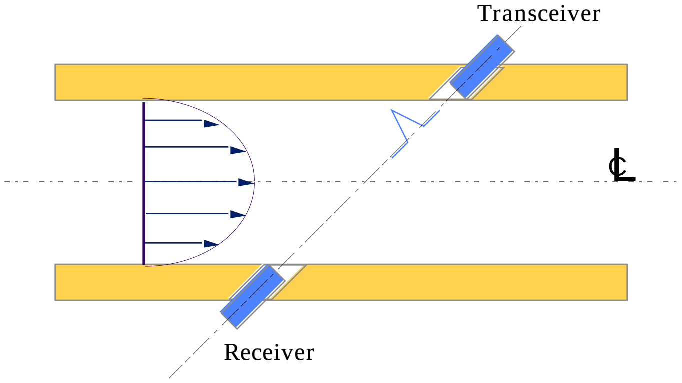


Figure 2. Ultrasonic Transducers Orientation.

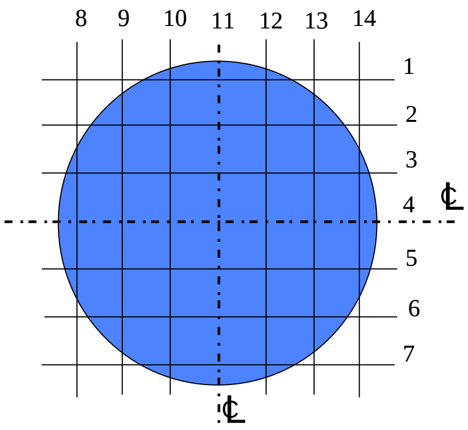


Figure 3. Grid for Tomographic Measurement.

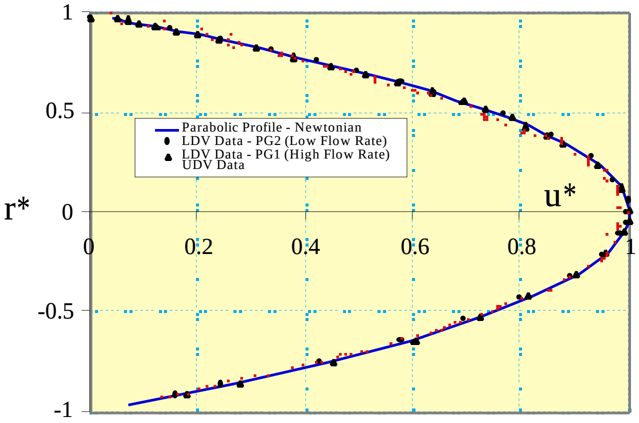


Figure 4. Distribution of Newtonian Fluid (Propylene Glycol) Velocity in the Pipe Measured with LDV.

LDV RESULTS

The axial velocity distribution was measured in the pipe for two different flow rates of propylene glycol, producing Reynolds numbers of 250 and 500. Figure 4 shows the profile of normalized velocity for both conditions. The data collapsed very well on the theoretical parabolic distribution, suggesting that the velocity had reached the fully-developed condition well before reaching the ultrasonic transducers. Current UDV measurements are also shown on this plot for comparison. In the next section we will explain how these UDV data were obtained.

SINGLE TRANSDUCER UDV RESULTS

Figure 5 is a radial profile of the probability density function (PDF) of the axial velocity within the non-Newtonian flow obtained using the current UDV system. The speckled appearance of this profile is due to the random nature of the incoming signal from the scatterers as well as finite domain FFT aliasing.

