NEW APPLICATIONS OF SONAR-BASED TECHNOLOGY IN THE MINERALS PROCESSING INDUSTRY: VELOCITY PROFILE MEASUREMENT AND PIPE WALL WEAR MONITORING IN HYDROTRANSPORT LINES

Robert J. Maron[1]
Mark Fernald[2]
Dr. Christian O'Keefe[3]
John Viega[4]
Tim Bailey

CiDRA Minerals Processing Corp.
50 Barnes Park North
Wallingford, CT 06492, U.S.A
01-265-0035
Phone: www.cidra.com

[1]Director, Business Development and Application Engineering, Latin America (Author Correspondent)
[2]V.P. Advanced Technology
[3]Director, Regional Business Development and Application Engineering
[4]V.P. Gen. Mgr. Oil Sands Performance Services

ABSTRACT

SONAR-based non-invasive flow measurement technology has been available for approximately five years in industrial processes and is becoming an accepted method of measuring challenging single and multi-phase flows in the mineral processing industry. This fundamental sensor and measurement technology has been extended to two developments that provide new measurement capabilities useful for monitoring and managing slurry flows, and measuring pipe loss due to erosive slurry flow.

The first development is the non-invasive measurement of real-time velocity profile of slurry flow in horizontal pipes. Multiple non-invasive sensors measure localized velocities and are combined to provide a velocity profile measurement. This information can be used to determine the approach and onset of solid deposition on the bottom of the pipe. Having this information in real time can enable operation at lower velocities and/or higher solids concentration while avoiding solids deposition and its associated operational costs. An example benefit of such a system is the operation of a tailings disposal line at higher solids density to reduce water usage.

The second development is the non-invasive measurement of pipe wear on slurry lines without internal liners. Presently, such measurements are made by hand-held portable ultrasonic thickness gages which have problems with poor repeatability and accuracy, and high labor cost. The SONAR-based system uses a permanently installed non-invasive ring with twelve ultrasonic wall thickness sensors equally spaced around the circumference. Simultaneous measurements provide a "picture" of the pipe wall thickness around its entire circumference. The benefit is significantly improved pipe wear monitoring, safer operation and avoidance of costly environmental damage due to leaks caused by pipe wear.

INTRODUCTION

Historically, flow measurements in the mineral processing industry have suffered from the limitations of previously available flowmeter technology including the commonly used instruments such as ultrasonic metes, electromagnetic meters, turbine meters, orifice plate meters, vortex flow meters, Coriolis meters, and venture meters. Sonar flow measurement technology, which entered the mineral processing industry about three years ago, has overcome many of these limitations. The development of this technology began about ten years ago with the specific goal of non-invasively measuring multi-phase flows in the petroleum industry. The same technology was later adapted to the mineral processing industry where it has experienced rapid adoption.

The specific sensor technology, based on piezo electric film sensors, provides unique measurement capabilities. The first of these is the ability to non-invasively measure localized flow velocities within a pipe. Using this principle, circumferential array of these sensors can measure several velocities simultaneously at a single axial location, thus providing a real-time velocity profile.

A second application of this sensor technology once again uses a circumferential array of permanently mounted piezo film sensors to obtain multiple measurements of pipe wall thickness at a single axial location, thus providing a highly accurate and repeatable means of monitoring pipe wear due to abrasive slurry flow.

Sonar Based Flow Measurement – Principle of Operation

Although there are a number of distinct flow disturbances related to process flows, the most common is turbulence. Turbulent eddies, or vortices, are naturally present in flow regimes where Reynolds numbers are greater than 4000. The Reynolds number represent the ratio of inertial forces to viscous forces and numbers greater than 4000 as said to be turbulent and less than 2000 are considered to be laminar. The larger the Reynolds number the broader the range of turbulent eddies within the flow. The fundamental principle of sonar flow measurement is based on the tracking these turbulent eddies or unsteady pressure disturbances, as they pass through an array of sensors.[1] The turbulent pressure field within the pipe exert forces on the inside wall of the pipe which are both spatially and temporally distinct. The strain induced into pipe wall from these pressure fluctuations is measured by an array of sensors located axially on the outside wall. These sensors convert the strain into a voltage signals that contain both phase and frequency information. The separation between sensors in the array is shorter than the coherence length of the vortices, thereby resulting in similar voltage signatures from each sensor with only a delay in time. When sonar array processing is applied to the output signals of the array, the propagation speed of the fluid within the pipe can be determined.[2]

Velocity Profile

This broad range of eddies can be viewed as a propagating unsteady pressure field within the pipe that forms a distinct velocity profile across the pipe's cross section. This profile represents the time averaged velocity of the vortical field and is dependent upon the radial location within the pipe. The shape of the profile is dependent upon a number of parameters such as fluid properties, piping geometries and orientation, surface finish, and flow rate. In fully developed homogeneous liquid flows, the profile is symmetric about the pipe axis.

