NEW DEVELOPMENTS IN FLOW AND PIPE MANAGEMENT CAPABILITIES THROUGH NEW VELOCITY PROFILE MEASUREMENT AND PIPE WALL WEAR MONITORING INSTRUMENTATION

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Abstract

New developments in the non-invasive and real-time measurement of the velocity profile of slurry flow in horizontal pipes will be described. 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 or higher solids concentration or both while avoiding solids deposition or plugging and their associated operational costs.

In addition, advances have been made in the measurement and trending of pipewear on slurry lines. In contrast to manual methods, CiDRA's system uses a permanently or semi-permanently installed ring of conformable ultrasonic transducers clamped onto the outside of the pipe. These transducers are used to measure the thickness of the pipe under their respective locations. This results in better repeatability, accuracy, and failure prediction, along with reduced labor costs. The benefit is significantly improved pipe wear monitoring in pipelines with abrasive solids. This provides an improvement in the ability to insure safe operation and avoidance of costly operational and 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 commonly used instruments such as ultrasonic meters, electromagnetic meters, turbine meters, orifice plate meters, vortex flow meters, Coriolis meters, and venturi meters. Sonar array flow measurement technology, which entered the mineral processing industry about four 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 piezoelectric film sensors, provides unique measurement capabilities. The first of these is the ability to non-invasively measure localized strains in the walls of pipes. Combined with sonar array processing algorithms, an axial array of such sensors can measure flow velocities within a pipe. Using this principle, sets of these axial sensor arrays arranged at different circumferential locations of a pipe can measure several fluid velocities at various heights in the pipe, thus providing a real-time velocity profile.

A second application of this piezoelectric sensor technology once again uses a circumferential array of permanently mounted piezoelectric film sensors but without the axial array components. Through active excitation of the piezoelectric film sensors, multiple measurements of pipe wall thickness at a single axial location can be obtained, thus providing a highly accurate and repeatable means of monitoring pipe wear due to abrasive slurry flow

Non-Invasive Velocity Profile Measurement

Principle of Operation for Passive Array Based Flow Measurement using Sonar Processing Algorithms

Sonar array-based meters track and measure the mean velocities of coherent disturbances traveling in the axial direction of a pipe. These disturbances can take many different forms and can propagate at different velocities. Their propagation method and velocities include convection with the flow (slowest velocity – fluid flow), propagation in the fluid or slurry (mid-range velocity - acoustics), and propagation in the pipe walls (fast velocity - vibrations). The sonar array-based meters discriminate between the three main propagation modes through a combination of frequency and velocity differences.

First let us focus on the disturbances that convect with the flow. These disturbances can be density variations, temperature variations, turbulent eddies, or others. Within most industrial processes, the most common flow disturbance 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 are said to be turbulent and less than 2300 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 tracking these turbulent eddies as they pass through an array of sensors (Gysling and Mueller, 2004). A cutaway illustration of these turbulent eddies within a pipe under a sonar array sensor band is shown in Figure 1.

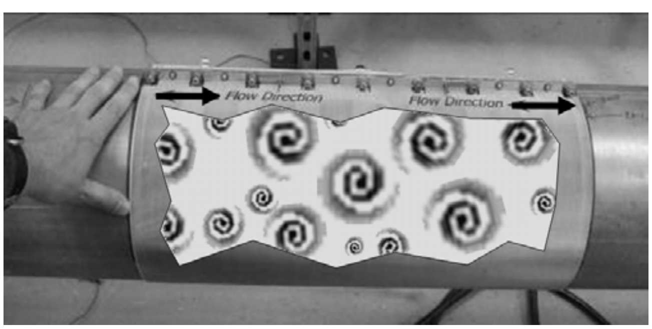


Figure 1. Cutaway of pipe under sonar array sensor band illustrating turbulent eddies

Through the combination of an array of passive sensors and the sonar array processing algorithms, the average axial velocities of a collection of vortices is obtained. The sequence of events that occur to make this measurement possible is as follows:

- As these turbulent eddies pass by any fixed location on the pipe, they will exert a small dynamic stress on the inside of the pipe wall
- The strain induced in the pipe wall from these dynamic stress fluctuations is converted to an electrical signal through a passive sensor wrapped partially or fully around the pipe (Figure 2 exaggerates) – no couplant gels or liquids are required since these are low frequency mechanical strains and not ultrasonics
- The unique electrical signal from each collection of turbulent eddies is detected by each element of the array of sensors. These sensors are spaced a precisely set distance from each other along the axial direction of the pipe.
- The separation between sensors in the array is shorter than the coherence length of the turbulent eddies, thereby resulting in similar voltage signatures from each sensor in the array with only a delay in time.
- When sonar array processing is applied to the output signals of the array, the velocity at which these turbulent eddies pass through the array of sensors is determined, thus providing the propagation speed of the fluid within the pipe (Nelson, 2001).

This process is illustrated with one collection of turbulent eddies in Figure 2 but in practice is applied to numerous collections of turbulent eddies.

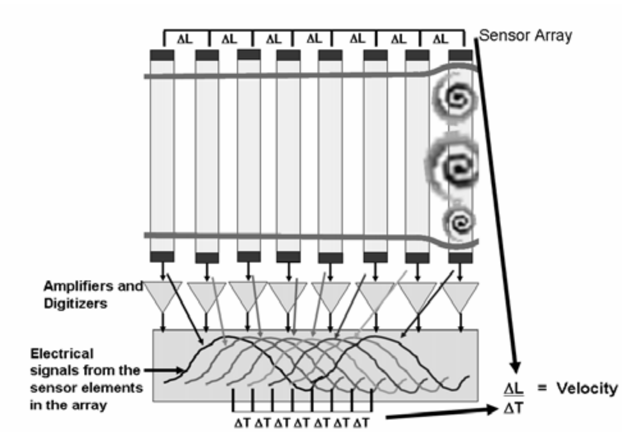


Figure 2. Illustration of signal detected by passive sensors in array from one collection of turbulent eddies

Velocity Profile in Horizontal Pipelines

In mining and oil sands applications a vast majority of product and tailings transport is done as slurry. 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 (Cheremisinoff 1986). 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. Figure 3 shows the particle distribution for each of these regimes.