With such high level of shear-thinning behavior, the velocity profile commonly shows a plug-like regime in the core. Figure 5 clearly shows such behavior. Indeed, it was observed that at lower velocities the size of the plug increases in the radial direction, as is reported by other investigators. Therefore, qualitatively, we believe the ultrasonic measurements are providing the correct results. On this figure, we also show the results of our tests on the effect of number of cycles in a pulse transmitted into the fluid on broadening of the velocity distribution (Figure 5). We found that consistent with our intuition, the velocity density function at each radial location broadens as the number of cycles decrease from 10 to 2 cycles per pulse. However, when we increased the number of cycles to 20, our spatial resolution became poor and we did not obtain any better results than 10 cycle pulse conditions. Therefore, most of our experiments were performed with 5 or 10 cycle pulses.

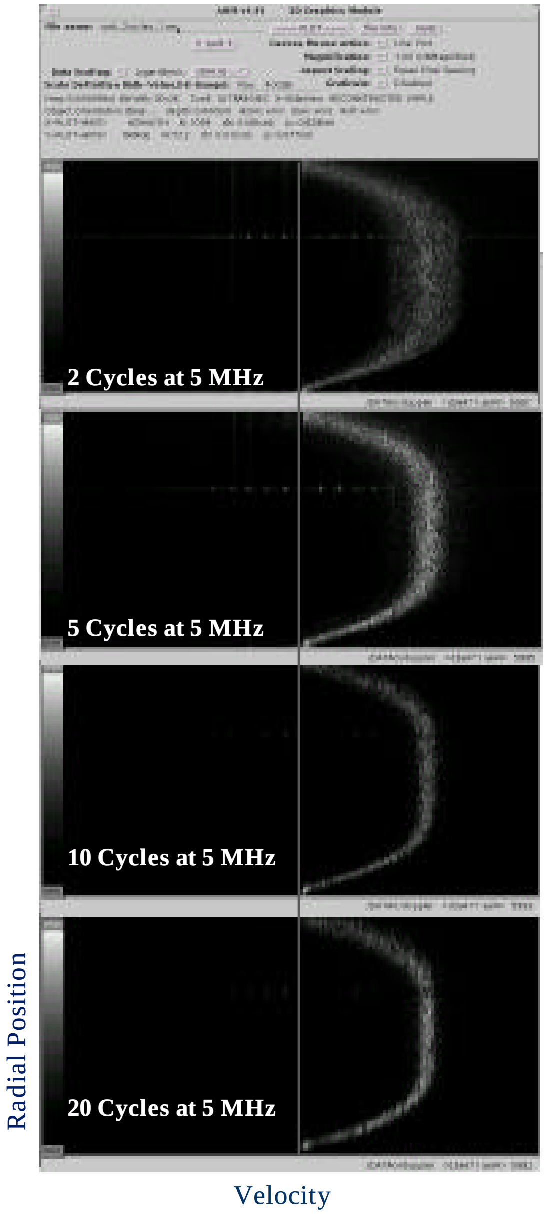


Figure 5. Effect of Ultrasonic Pulse Width on the Distribution of Fluid Velocity -- Non-Newtonian Flow in the Pipe Measured with UDV.

To obtain a unique velocity distribution from the images shown on Figure 5, it is necessary to process the data further such that at each radial position a single number representative of the local velocity is obtained. We take advantage of the fact that the velocity at each radial location is represented by a probability density function (PDF). A typical PDF of velocity is shown in Figure 6. This PDF was obtained by averaging over 0.512 sec which results in a rather smooth distribution. The peak of this distribution was selected as the maximum likelihood of the local velocity.

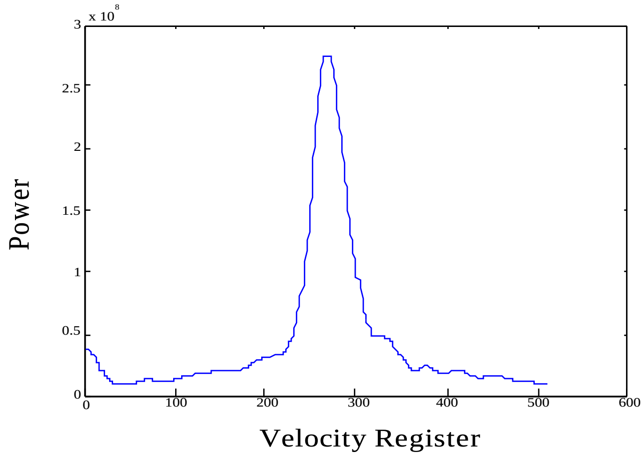


Figure 6. A Typical Probability Density Function (PDF) of Axial Velocity in the Pipe.

