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In-Line Ultrasonic Monitoring of Waste Slurry Suspended Solids*

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Abstract:

During the transport of tank waste, it is very important to quantitatively measure the percent solids concentration (PSC) of the waste, which indicates the flow conditions and the extent of solids settling. At Argonne National Laboratory, an in-line, real-time, nonintrusive ultrasonic monitoring system has been developed to measure the PSC and flow density of tank waste by measuring sound velocity and attenuation in the flow. This system consists of a pair of longitudinal transducers bonded to waveguides on the opposite sides of the pipe and operating at 1MHz simultaneously in pulse-and-echo and pitch-and-catch modes. The PSC measurement is provided by attenuation, while the density measurement is calculated by impedance and sound velocity. A thermocouple is attached to one of the waveguides for automatic temperature correction of the measurements. This system was one of four evaluated for in-line measurement of slurry at Oak Ridge National Laboratory in 1998. The results indicate that the measurements are in good agreement with a Coriolis meter and that the system can be used to monitor PSC up to 40 wt.%. However, the system is greatly affected by entrained air bubbles within the solid flow during Pulsair mixing. A different mixing mechanism will solve this problem.

Introduction

In recent years, power plants and waste management firms have been looking for an on-line, nonintrusive instrument capable of monitoring slurry flow during transport. Close monitoring of percent solids concentration (PSC) is important in the pumping of tank waste because it can provide a quantitative measure of the solid waste being transported, as well as an indication of flow conditions, particularly the extent of solids settling. Acoustic/ultrasonic approaches that have been developed into flow-monitoring instruments are the Doppler, cross-correlation, attenuation, and transit-time methods[1,2]. At Argonne National Laboratory (ANL), ultrasonic properties of coal slurries and flow measurements by cross-correlation were examined for on-line monitoring of coal slurries[3]. An ultrasonic viscometer was also developed at ANL to simultaneously monitor fluid density and viscosity, an essential requirement in the plastic, polymer, and food industries for process and quality controls[4,5].

In 1996, a laboratory prototype of the ultrasonic viscometer was demonstrated at Argonne[6] and performance tests were conducted at Oak Ridge National Laboratory (ORNL) under dynamic conditions with variations in flow rate, temperature, pressure, and presence of solid particles [7]. Development of a prototype instrument for monitoring PSC of waste slurries was completed at ANL in 1997. Performance evaluation tests and evaluation of the nonintrusive ultrasonic system for on-line and real-time monitoring of PSC were conducted at ORNL in 1998[8-9].

In this paper, the ultrasonic principles for measuring fluid density and PSC and the design of the prototype instruments are discussed, Some interpretation and comments on laboratory calibration and ORNL test results are also presented.

Ultrasonic Principles

1. Longitudinal Acoustic Impedance of Fluid

Acoustic impedance of a fluid Z_l is the product of fluid density ρ and phase velocity V of sound in the fluid; it can be determined by measuring the reflection coefficient R at the boundary of the fluid and transducer wedge. For a normal-incidence setup, R is given by

$$R = \frac{Z_l - Z_w}{Z_l + Z_w}, \qquad (1)$$

where Z_W is the acoustic impedance of the wedge in which longitudinal waves propagate from transducer to fluid. If the phase velocity in the fluid can be determined accurately by other measurements (e.g., time-of-flight [TOF] of

longitudinal waves traveling in the fluid), the fluid density can be derived from

$$\rho = \frac{Z_w(1-|R|)}{V(1+|R|)}, \qquad (2)$$

where the absolute value of R is used because, in principle, R is a complex number[1, 4].

2. Acoustic Attenuation in a Slurry

Acoustic attenuation in a solid/liquid slurry is caused by viscous, thermal, and scattering effects. Ideally, one prefers to design a percent solids monitor that operates in the frequency range where scattering dominates. In practice, however, because of the wide range of particle concentration and particle-size distribution, such an optimal frequency range cannot be realized. The alternative approach is to use a fixed frequency (1 MHz in the present case) with a wavelength much longer than the average particle size and to measure the relative attenuation of the slurry with respect to the suspending fluid. The relative attenuation α_r can be given as

$$\alpha_r = 20\log\frac{P_s}{P_f} = \alpha_s - \alpha_f, \qquad (3)$$

where α is attenuation, P is for acoustic pressure, and subscripts s and f are slurry and fluid, respectively.

The relative attenuation defined in Eq. 3 is then directly related to absorption by and scattering from particles. However, to determine relative attenuation, one must know the attenuation in the suspending fluid, and this is typically obtained from off-line calibration measurements. Error will be introduced if the actual fluid of the slurry differs from the calibration fluid. Therefore, the proposed technique requires additional measurements to provide real-time signals that relate to fluid properties.