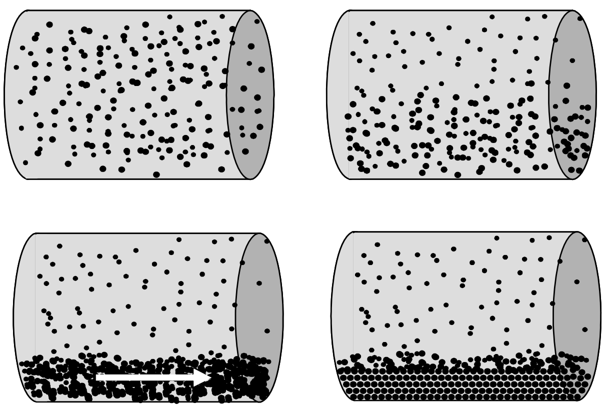


Figure 3 (Top Left) Homogeneous flow (Top Right) Heterogeneous flow – full suspended particles (Bottom Left) Heterogeneous flow – moving bed (Bottom Right) Heterogeneous flow – stationary bed

In fully developed homogeneous liquid flows, the profile is symmetric about the pipe axis, and does not pose the danger of developing a sand bed which can potentially lead to plugging of the pipeline. In this type of flow, the profile has a radial position dependency. Few slurry flows will be purely homogeneous flows. Most slurry flows will fall into the category of heterogeneous flow with some containing the characteristics of both homogeneous and heterogeneous flow. In heterogeneous flows, there is a stratification of the solids with a higher concentration of solids at the bottom of the pipe. For the same particle size, density, viscosity, particle size distribution and physical attributes of the pipeline, the flow velocity will determine the type of heterogeneous flow, that is whether or not a sand bed has developed and the characteristics of the sand bed. In heterogeneous liquid flows, the profile is not symmetric about the pipe axis. Instead, it is symmetric about the horizontal axis but asymmetric about the vertical axis due to the vertical distribution of particles.

Sonar Array Velocity Profiling Meter

The standard clamp-on flow meter is based on using a single multiple element array which provides for a measurement of the average flow velocity in a pipe. This clamp-on technology has been extended by implementing multiple arrays located at different circumferential positions on a single band, 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. The following sections summarize the results of flow loop testing and field testing performed on a sonar array 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.

The velocity profile meter uses arrays located circumferentially on the outside of the pipe at the top, 45 degrees from the top, on the side, 135 degrees from the top and at the bottom of the pipe. The circumferential location of the sensor arrays is shown in Figure 5. The size of the array elements, the size of the pipe, and the circumferential location of each array on the pipe determines the vertical distance over which the flow is averaged for each array. Testing of this technology has been accomplished at several customer sites and at research facilities.

SRC Flow Loop and Test

One series of tests were conducted in a slurry test loop, shown in Figure 4, at the Pipe Flow Technology Center of the Saskatchewan Research Council (SRC) in Canada. The scope of this test was to test slurries representative of different processes and different stages in a process. For the first slurry test an 89 μm d50 particle size was selected with a mixture density of 1300 kg/m^3. The second slurry test started out with a coarser sand slurry containing 186 μm particles. Clay and larger stones were added subsequently to the mixture. A velocity step down test was run for each slurry type to measure the velocity profile as a function of velocity.

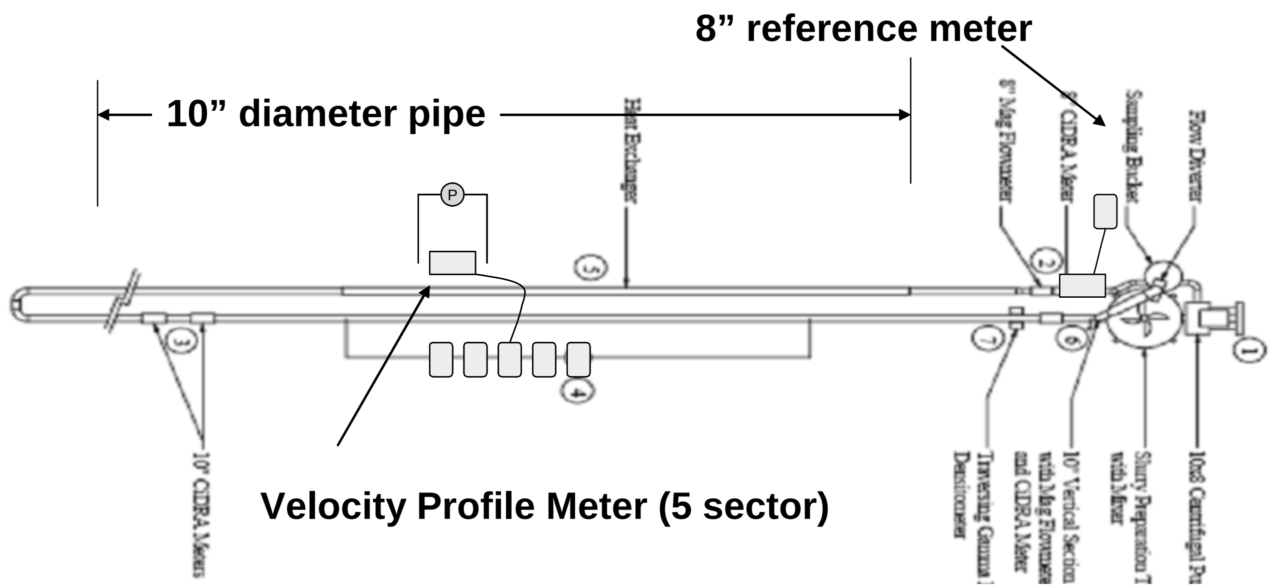


Figure 4: Test loop setup

Slurry Test Results – 89 µm Slurry

The results of the 89 µm slurry test are graphed in Figure 5. The velocity was stepped down in the following increments to develop a sand bed – 4 m/s, 3 m/sec, 2 m/s, 1.75 m/s 1.5 m/s, 1.4 m/s, 1.3 m/s, 1.2 m/s, 1.1 m/s, 1.0 m/sec, 0.9 m/s, 0.8 m/s, and 0.7 m/s. 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. Figure 5 shows the step down in flow rate and the corresponding velocities measured at each of the five sensor array positions. Also shown is the output of a densitometer positioned near 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 Figure 5.