In mining and oil sands applications a vast majority of product transport is done as a slurry. A majority of these transport lines are oriented horizontally which results in the solids stratifying with a higher concentration of solids at the bottom of the pipe. Flow regimes of horizontal flows can be classified into four distinct groups: homogeneous flow with fully suspended particles, heterogeneous flow with all particles suspended, flow with a moving bed, and flow with a stationary bed [3]. The flow regime is dependent upon properties of the slurry such as particle size, density, flow velocity, viscosity, and particle size distribution, as well as the physical attributes of the pipeline such as diameter and surface roughness. Each of these flow regimes has a distinctive characteristic velocity profile.

CLAMP-ON SONARTRAC VELOCITY PROFILING METER

Clamp-on sonar based flow measurements are becoming widely used in industrial application where slurries are used. One of the many advantages of this technology is the flow sensing array is clamped to the outside of the pipe and therefore never comes in contact with the slurry. This circumvents shutting down the process flow for installation and eliminates the common problem of wear due to the aggressive nature of the flowing slurry. The standard clamp-on flow meter is based on using a single multiple element array which measures flow velocity, which is converted to a volumetric flow based on the pipe inner diameter, and gas volume fraction which is determined by measuring the acoustic velocity within the fluid. This clamp-on technology has been extended by implementing multiple arrays located at different radial positions on a single meter, to measure the velocity profile of the fluid. This new tool offers process operators a non-invasive measurement tool with the ability to monitor and control the profile of their process flow. This report summarizes the results of flow loop testing performed on a Sonartrac™ profiling system and demonstrates some of the potential benefits, one of which is the ability to detect the onset of sand-out conditions. Early detection of this condition allows operators the time to apply corrective actions and avoid catastrophic process shutdown. In addition, monitoring the profile can provide useful information about the properties of the process fluid which can allow operators to adjust production variables to optimize the process.

CiDRA Corporation has developed a new profiling system called SANDtrac™. This system uses a multiple arrays located radially at the top, 45 degrees, 90 degrees, 135 degrees and bottom of the pipe. The circumferential location of the sensor arrays is shown in Figure 3. The local velocity of each sensor array is simultaneously measured. As certain properties of the slurry change, the flow profile can be monitored in real time to allow the operators control to optimize the process. One example reported in this paper is the ability to detect the precursors to "sanding out" a pipeline by monitoring the velocity profile.

Flow Loop and Test Setup

Testing was conducted in a slurry test loop, shown in Figure 1, at the Pipe Flow Technology Center of the Saskatchewan Research Council (SRC) in Canada.

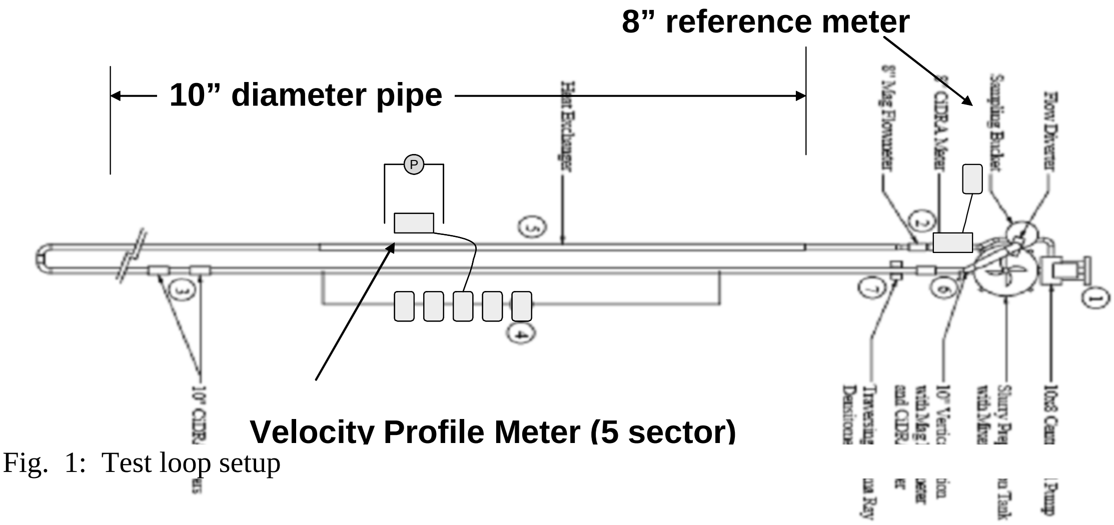

Fig. 1: Test loop setup

Test Results

Slurries Tested

The scope of this test was to test slurries representative of both mining applications and oil sands. For the mining slurry an 89um d50 particle size was selected with a density of 1300 Kg/m^3. The oil sands slurry was tested by first starting out with a coarse sand slurry with 186um particles. Clay and larger stones were added subsequently to the mixture. A velocity step down test was run for each slurry to measure the velocity profile as a function of velocity.