The Instrument

Close monitoring of PSC is important to the transport of tank waste because it can provide a quantitative measure of the solid waste being moved and also an indication of flow conditions, particularly the extent of solids settling. Approaches applicable to in-line measurement of solids concentration are limited; most common are optical and ultrasonic techniques. Solids concentration is typically monitored by measuring ultrasound velocity and attenuation. Attenuation generally provides a better correlation with solids concentration.

Figure 1 is a photograph of the ultrasonic sensor assembly and control electronics. The sensor assembly consists of two 1-MHz longitudinal transducers epoxy-bonded on stainless steel wedges, respectively. The wedges are fabricated with a multiple of one-quarter wavelength with pipe threads and assembled on a 2-in.-diameter pipe. Two longitudinal transducers along the same axis measure sound velocity and catch-signal attenuation through the flow to calculate suspended solids concentration.

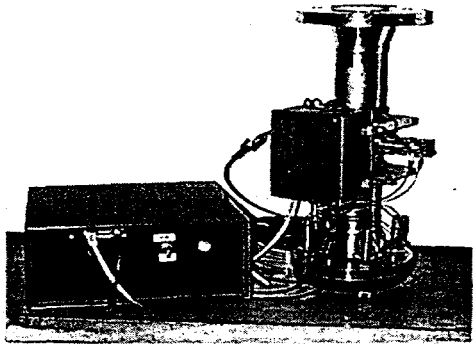

Figure 1. Ultrasonic instrument for measuring solid concentration, together with control electronics.

The instrument will operate in both the pitch-catch and pulse-echo modes shown in figure 2. The pitch-catch mode measures both sound velocity and attenuated signal amplitude, while the pulse-echo mode gives an estimate of the acoustic impedance of the slurry. Acoustic impedance and sound velocity measurements will be used to characterize slurry properties, from which a correct calibration constant can be applied to the percent solids concentration and density measurements.

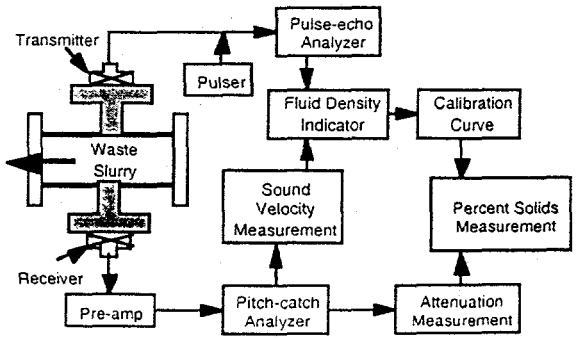

Figure 2. Schematic representation of ultrasonic instrument for measuring solids concentration.

Ultrasonic sensor spoolpiece is mounted on the waste slurry line in a sealed sensor cabinet. A pre-amp box containing two two-stage pre-

amplifiers with bandpass filters, is mounted on the spoolpiece and connected to both transducers to amplify the receiving pitch-catch and pulse-echo signals before sending them to the main electronic box hung outside the cabinet. It is very important to have the pre-amps close to the transducers and also to shorten the CAT-5 cable between the pre-amp and main electronic boxes to reduce possible electromagnetic interference (EMI) for a better signal-to-noise ratio. The TOF and amplitudes of the echo and catch signals are digitized before being sent to a control computer, which is 200ft away outside the control area, through a 25 twist-pair insulated CAT-5 cable. After 200 averages of the receiving amplitudes and TOF, the PSC and density of the waste slurry are calculated and presented on the basis of on-line calibration curves obtained before the actual performance tests were made.

Laboratory Tests and Results

Wedge materials determine the sensitivity and accuracy of the density measurement. Table 1 lists the common wedge materials and their acoustic properties. Two prototype sensor wedges were fabricated from polyetherimide and stainless steel. The polyetherimide wedges are used for the evaluation tests of kaolin/sugar slurry and are epoxy-bonded to the pipe. The stainless steel wedges are used for the in-situ performance tests of radioactive waste slurry and are screw-sealed on the pipe. For both tests, the longitudinal transducers are epoxy-bonded on the wedges and excited by a 48V pulse.

Table 1. Characteristics of various wedge materials.