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 1.5 m/s. 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 relative velocities of the lower two 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, due to the stratification of the slurry resulting in denser and slower moving layers near the bottom. When the bottom bed stops moving the bottom sensor detects signals from higher up in the pipe where the velocity is faster. This condition can cause the reported velocities of the bottom and 135 degree sensors to become more similar. Figure 6 shows alarm conditions that can be generated based on the velocity differences measured by the different sensor bands. In Figure 7 and Figure 8, measured velocity profiles are shown at three different flow velocities each showing three distinct flow regimes: mostly homogenous with all particles suspended (Left Figure 7), heterogeneous flow with all particles suspended (Right Figure 7) and heterogeneous flow with a stationary bed (Figure 8). In the latter, the characteristic signal seen from a sand bed deposition is detected and the velocity calculated for pipe heights at the bottom and near the bottom of the pipe is set to zero.

Slurry Test Results – 186 µm Slurry

For comparison with the previously discussed 89 µm slurry, Figure 9 shows a step down test with the 186 µm d50 particle sized 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 2.4 m/s it suddenly undergoes a step change reflecting an increase of solids at the bottom of the pipe. Additionally, Figure 9 shows the pressure drop measured

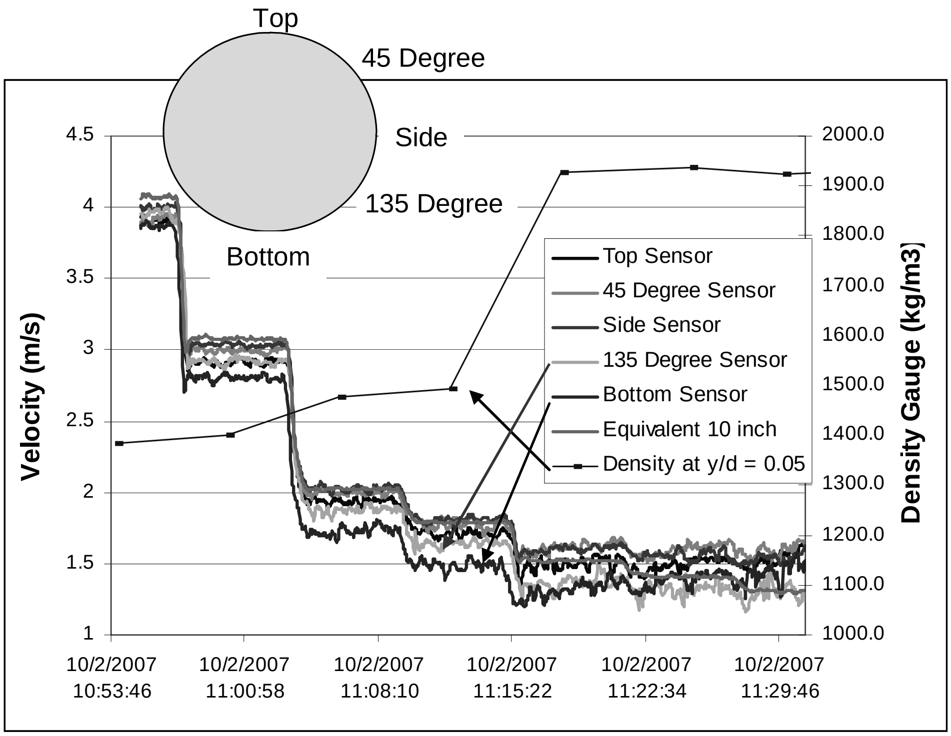


Figure 5: Velocity profile of 89 µm mining slurry.