Figure 7 shows the results of the velocity distribution for both LDV and UDV measurements. These distributions were found for the same flow conditions and normalization was done using the maximum velocity in the pipe. In most parts, the UDV and LDV measurements show less than 5% discrepancy. This is due to higher variance in UDV measurements at specific points in the pipe, caused by multiple reflection interference. That is the echo of the previous pulses created a high background noise level and as a result increased fluctuation in the measurements (see Figure 5). Further, the UDV data seemed to show anomalous behavior near the wall caused by probe penetration into the wall. These two effects can be corrected by more careful design of the transducer block.

Figure 8 is a plot of the center chord velocity profile measured using the current ultrasonic approach versus the theoretical prediction using an analytic solution for a power-law fluid. These results are plotted separately from those shown on Figure 7 because the rheology of the fluid was slightly different. The fluid was more non-Newtonian in the case shown on Figure 7 than that on Figure 8.

The closed-form analytical solution for a fully-developed laminar pipe flow of a power-law fluid may be written as (Barnes et al. 1993),

$$v(r)=\frac{Q(3n+1)}{\pi R^2(n+1)}\left[1-(r/R)^{\frac{n+1}{n}}\right] \qquad (4)$$

where v is the axial velocity, Q is the volumetric flow rate in the pipe, R is the radius, and n is the behavior index of the pseudoplastic fluid. Substitution of the flow rate measured (367±5 ml/s), radius of the pipe (26±0.1 mm), and the behavior index of the fluid obtained from rheological measurements (0.38±0.1) results in the following relation:

$$v(r)=26.8\left[1-(r/R)^{3.63}\right] \qquad (5)$$

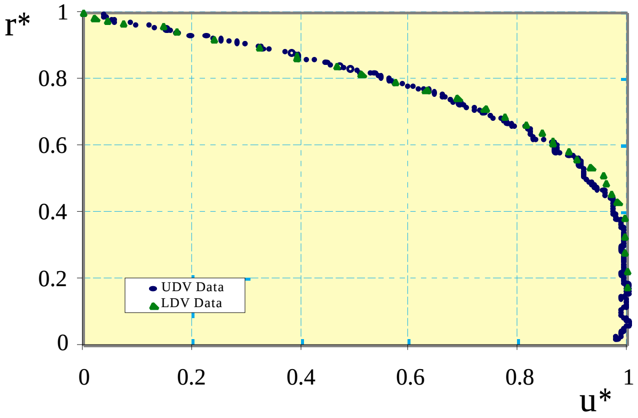


Figure 7. Comparison of LDV versus UDV Velocity Measurements for the Non-Newtonian Flow.

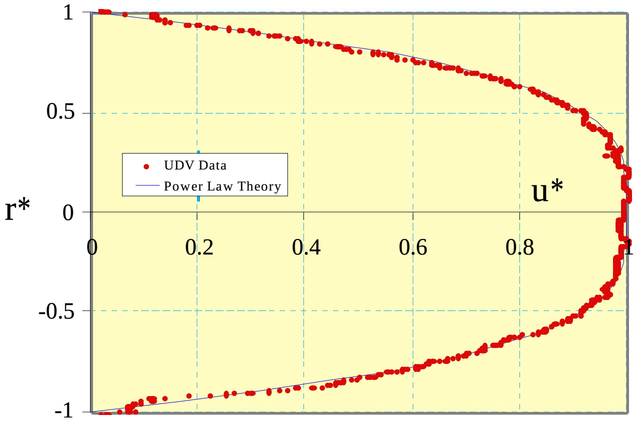


Figure 8. Comparison of UDV Velocity Measurements with the Power-Law model for the Non-Newtonian Flow.

where the velocity is in cm/s and r is in cm. Using this relationship, the analytic results, shown as solid line on Figure 8, closely matched the experimental results obtained with the ultrasonic velocimeter. Further, the profile of velocity found from ultrasonic measurement was numerically integrated over the cross-section of the pipe. The flow rate was found to be 356 ml/s which is within 3% of the flowmeter reading.