Material	Density g/cm^3	Longitudinal Velocity cm/μs	Working Temperature °F
Acrylic	1.18	0.2731	200
Aluminum	2.70	0.632	600
Delrin	1.0341	0.2137	180
Lucite	1.28	0.2335	200
Plexiglas	1.1897	0.2701	200
Polyetherimide	1.27	0.2403	338
Stainless Steel	8.03	0.566	1200

1. Measurement of Density

The reflectance method is used to measure fluid density. Table 2 lists the density of standard liquids used to calibrate density. The phase velocity in each liquid, deduced from the TOF measurement, is also given. Note that variation in phase velocity of the standard liquids does not correlate with their density changes; thus, phase velocity alone cannot be used to predict liquid density. However, by combining phase velocity and acoustic impedance measurements, we can obtain an accurate measure of liquid density. Figure 4 shows density calibration results for polyetherimide and aluminum the wedge materials. The polyetherimide wedge gives an accuracy of better than 0.5% for the test liquids, while the results for the aluminum wedge are significantly lower than the actual values. The discrepancy with the aluminum wedge may be due to wetting problems and wedge geometry which consistently give a 4% higher reflection coefficient. After applying a 4% correction to both wedges, the discrepancy is significantly reduced (as shown in Fig. 3).

Table 2. Liquids used for density calibration test

Liquid*	Chemical Constituents	Density g/cm^3	Velocity cm/μs
R-827	Kerosene Chloronaphthalene Naphthol	0.818	0.12766
G-1000	2-Butoxy Ethanol 51.9% Ethylene Glycol 47.2% BASACID Green <1%	1.002	0.15906
Y-120	Chloronaphthalene 99% Kerosene <1% Mono Azo Dye <1%	1.194	0.14272
B-175	Diazene-42 99% *Diazene*-200 <1% Solvent Blue 36 <1%	1.730	0.11452

*Supplied by ALTA Robbins, Anaheim, CA.

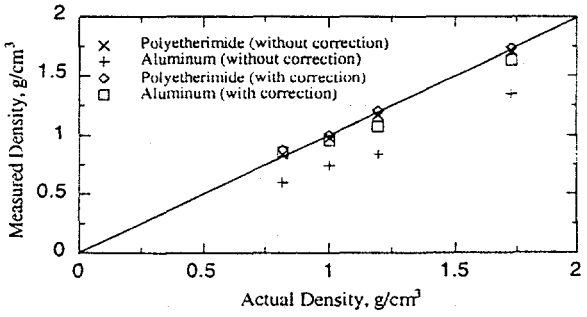

Figure 3. Density calibrations for polyetherimide and aluminum wedge materials.

2. Measurement of Solids Concentrations

Laboratory tests have been conducted to obtain calibration data. Slurries of kaolin particles (<50 μm) suspended in sugar water were used for the tests. Figure 4 shows that TOF values in the slurries are constant. This implies that the sound velocity measurement derived from the TOF data is independent of solids concentration but may indicate the fluid overall property. Figure 5 shows measured amplitudes over the 0-30% solids concentration range. Linear decreases in signal amplitude illustrate the feasibility of using ultrasonic attenuation to monitor solids concentration.

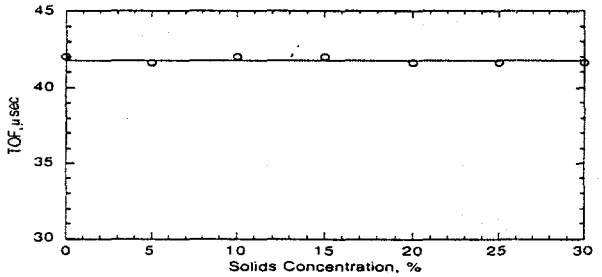

Figure 4. Time-of-flight measurement over a range of kaolin/sugar-water slurries.

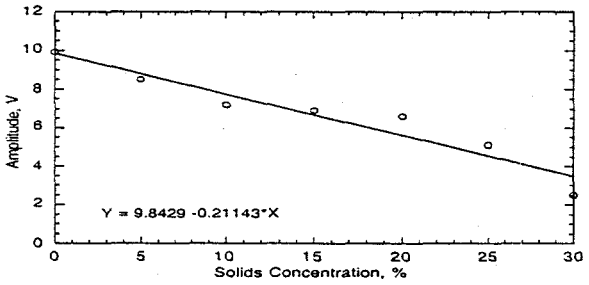

Figure 5. Amplitudes of transmitted signals over a range of kaolin/sugar-water slurries.

Field Tests and Results

Instrument performance was evaluated at ORNL in 1997-98. The instrument was installed on a vertical pipeline upstream of an exit sampler. The instrument was evaluated for its capability to measure density and percent solids concentration.