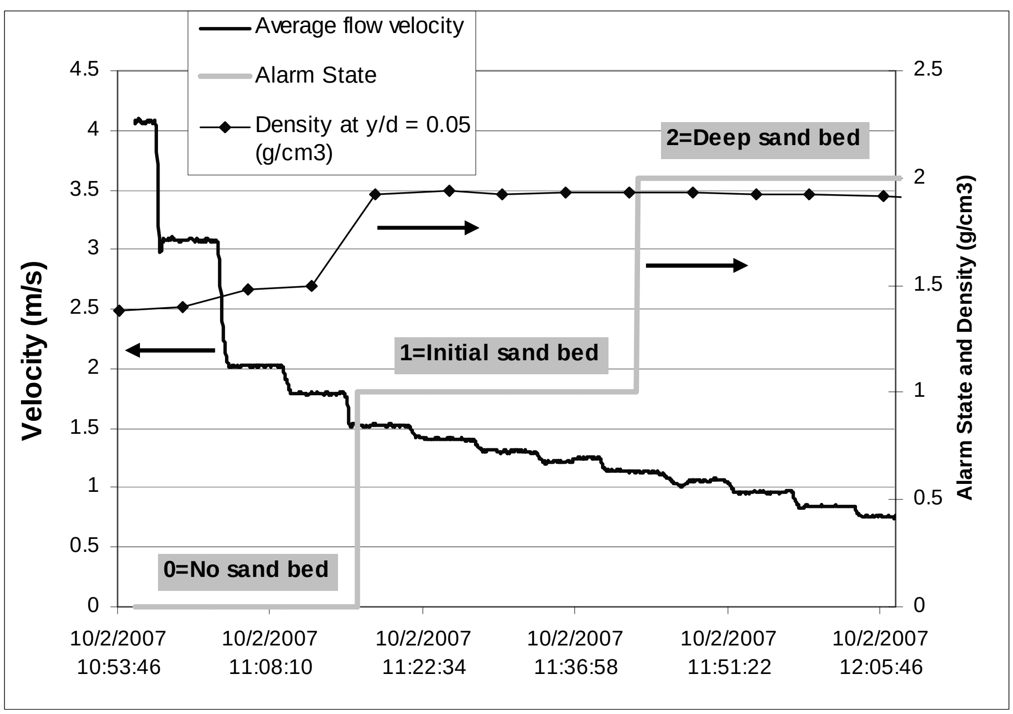
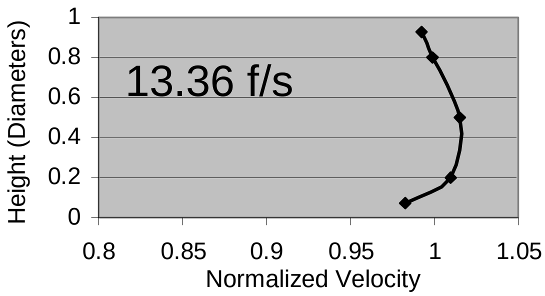


Figure 6: Alarm States– 89 µm slurry.

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



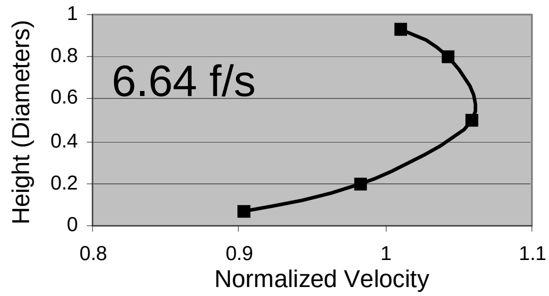


Figure 7: (Left) Mostly homogenous flow, suspended particles and (Right) Heterogeneous flow, suspended particles

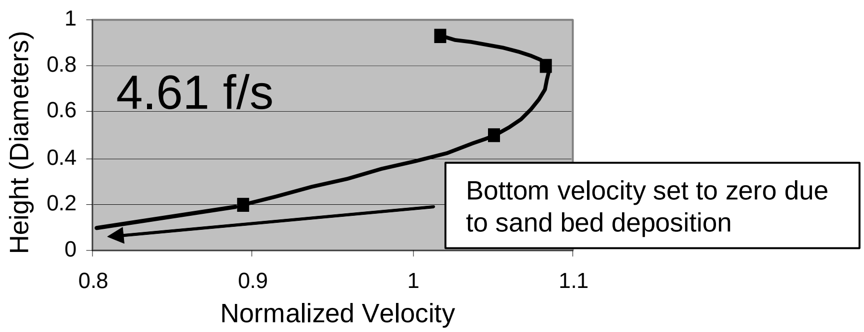


Figure 8: Heterogeneous flow, stationary solids bed

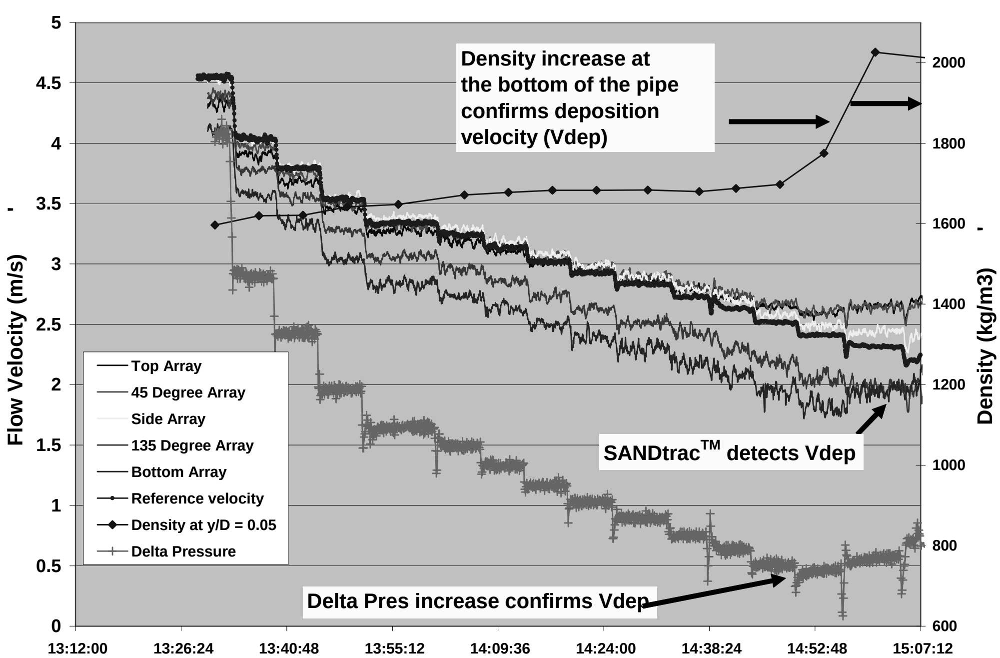


Figure 9: 186 μm Slurry solid deposition detected by sonar meter, densitometer, and delta-pressure

across the velocity profile meter, which in this case shows a sudden increase that coincides with the densitometer increase and the velocity overlaps of the bottom and 135° arrays 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.

The velocity profile versus reference flow velocity is shown in Figure 10. This plot shows 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. This velocity 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 as seen in the 1.9 m/s and 2.0 m/s flow rates.