Mining Slurry Test Results

Below the results of the mining slurry test are graphed (Fig. 2). The velocity was stepped down in the following increments to develop a sand bed – 4 m/sec, 3 m/sec, 2 m/sec, 1.75 m/sec, 1.5 m/sec, 1.4 m/sec, 1.3 m/sec, 1.2 m/sec, 1.1 m/sec, 1.0 m/sec, 0.9 m/sec, 0.8 m/sec, and 0.7 m/sec. The flow was held at each flow rate for a period of 5 minutes to allow the loop to stabilize. Continuous flow data was recorded during the entire testing time. Fig. 2 shows the step down in flow rate and the corresponding velocities measured at each of the 5 sensor array positions. Also shown is the output of a densitometer positioned at the bottom (y/D =0.05) of the pipe to measure solids that stratify to the bottom. To obtain a reference flow velocity, a separate flowmeter was installed in an 8” loop section where the higher flow velocity prevented solid deposition. This flow rate was then converted to an “equivalent 10 inch” velocity and graphed with the velocity profile data shown in Fig. 2.

As the flow rate is lowered the velocity profile changes to reflect the stratification changes within the pipe. It can be seen that as the flow rate decreases the densitometer reading increases only slightly until approximately 1.75 m/sec. At this velocity the density reading undergoes a step change reflecting an increase of solids at the bottom of the pipe.

Good agreement can be seen between the rapid increase in the Gamma Densitometer reading (set to measure density across the bottom of the pipe) and the inversion of the lower sensors. Both indicate the formation of a bed at the same time. When the flow rate drops below the deposition velocity a bed starts to form on the bottom of the pipe and the Gamma Densitometer detects this rapid increase in density. The bottom sensor in the profile meter typically reads a lower velocity than the 135 degree sensor, this is because slurries usually stratify and the lower layers are more dense and slower moving. When the bottom bed stops moving the bottom sensor can no longer detect that lowest layer and looks higher up in the pipe where the velocity is faster, this condition can cause the reported velocities of the lower sensors to become more similar or even invert (the bottom reading higher than the 135 reading). Fig. 3 shows a detailed view of the occurrence of solid deposition. In Figures 3 – 5, measured velocity profiles are show at three different flow velocities each showing three distinct flow regimes: homogenous with all particles suspended (Fig. 4), heterogeneous flow with all particles suspended (Fig. 4), and flow with a stationary bed (Fig. 5).