In ORNL "field tests," the instrument was evaluated under dynamic conditions. Before the tests, the instrument was tested mainly in a controlled laboratory environment. The density and PSC were calibrated against laboratory standards at room temperature. After data from the performance tests were collected and analyzed, minor software modifications and noise reduction were made. Based on our observation and the results provided by ORNL, the major problems that the instrument experienced were

(a) poor signal-to-noise ratio due to EMI,

(b) measurement bias and baseline drift, and

(c) difficulty in monitoring PSC because of entrained air within the slurry during the Pulsair mixing. Interpretations and remediations of these problems are presented below.

1. EMI Problem

The source of EMI was the slurry mixer motor. The instrument picked up EMI pulses primarily through the 200ft cables connecting the transducers to the control electronics. An additional layer of cable shielding with proper grounding significantly reduced the interference. Two additional two-stage pre-amplifiers with band-pass filters are connected to the transducers within 12 in. to boost the signals before sending them through the cables.

2. Measurement Bias and Baseline Drift

Results from the ORNL performance evaluation tests showed that the average bias of the ANL instrument was >2% for data. This phenomenon was later examined in our laboratory during a long-term stability test in which we monitored the reflected signals from both wedges over a period of three days in a normal laboratory environment. We found that temperature variation was the primary cause of the bias. Temperature calibration tests were later conducted in our laboratory for density measurement. Figure 6 shows the calibration curve and its best-fit linear function. By applying the calibration function to the measurements, we can effectively remove the biases and obtain an accuracy ±1% for density. Figure 7 illustrates the removal of the temperature effect.

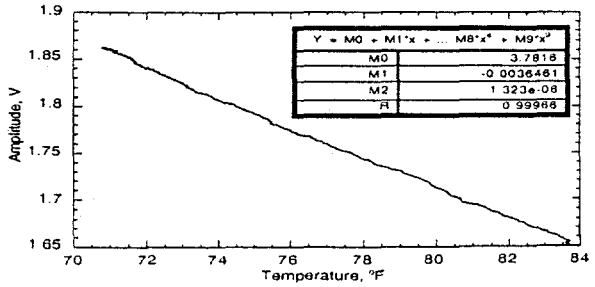

Figure 6 Temperature calibration curve for reflected longitudinal-wave signals

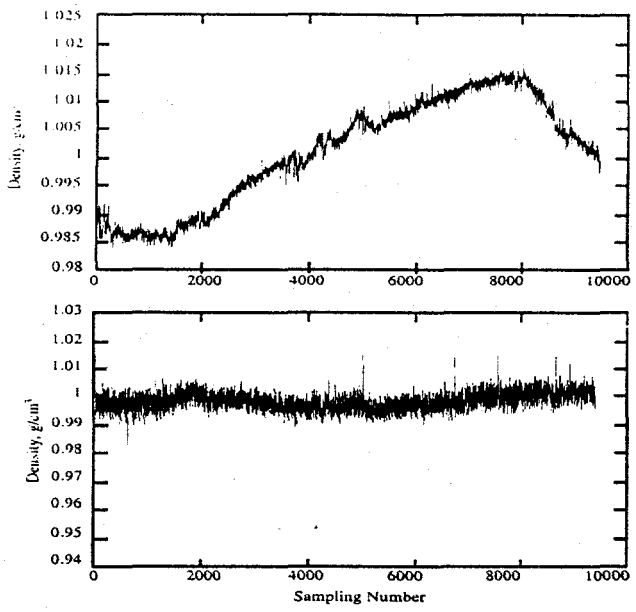

Figure 7. Measured density without (top) and with (bottom) compensation for temperature effect

From our long-term laboratory tests, we observed a slight baseline drift over one month of operation. The drift may have several causes, including aging of the transducer and bonding material. Therefore, regular recalibration (once every few months) is suggested.

3. Entrained Air during Pulsair Mixing

Because the system uses ultrasonic amplitude attenuation to measure PSC entrained air must be eliminated to avoid faulty measurement of both density and PSC. The field-test site used a Pulsair mixer to mix the waste slurry. The Pulsair generates large air bubbles on the bottom of the waste tank and causes mixing when the bubbles grow and move upward to the surface. Meanwhile, many small air bubbles are entrained in the slurry flow causing faulty measurements. The system operated normally when the mixer was off. This problem can be resolved by using a different mixing mechanism.

4. Measurement of Density

Evaluation of ultrasonic and other techniques for density measurement was conducted at ORNL in 1997 with a test loop designed to provide variability in slurry flow rate, temperature, and induced air flow. Reference 7 reports the complete test results and comparison of all seven devices tested. The ultrasonic system completed 77.3% of its 211 runs. Slurries with 0~30% PSC were composed of kaolin powder, sand, and gravel in sucrose (sugar/water of 40%-60 wt.%). Table 3 shows the percentage of experimental runs completed under various testing conditions.