Time-of-flight measurements were made to determine the speed of sound locally in the pipe. Figure 9 is a typical time trace of the signal amplitude measured at the receiver. This particular signal is for the corner transducer pairs (1 on Figure 3). The time it takes for the signal to be detected at the receiver is the transit time or time-of-flight of the ultrasonic wave. In this case, it took approximately 33 μsec for the signal to reach the receiver. The first peak in this figure is simply leakage from the transmitter into the receiver via the electronics and it should be ignored. Since the distance between the transmitter and receiver is known and fixed, the speed of sound in the fluid as a function of time can be detected, in real-time (~1485 m/s for our fluid).

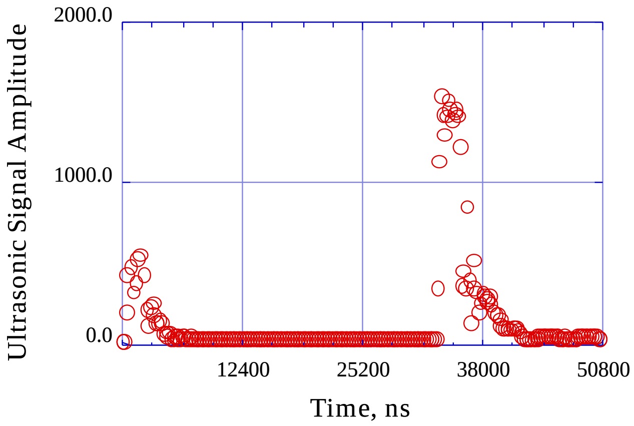


Figure 9. Transmit-Receive Signal for Speed of Sound Measurements.

TOMOGRAPHIC UDV RESULTS

We used the orthogonal grid arrangement shown on Figure 3 for tomographic measurements of the velocity profile and speed of sound. For flows where settling or segregation of particles do not exist, or if the velocity profile is axisymmetric, the measurements along several of the chords shown should ideally be identical. Conversely, any flow nonuniformity due to lack of symmetry (coming from swirl or secondary flow in the pipe) or settling, saltation, or segregation in the solids within the pipe would be observable by comparison of the results obtained from the different symmetric chords. Of course in the current measurements we did not expect to see any difference in the measurements made by symmetric transducers (see Figure 3). Nonetheless, such measurement could provide an indication on the measurement uncertainty.