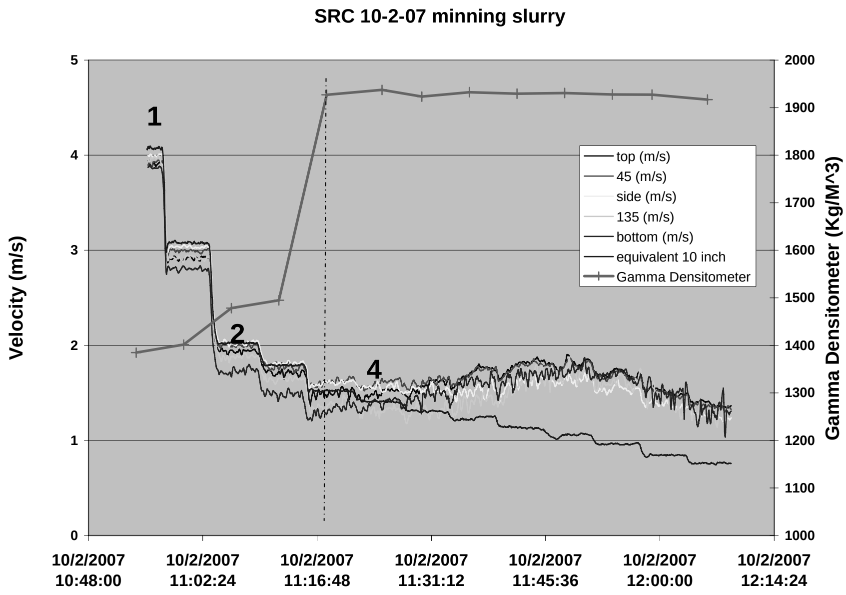

Fig. 2: Entire Run, mining slurry

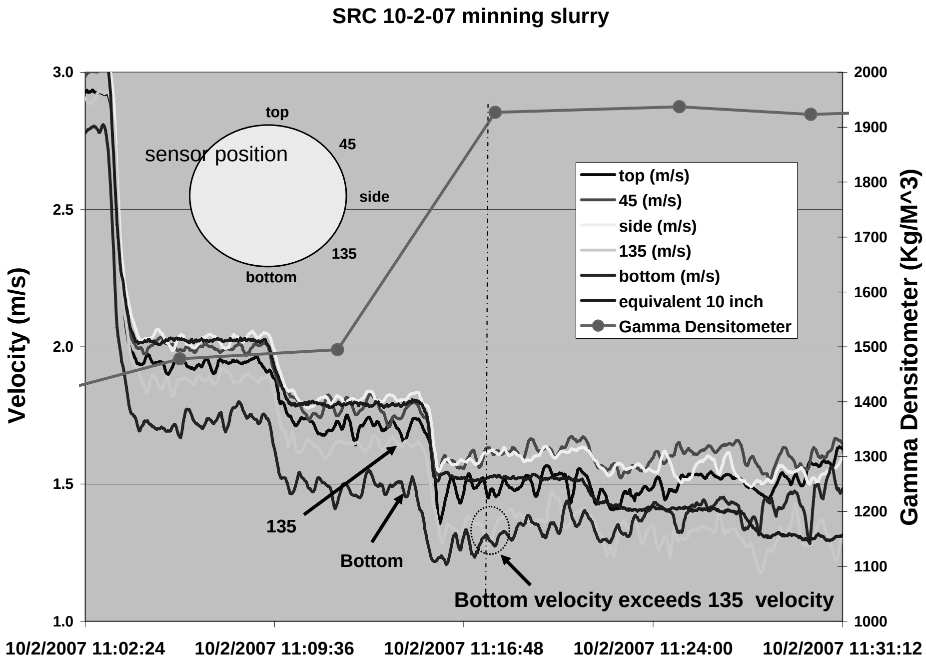

Fig. 3: zoom view, mining slurry

Below the selected velocity profiles are plotted for different reference velocities:

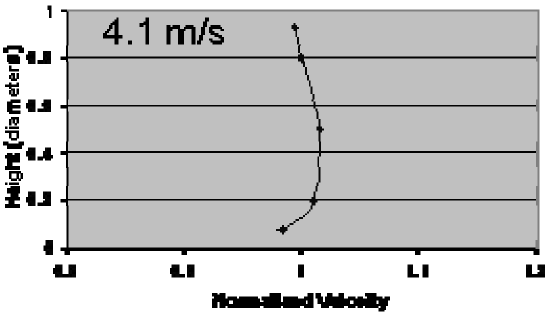

Fig. 4: Homogenous flow, suspended particles

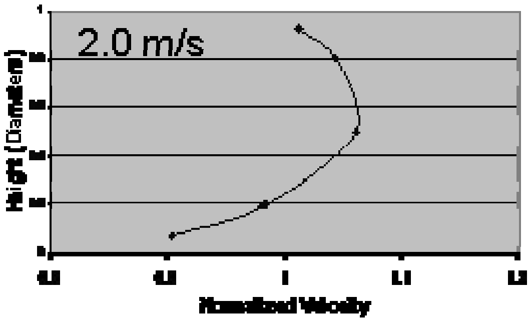

Fig. 5: Heterogeneous flow, suspended particles

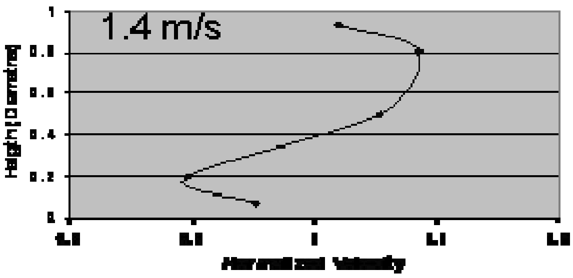

Fig. 6: Stationary solids bed

Oil Sands Slurry Test Results

For comparison with the previously discussed 89 um mining slurry, Fig. 7 shows a step down test with the 186 um oil sands slurry. Once again, as the flow rate is lowered the velocity profile changes to reflect the stratification changes within the pipe. It can be seen that as the flow rate decreases the densitometer reading remains relatively constant at about 1600 – 1700 kg/m^3, until at approximately 2.5 m/s it suddenly undergoes a step change reflecting an increase of solids at the bottom of the pipe. Additionally, Fig. 7 shows the pressure drop measured across the velocity profile meter, which in this case shows a sudden increase which coincides with the densitometer increase and the “velocity inversion” of the bottom and 135° array of the velocity profile meter. Therefore the formation of the stationary solids bed was detected by the sonar velocity meter and confirmed by both the density and differential pressure measurements.