Table 3. Percentage of experimental runs completed

Conditions	Runs	Percentage
Total (211)	211	77.3
Initial and Final Water	8	75.0
Excluding Water	203	77.3
Excluding Water (Air Flow = 0 cfm)	168	77.4
Excluding Water (Vs = 5 ft/s)* (Air Flow ,= 0, 0.33, 0.66 cfm)	57	77.2

*Vs: Slurry Flow Velocity

The experimental results were compared with the sampling results. A density bias for each run was calculated by the following:

$$\text{Density Bias} = \text{Average Density} - \text{Reference Laboratory Value.} \quad (4)$$

Statistical results for density measurements are listed in Table 4.

Table 4. Statistical results for density measurements

Statistical Items	Results, g/mL
Average Density Bias	0.02
SD of Density Bias	0.07
Range of Calculated SD for Density	±0.15

The ANOVA model was used to represent the sources of variation for density bias, which are then compared with the experimental error to test for effects at the 5% significance level according to

$$\text{Density Bias} = \text{Mean} + \text{Temp} + \text{Matrix} + \text{wt.\%} + (\beta \times \text{Flow}) + \text{Error}, \quad (5)$$

where

- Mean: overall average density,
- Temp: temperature effect,
- Matrix: matrix effect,
- wt.% (matrix): weight percent effects in matrix,
- β: slope or linear change in density bias with slurry flow rate,
- Flow: slurry matrix flow rate, and
- Error: experimental error or bias variation not explained by other sources.

Statistical results for density measurements with slurry flow-rate variations are listed in Tables 5 and 6.

Table 5. Average Density Bias with carious effects for density measurement

Slurry Types	Wt.%	Average Density Bias 25°C	50°C
Sugar/Water	40	-0.01	0.01
	50	-0.01	0.09
	60	-0.00	0.08
Kaolin/Water	10	-0.04	0.06
	20	-0.03	0.03
	30	-0.06	0.01
Kaolin/Sugar/	8.5	0.02	0.09
	15	-0.00	0.08
	22	0.02	0.10
Kaolin/Sand	30	-0.03	0.01
Kaolin/Sand/Gravel	10	-0.00	0.15
	20	N/A	0.08

Table 6. Statistic results for density measurement

Types	Statistical Items	Results, g/mL
Slurry Flow Rate	Average Density Bias	0.02
	SD of Density Bias	0.027
Air Flow Rate	Average Density Bias	0.005
	SD of Density Bias	0.01

For both the slurry and air flow rate tests, the system has very insignificant experiment errors that have no effect on density measurement. Among seven different systems tested at ORNL, the overall performance of the ANL system was ranked second.

5. Measurement of Solids Concentrations

The ANL ultrasonic system is one of the three systems evaluated at ORNL in 1998 for in-line PSC monitoring of radioactive. The configuration of the in-line test loop and test report was documented in Ref. 9. The ANL system measures PSC based on TOF and amplitude attenuation (AMP) of the ultrasonic signal. Table 7 summarizes the bias of average PSC measurements in 18 data points for each of the six test experiments.

Table 7. Bias of average PSC measurements in 18 data points for each of the six test experiments

Pump Position,* ft	Pulsair Dwell Time, sec	TOF Bias, %	AMP Bias, %
4	10	13.2	14.4
	14	12.1	15.1
	18	9.15	13.3
6	10	12.5	15.9
	14	8.1	11.8
	18	7.2	9.05

*Distance from bottom of tank to pump.

Although the system is greatly affected by entrained air within slurry flow during Pulsair mixing, the measurements are in good agreement with the Coriolis meter when mixing is not operated. The system can be used to monitor PSC up to 40% by weight. Use of a different mixing mechanism will solve this problem.

Conclusions

The results for density measurement show that Argonne's ultrasonic technique can be used for in-line, real-time density monitoring. The advantage of this system over the others is that the system is nonintrusive and will not interfere with the flow or cause plugging. When the Pulsair mixer is off, results indicate that the measurements are in good agreement with the Coriolis meter and the system can be used to monitor PSC up to 40 wt.%. However, the system is greatly affected by entrained air within the slurry flow because of the Pulsair mixing. Use of a different mixing mechanism will solve this problem. It is also proved that the ultrasonic system can be a good low-cost instrument for process control and monitoring. In conjunction with a better electronic design and microcontroller, the system can operate as a stand-along unit. However, to provide the necessary accuracy and stability, higher-power and temperature-stable ultrasonic sensors need to be developed.

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