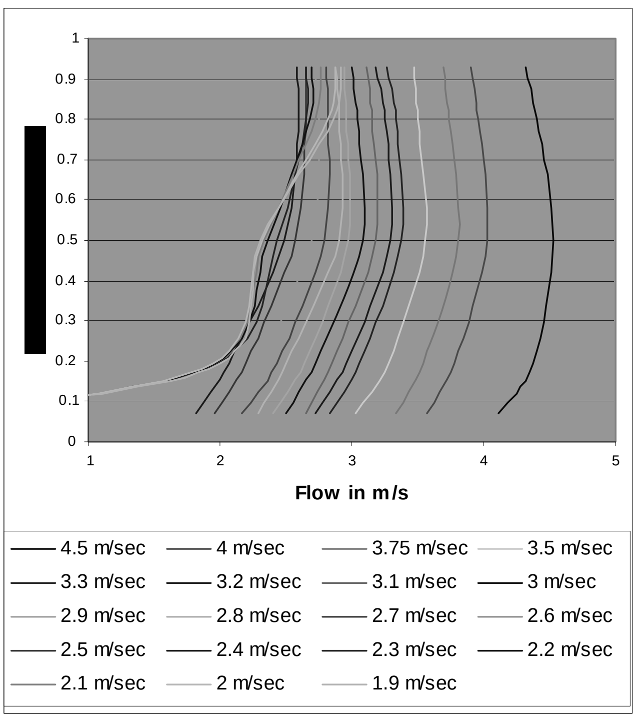


Figure 10: Velocity profiles vs. reference velocity

Figure 11 is a representation of the flow derived from the velocity profile data when coupled with flow profile models. The resulting velocity calculations in the horizontal and vertical orientations can be visualized in a three-dimensional format and through contours.

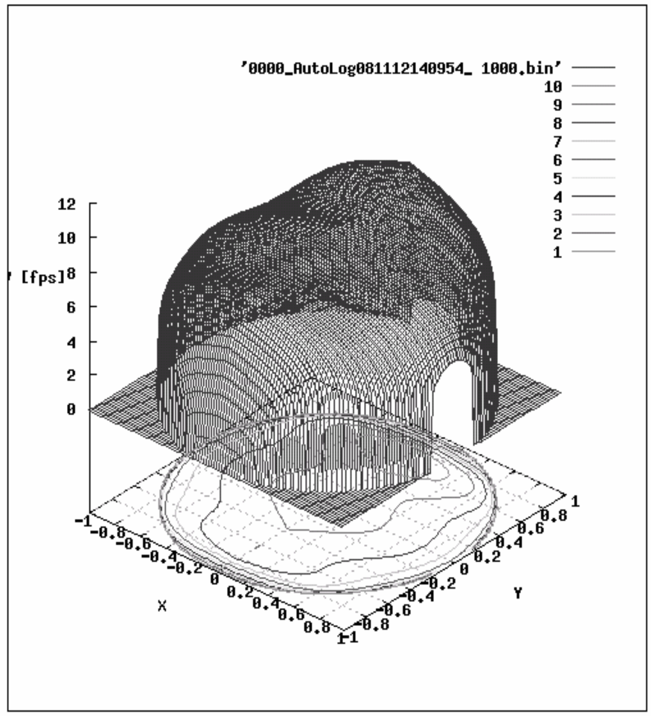


Figure 11: Three-dimensional velocity profiles and velocity contours in an inhomogeneous flow

Field Implementation

A field system has been monitoring velocity profile in a slurry solution with a wide range of particle sizes. This system directly reports the flow profile and sanding condition. A picture of this system in the field is shown in Figure 12. The multiple sensor arrays are incorporated into a single band that is placed under the cover seen in the figure. This system monitors and logs the velocity at the previously discussed circumferential positions, which can be processed to determine the conditions leading to a potential sand bed development condition. In Figure 13, velocity and alarm states from this field system are shown. The degree of stratification and other indications are used to determine when a sand bed has developed and when a sand bed is likely to develop. The slurry being monitored has a wide distribution of sizes and as a result a high level of stratification is expected even at the relatively high flow rates experienced by this pipeline. In Figure 14 three states can be seen, heterogeneous flow, homogenous flow during a water flush and heterogeneous flow with a sand bed.

Figure 12 Operation of velocity profile monitoring system at customer site.

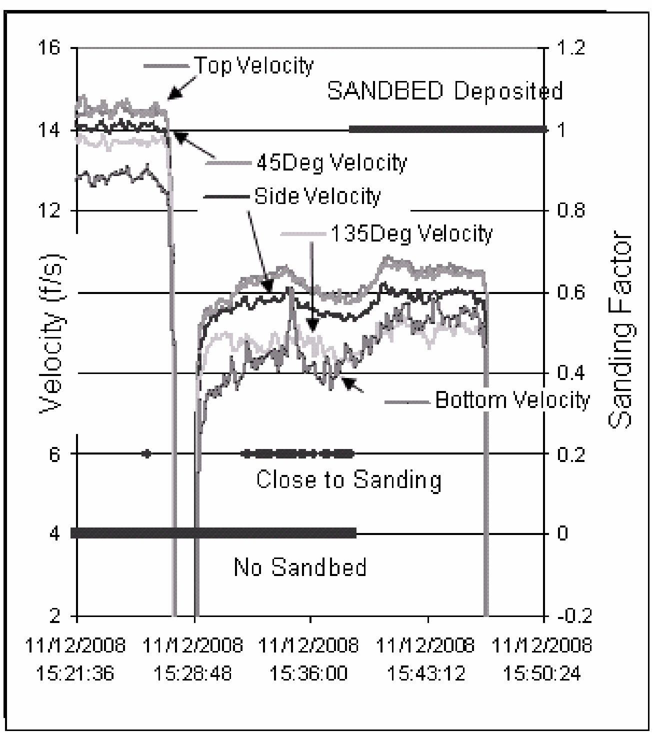


Figure 13 Detection of sand bed and development of sand bed in slurry pipeline in the field