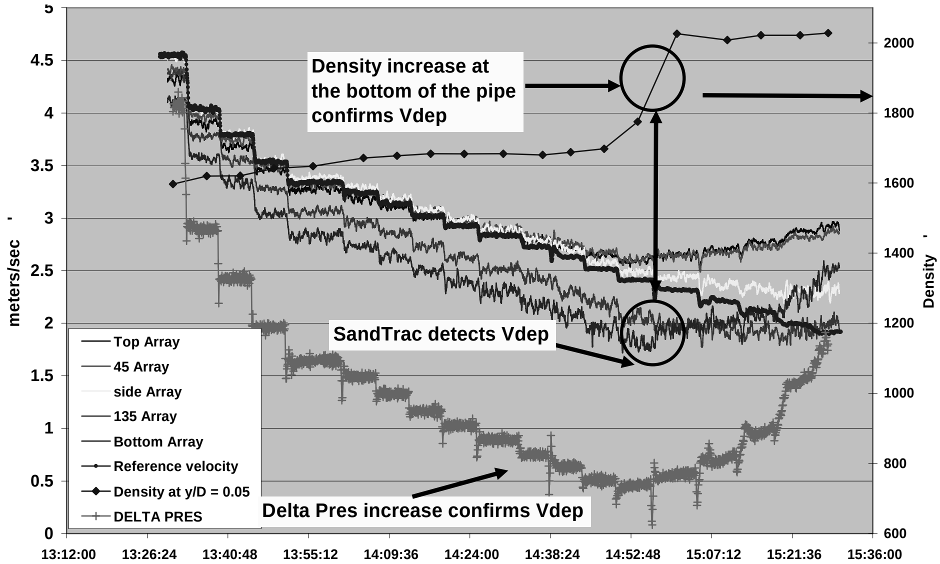

Fig. 7: Solid deposition detected by sonar meter, densitometer, delta-pressure

The velocity profile vs reference flow velocity is shown in Fig. 8, and Fig. 9 shows a normalized plot where all velocities are normalized to the center velocity. The Fig. 9 plot emphasizes how the effects of stratified flow impact the velocity profile. Together, these plots show that as the flow rate is reduced, two distinct changes occur to the profile. The first change is the velocity detected at the bottom of the pipe, which is the lowest velocity due to the high solids concentration, is slower relative to the velocity at the center of the pipe. Likewise, the velocities measured in the upper section of the pipe begin to move faster relative to the center of the pipe. The second change is that as the velocity is decreased further, solids are deposited on the bottom of the pipe causing the "velocity inversion" between the bottom and 135 arrays, as previously described.