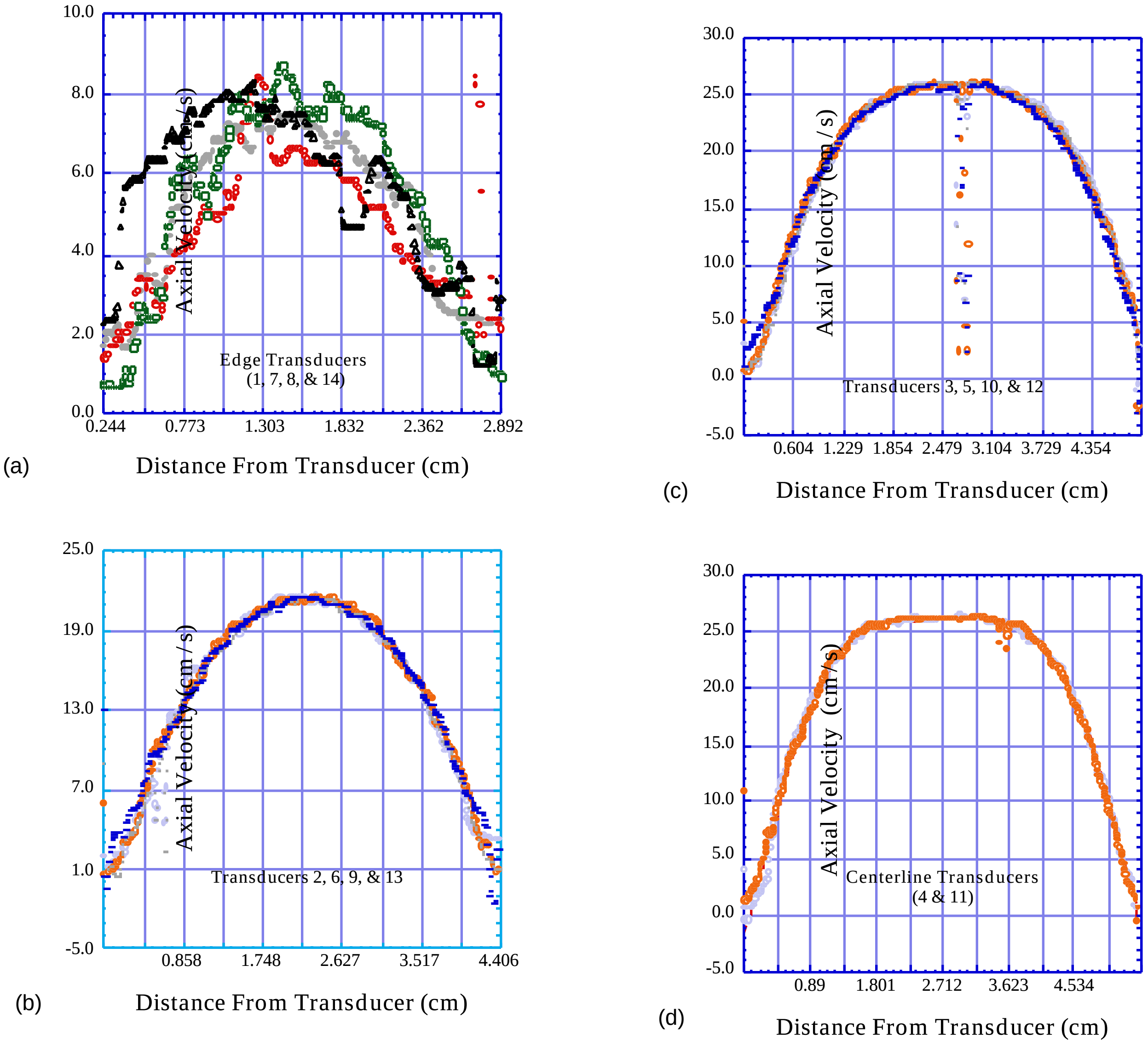
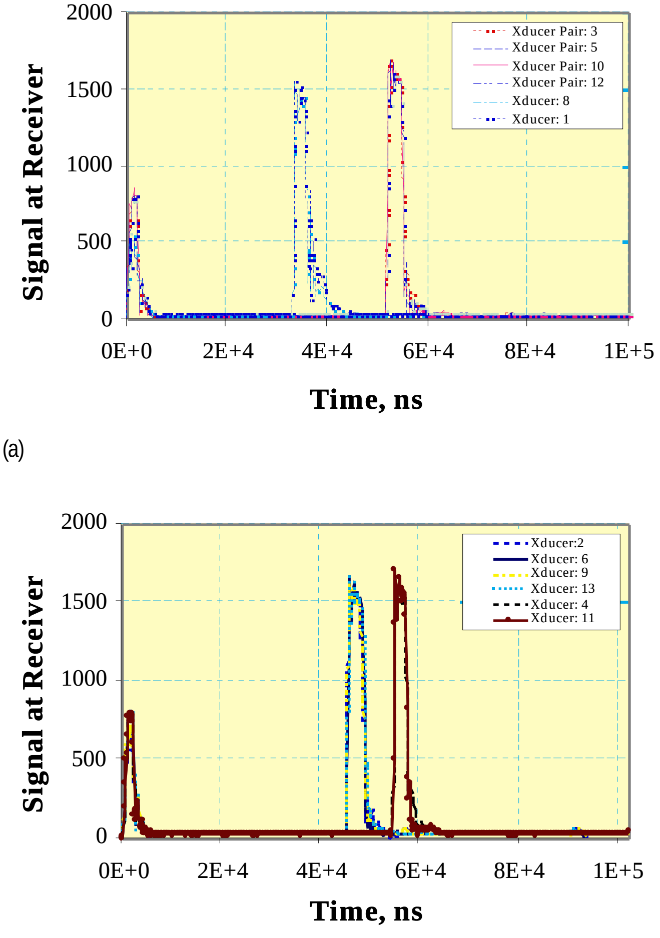