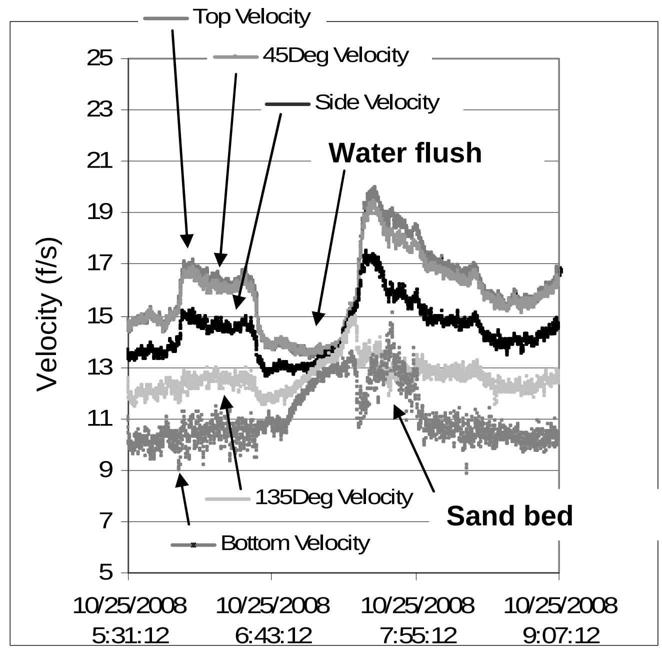


Figure 14 Detection of water flush (no stratification) and sand bed deposition in slurry pipeline in the field

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^{TM}, 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 15.

Principle of Operation for Pipe Wall Thickness Monitoring

The new pipe wear monitoring system, HALO^{TM}, 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 (ultrasonic 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. This system is designed to measure the thickness of steel walled pipes but can be possibly extended to polymer pipes, depending on the wall thickness and material acoustic properties.

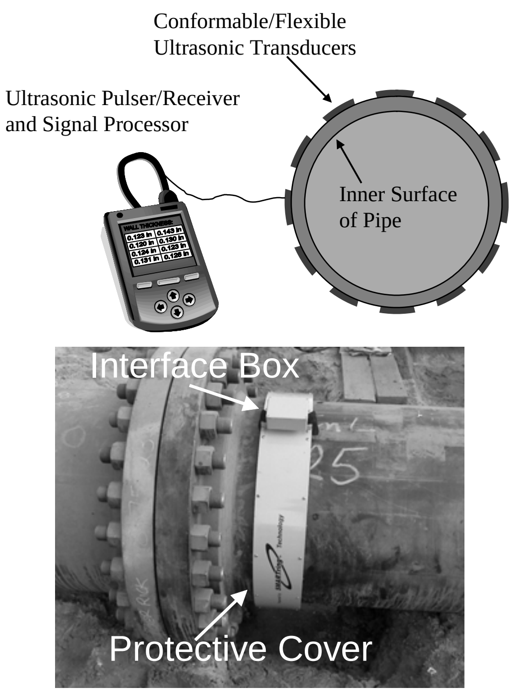


Figure 15: Conceptual layout of HALO^{TM} system and picture of system in operation at a customer site

Comparison to Conventional Ultrasonic Thickness Measurement Instrumentation and Techniques

The current baseline pipe wall thickness measurement technique consists of a handheld ultrasonic transducer and a portable pulser/receiver. One comparison between the HALO^{TM} system and a sophisticated handheld ultrasonic pipe wall thickness measurement tool revealed similar results. Measurements taken at the exact same points were not possible since the HALO^{TM} system was installed before the conventional ultrasonic measurements could be performed. The location difference was in the axial direction but the circumferential locations were kept the same as shown in Figure 16.

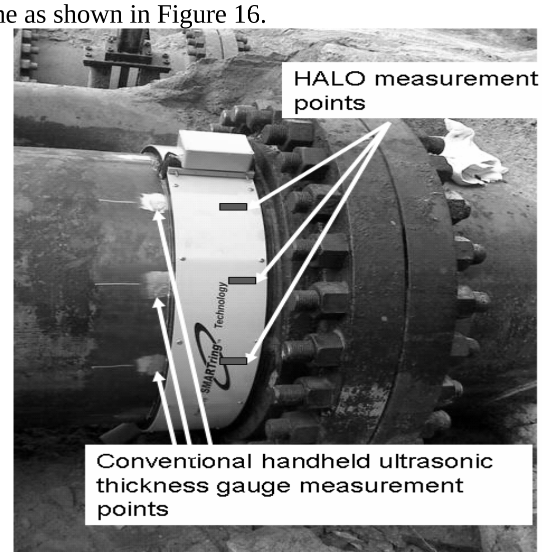


Figure 16: Pipe wall thickness measurement points to compare conventional technique with HALO^{TM}

Small variations between the conventional ultrasonic technique and HALO^{TM} are due to the differences in axial location. The comparison was performed at two different periods of time to ascertain the ability to measure pipe wall thickness trends. The results shown in Figure 17 reveal that there are some differences in the absolute wall thickness measured but more importantly that there are differences in the trends recorded between the two instruments. The HALO^{TM} system measured a reduction in wall thickness at all points, which was expected. In contrast, the conventional ultrasonic approach indicated that some measurement points showed no or minimal wear.