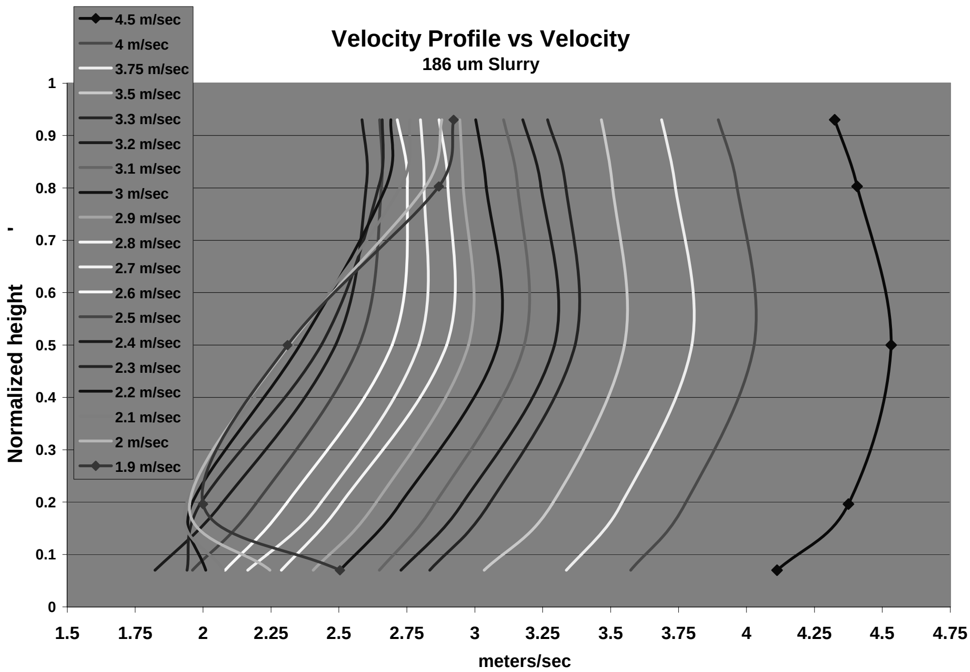

Fig. 8: Velocity profiles vs reference velocity

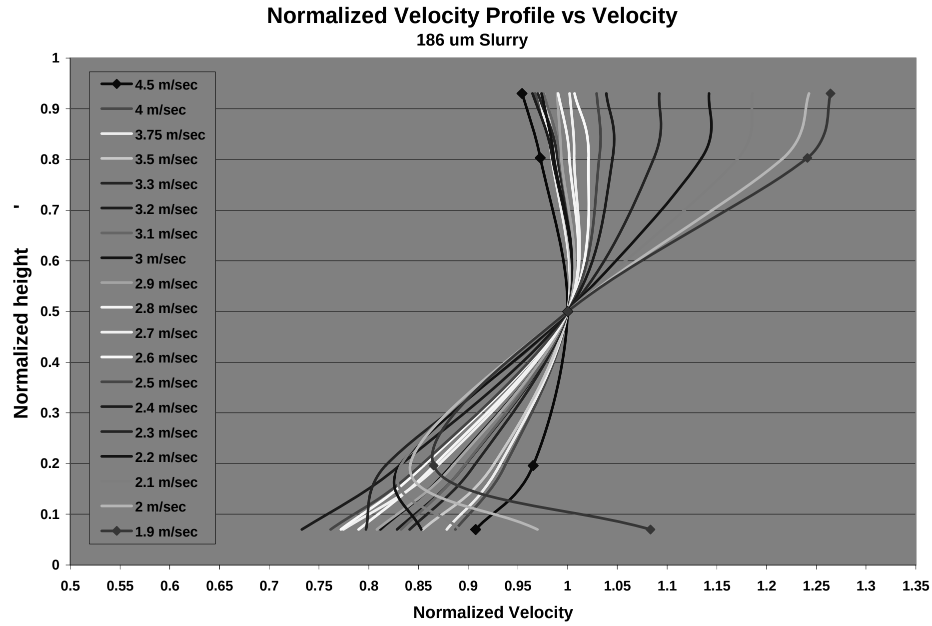

Fig. 9: Velocity profiles (normalized to pipe center velocity) vs reference velocity

PIPE WALL THICKNESS MONITORING

There has been a long history of using ultrasonics based nondestructive testing to determine the wall thickness of metallic pipes. To date this method of determining wall thicknesses has been costly, unreliable, and of limited use for trending wear rates. To reduce the high labor costs associated with this method and to decrease the variance found in these manually performed measurements, a new approach to pipe wall thickness monitoring has been developed and tested. The new system, HALO™, has resulted in decreased labor costs, better measurement repeatability, and more timely pipe wear measurement results. It also has allowed pipe wall measurements to be performed where inspectors cannot safely and easily perform these measurements currently. A conceptual layout of the system is shown in Figure 10.

Principle of Operation for Pipe Wall Thickness Monitoring

The new pipe wear monitoring system, HALO™, uses a series of conformable ultrasonic transducers that are permanently or semi-permanently mounted around the perimeter of a pipe. These transducers are coupled to an ultrasonic pulser/receiver that sends an electrical signal to the ultrasonic transducer. The ultrasonic transducers convert the electrical signal into a traveling stress wave (acoustic wave) that propagates through the pipe wall, reflects from the inner surface of the pipe and returns to the ultrasonic transducer. The ultrasonic transducer then reconverts this returning stress wave into an electrical signal that is amplified and processed by the ultrasonic pulser/receiver. The ultrasonic pulser/receiver then determines the amount of time that it has taken the stress wave to travel from the transducer to the inner surface of the pipe and back to the transducer. Using the well known velocity for these stress waves in the pipe wall material, the thickness of the pipe wall can be accurately determined.

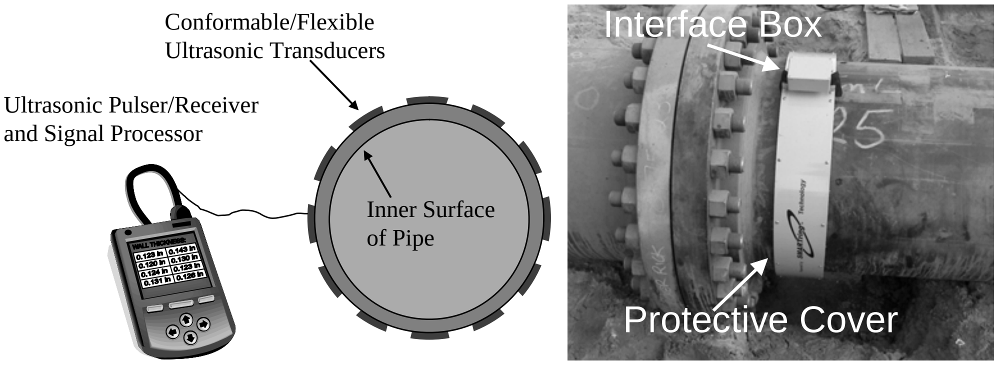

Figure 10: Conceptual layout of HALO™ system and picture of system in operation at a customer site