Figure 10. Velocity Distributions in the Various Chords.

Figure 10 is a sequence plots for the velocity profile at different symmetric chords. Note that with the exception of the near-wall chords, most of the velocity profiles at each chord closely overlap. The close agreement in the results is an indication of the level reasonably low level of uncertainty in the measurements, indicating the not only the flow was very symmetric, but also our ultrasonic measurement approach produces repeatable and accurate results. The reason the near-wall chords produced high scatter in the measurements is believed to be due to possible presence of cavity flow where the transducers penetrate the pipe wall. We are currently in the process of improving our transducer block design in order to minimize flow disturbance.

Figures 11 (a) and (b) are the time-of-flight measurements by various transducer pairs. Each figure includes the signal from two different groups of symmetric transducer pairs (e.g., 4 and 11 are symmetric pairs and likewise 2, 6, 9, & 13). For clarity in presentation of results, we have intentionally separated the different signals into two different plots.



(a)

(b)

Figure 11. Comparison Between Transit Time Between Different Transducer Pairs.

Table 1 summarizes the results obtained from these different transducers. Similar to the velocity profile results, these measurements indicate that there is no variation in the speed of sound measured by all the transducer pairs. We expected these results, since the fluid tested is homogeneous. However, nonuniformity in concentration of solids in a slurry flow would be detectable using this approach, provided sufficient concentration differences exist.

Table 1. Speed of Sound Measurements from Various Transducer Pairs.

Xducer Pairs	Transit Time (μs)	Xducer Dist. (mm)	Speed of Sound (m/s)
4 & 11	55	81.5	1482
3, 5, 10, & 12	53	78.5	1481
2, 6, 9, & 13	46	68.6	1491
1 & 3	32	47.5	1484

SUMMARY

In this paper, we presented our preliminary results for demonstration of a new approach for measurement of the velocity profile in a heterogeneous slurry pipe flow. Measurements in dense slurries are encumbered by the variation of the fluid properties as a result of nonuniformity in the slurry concentration. This technique allows measurements under such conditions through simultaneous tomographic pulse-echo ultrasonic flow velocity and time-of-flight speed of sound measurements. Reconstruction of the velocity distribution is based on the measured local speed of sound, which depends on the local slurry concentration. We showed the feasibility in applying this technique by performing controlled experiments in the laboratory with known fluids and flow conditions. The two fluids tested were a viscous Newtonian fluid, propylene glycol, and a non-Newtonian fluid, Carbopol 980. The flow conditions tested were fully-developed laminar pipe flow. The velocity measurements were validated against both LDV measurements and theoretical predictions. The speed of sound results were shown to produce reproducible measurements and consistent with existing data. Obtaining an accurate velocity profile is our first milestone for developing an on-line, real-time rheometer for measurements in dense slurries flowing within pipelines.

ACKNOWLEDGEMENTS

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