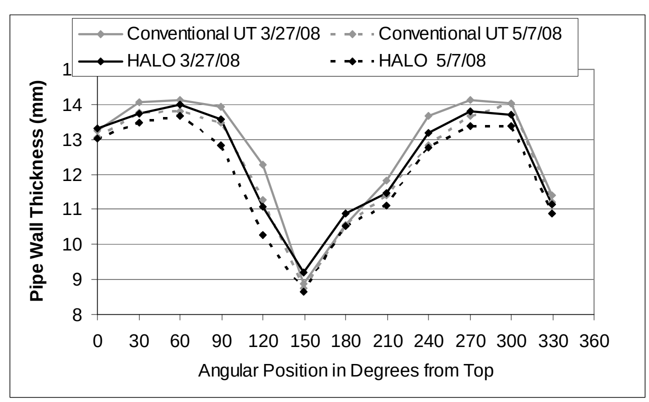


Figure 17: Conventional ultrasonic (UT) pipe wall thickness measurement versus HALO^{TM} measurements

Measurement and Visualization of Pipe Wear

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 a set reference point on the pipe. New software that interpolates between sensor points and provides robustness in the possibility of erroneous data or a failed sensor has been implemented. The hardware, analysis and data management takes into account pipe rotations to monitor wear trends and project to the point in time at which the pipe wall safety margins have been crossed. An example of the visualization of the pipe wall thickness around the pipe is shown in Figure 18. In the plots, one can see thinner pipe walls at various angular locations around the pipe due to intentional rotations of the pipe performed to increase the pipe lifetime. In other situations, uneven pipe wear will result from changes in the flow profile after elbows or other pipe geometry effects.

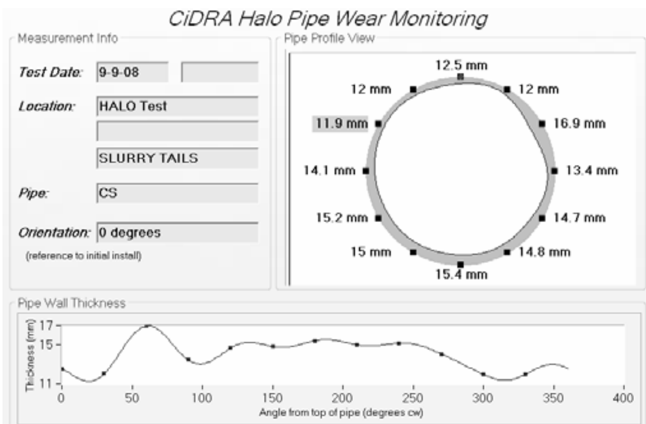


Figure 18: HALO^{TM} pipe wall thickness visualization software output

Short Term Temperature Effects and Repeatability

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 19. 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.

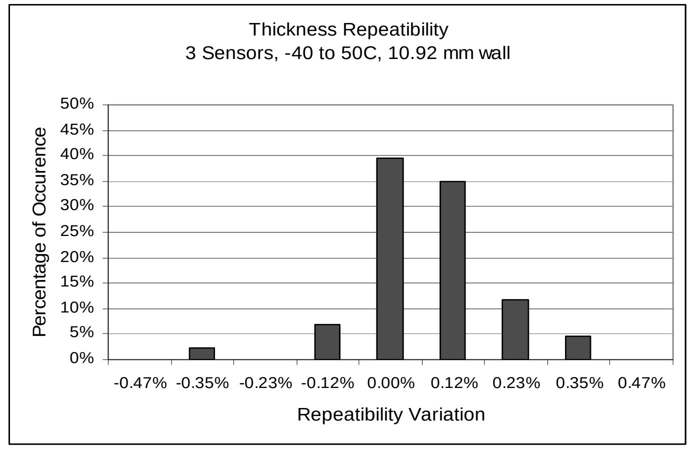


Figure 19: Small spread in data over 90C temperature range and over three sensors is shown

Pipe Wear Trend Monitoring

A demonstration of the ability to monitor and quantify the wear rates in a pipeline has been demonstrated in the field. In Figure 20 , the wear rate in a high wear rate environment shows the rapid decrease of wall thickness over a period of 23 weeks.

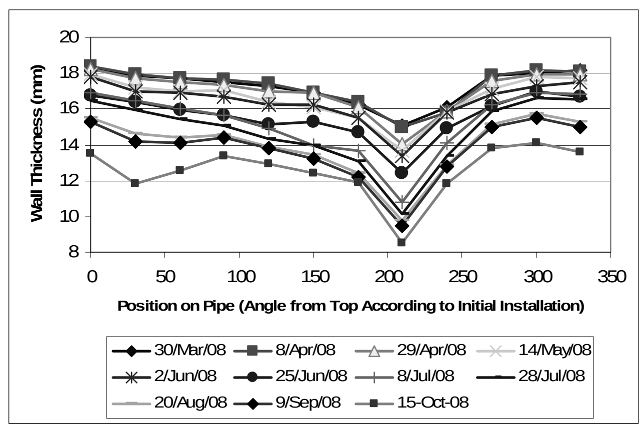


Figure 20: Measurement of pipe wall thickness as a function of angular position and time is shown

Pipe Surface, Thermal Cycling and Long Term Elevated Temperature Effects

It is to be expected that the inside surface of the pipe will have an impact on the strength and form of the reflected ultrasonic signal. Long term effects including temperature cycles and high temperature degradation will also play a role in the reliability of these measurements. Tests are underway to fully understand the impact of these effects. To date, a variety of pipes from steel to chromium-steel with a variety of inner surface topologies have been studied and tested with good results, as verified with caliper measurements. Three of these surfaces are shown in Figure 21.