Test Results – Temperature and Repeatability

The pipe wall thickness measurements can be graphed in a polar plot to provide a visual indication of the wall thickness as a function of the angular distance from the top of the pipe. A set of representative plots from data taken at a customer site clearly shows high wear rates on the pipes as seen in Figure 11. The degree of wear is unequivocally seen. In the plot shown in the left side of figure xx the high wear rate is on the bottom of the pipe as expected in a stratified (non-homogeneous) flow situation. On the right hand side of figure xx, the high wear rate appears to be on the top of the pipe due to an intentional rotation of the pipe performed to increase pipe lifetimes. In other situations, uneven pipe wear will result from changes in the flow profile after elbows or other pipe geometry effects.

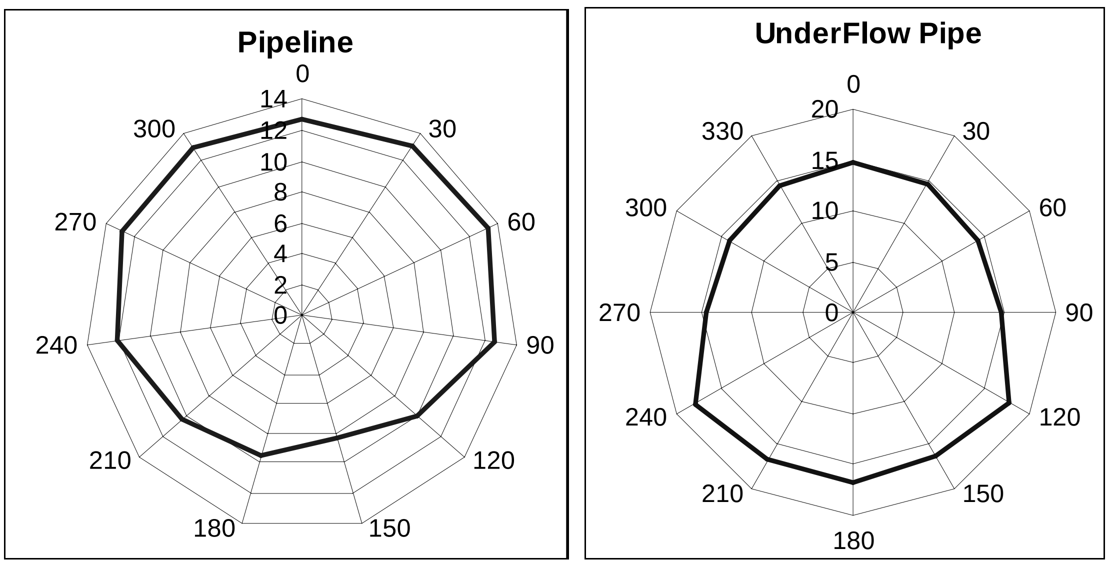

Figure 11: Pipe wall thickness as a function of angular position from top of pipe as shown on two different pipes at a customer site

This system has undergone testing for repeatability, impact of environmental temperature changes, and the impact of transducer to transducer variability. The results from varying these three factors have been consolidated into a single data set as shown in Figure 12. An examination of the graph reveals that over 81% of the data is within +/- 0.12% or +/- 0.013 mm, and all the results are within +/- 0.47% or +/- 0.05 mm. The repeatability is well within the requirements to determine impending failure due to pipe wall thinning or to reliably track wear rates.

