New Developments in Velocity Profile Measurement and Pipe Wall Wear Monitoring for Hydrotransport Lines

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ABSTRACT

Sonar array-based non-invasive flow measurement technology is becoming an accepted and many times a preferred 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 pipes.

The first development is the non-invasive measurement of real-time velocity profile of slurry flow in horizontal pipes. Multiple non-invasive passive 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 or plugging and its associated operational costs.

The second development is the non-invasive measurement of pipe wear on slurry lines. Presently, such measurements are made by hand-held portable ultrasonic thickness gages. The numerous shortfalls associated with the manual method are overcome with a set of permanently or semi-permanently installed transducers clamped onto the outside of the pipe. This ring of sensors contains a series of conformable ultrasonic transducers spaced around the circumference, which are used to measure the thickness of the pipe under their respective locations. Compared to manual methods, this system and approach results in better repeatability and accuracy. It also decreases inspection labor costs and pipe access requirements. The minimal accuracy variations in the presence of varying environmental temperatures will be shown. Trending of pipe wall thicknesses in high wear pipelines will be illustrated. The benefits of significantly improved pipe wear monitoring in hydrotransport lines with abrasive solids, and associated improvement in the ability to insure safe operation and avoidance of costly environmental damage due to leaks caused by pipe wear will be discussed.

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 sensor arrays arranged in the circumferential direction 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 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 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

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. Each such passive sensor element in an array of sensors will detect the unique signal from each collection of turbulent eddies. 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.

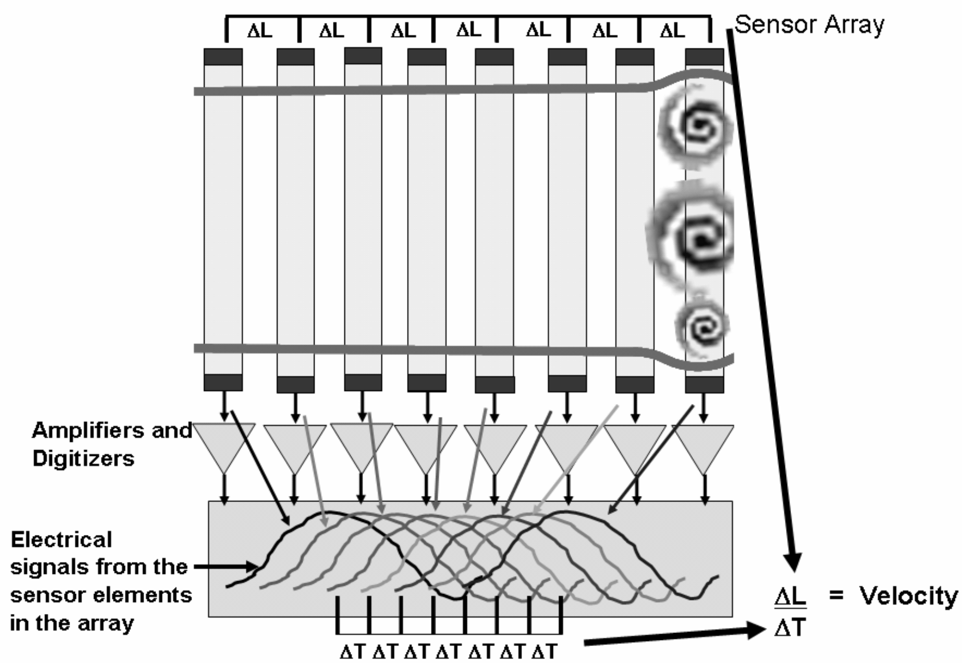


Figure 2: Illustration of signal detected by passive sensors in array from one collection of turbulent eddies.

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.

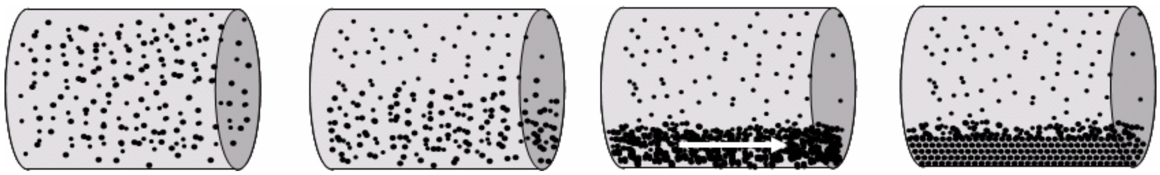


Figure 3: (Left to right) a) Homogeneous flow b) Heterogeneous flow – full suspended particles c) Heterogeneous flow – moving bed d) Heterogeneous flow – stationary bed

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. This paper summarizes the results of flow loop 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.