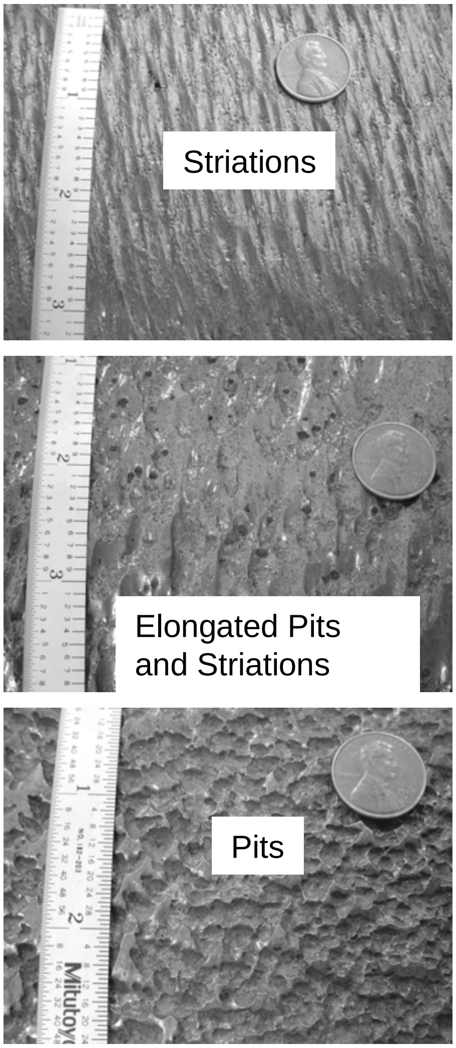
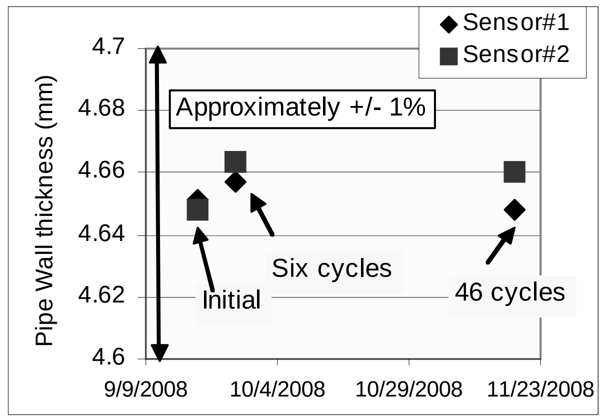


Figure 21: Inner surface irregularities seen on chromium-steel worn pipe

Temperature cycling from -40C to +40C with 10 hour holds on a semi-permanent style system using ultrasonic gel couplant has been initiated and the results of the first 46 thermal cycles reveals no discernable difference in pipe wall thickness as seen Figure 22. In addition, a comparison of the amplitudes of the signals from one of the sensors indicated no degradation in amplitude as seen in Figure 22. After 46 cycles, the amplitude of the signal increased relative to the initial pulse and the pulse after 6 cycles.

The long term testing at 50C to 70C showed no detectable change in the pipe wall thickness measurement, that is no detectable change in the time from the initiation of the trigger pulse to the detection of the reflected ultrasonic signal. The amplitude of the signal which has a bearing on the reliability of the sensing system and the signal to noise did show some slight degradation of less than 20% amplitude over a period of three months as seen in Figure 23. A new design has been implemented which is expected to see much lower amplitude changes in the ultrasonic signals during similar long term testing. In addition, a permanent style system which does not use ultrasonic gel couplant is expected to see even smaller changes.



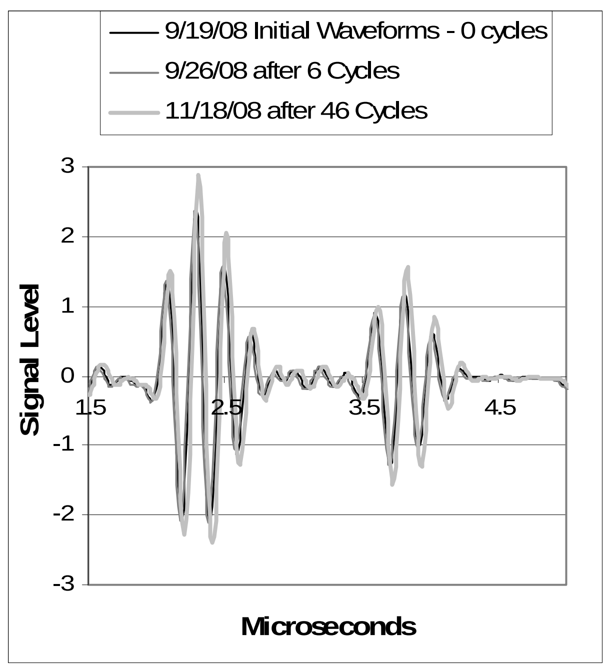


Figure 22: Impact of Temperature Cycling on Wall Thickness Measurement and Signal Amplitude (-40C to +40C with 10 hour holds)

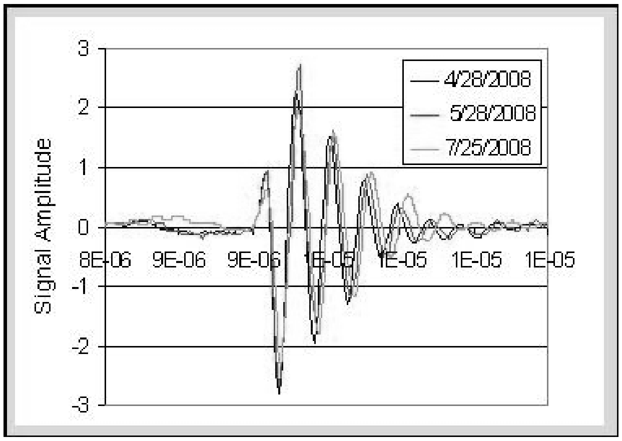


Figure 23: Long Term High Temperature Testing

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

Cheremisinoff, N.P., (1986). Encyclopedia of Fluid Mechanics. Vol. 5, Slurry Flow Technology, Golf Pub. Co.

Gysling, D. and Mueller, E., (2004). Application of Sonar-Based Clamp-On Flow Measurement in Oilsand Processing. *ISA 2004 Exhibit and Conference*.

Nelson, R.O., (2001). Sonar Signal Processing, Artech House Inc., Norwood, MA, USA, ISBN 0-89006-453-9