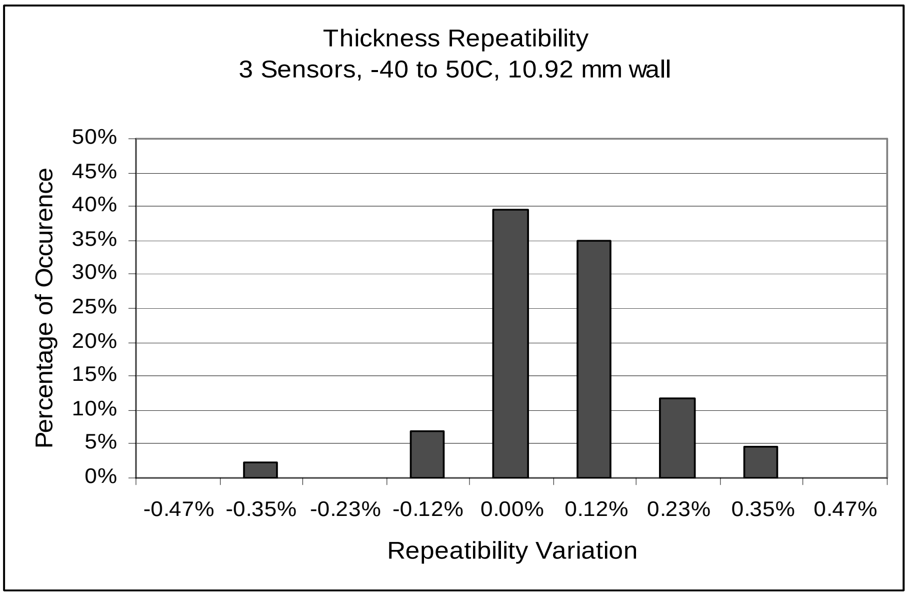

Figure 12: Small spread in data over 90C temperature range and over three sensors is shown

A demonstration of the ability to monitor and quantify the wear rates in a pipeline has been demonstrated in the field. In Figure 13 ,the wear rate in a high wear rate environment shows the rapid decrease of wall thickness over a period of nine and a half weeks.

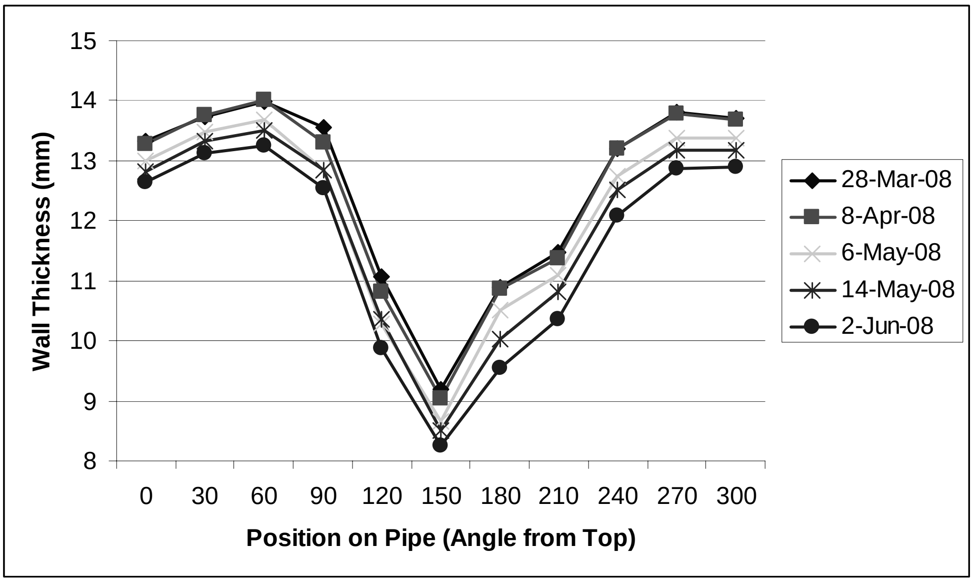

Figure 13: Measurement of pipe wall thickness as a function of angular position and time is shown

CONCLUSIONS

Existing sonar-based flow measurement technology has been extended to two new applications. It has been demonstrated that a sonar-based meter is able to measure the velocity profile in a horizontal slurry line in real-time. Measured changes in the velocity profile show the ability to detect different flow regimes: both homogeneous and heterogeneous flow with fully suspended solid particles, and flow with a stationary bed. The ability to detect a stationary bed was confirmed by separate measurements of density across the bottom of the pipe and differential pressure across the velocity profile meter. One potential benefit of this measurement for hydrotransport line operation is reduction of water and energy usage by operating at higher solids concentration and/or lower velocities while avoiding problems and costs due to solids deposition. The ability to reliably, accurately, and cost effectively provide pipe wall thickness measurements in a timely manner has been demonstrated. The repeatability over a variety of operating conditions including sensor to sensor variation, temperature ranges, and time has been clearly shown in both laboratory and field tests. This technology is easily extended into monitoring of most structures found in a pipeline including elbows, valves, and many others. The resulting cost savings for both the pipe inspections and production savings through enhanced production up-time can be quite large. Most importantly, the potential impact on personnel safety and environmental savings will be enormous.

REFERENCES

[1] Gysling, d. and Mueller, E. [2004] Application of Sonar-Based Clamp-On Flow Measurement in Oilsand Processing, ISA 2004 Exhibit and Conference.
[2] Nelson, R.O., "Sonar Signal Processing", Artech House Inc., Norwood, MA, USA, 2001, ISBN 0-89006-453-9.
[3] Cheremisinoff, N.P., "Encyclopedia of Fluid Mechanics. Vol. 5, Slurry Flow Technology", Golf Pub. Co. 1986.