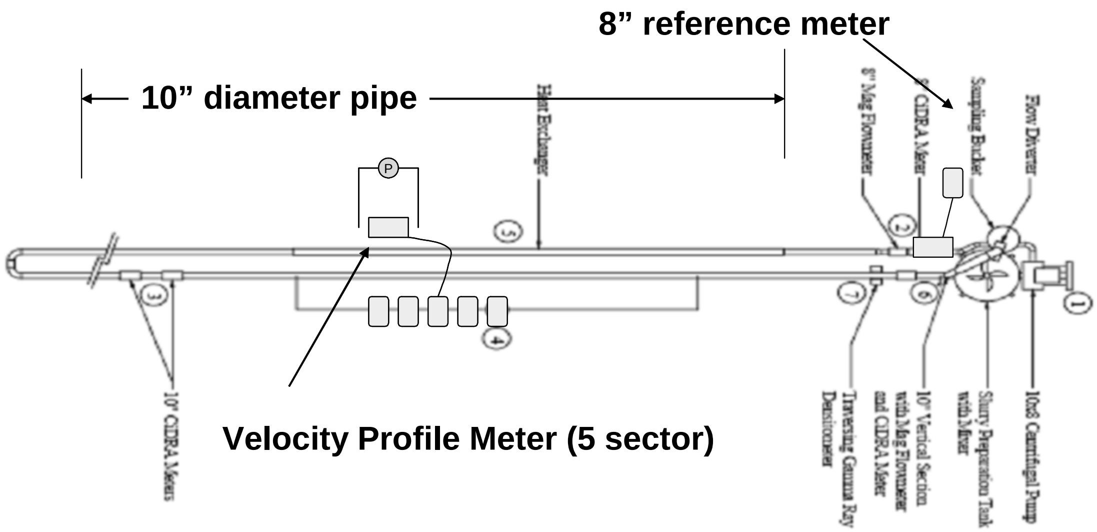


Figure 4: Test loop setup

Slurries Tested

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 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.

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 (Figure 7), heterogeneous flow with all particles suspended (Figure 7) and heterogeneous flow with a stationary bed (Figure 8). In the latter, the 135 degree sensor is measuring a combination of the sand bed and the fluid flow above the sand bed, resulting in the characteristic "hook" shape seen at the bottom of the figure.

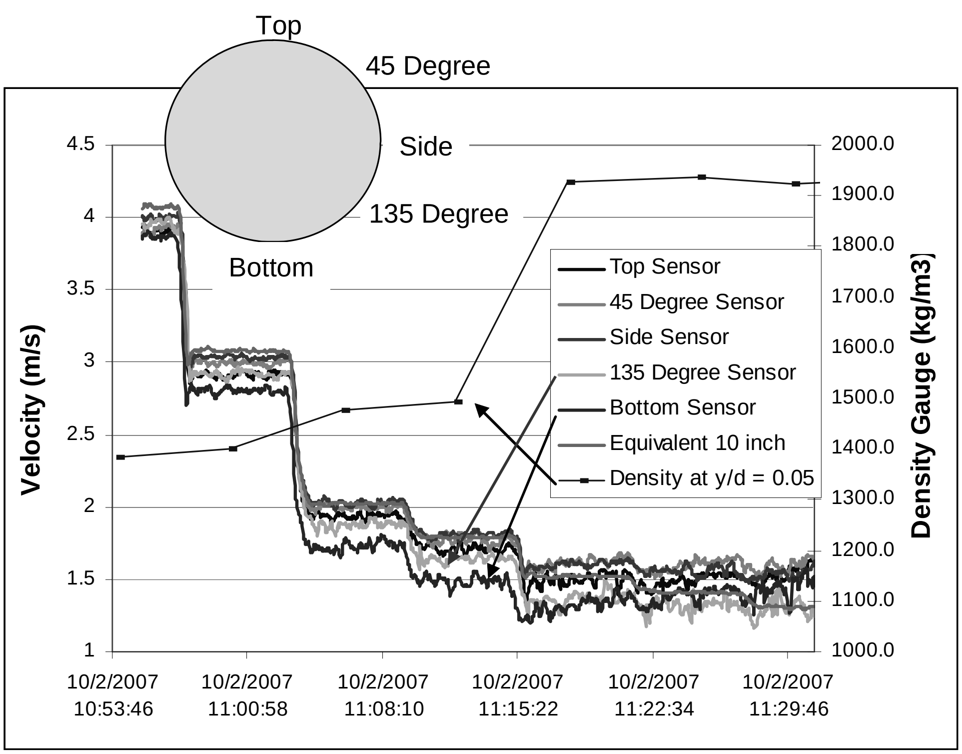


Figure 5: Velocity profile of 89 μm mining slurry.

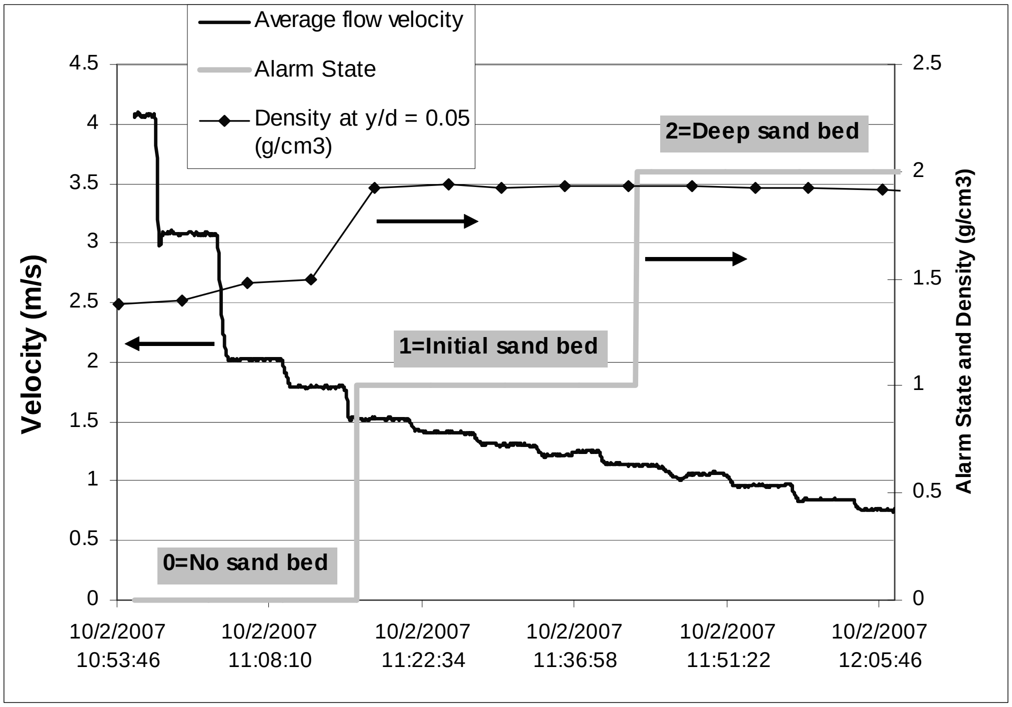


Figure 6: Alarm States– 89 μm slurry

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

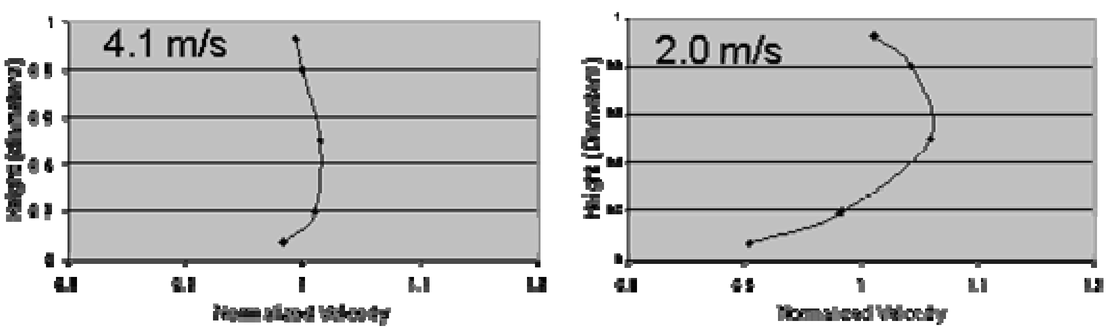


Figure 7: (Left) Mostly homogenous flow, suspended particles and (Right) Heterogeneous flow, suspended particles

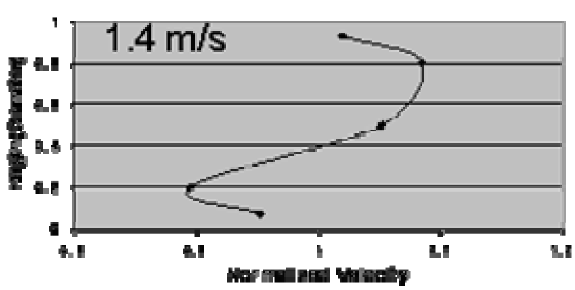


Figure 8: Heterogeneous flow, stationary solids bed

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 across the velocity profile meter, which in this case shows a sudden increase which 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.

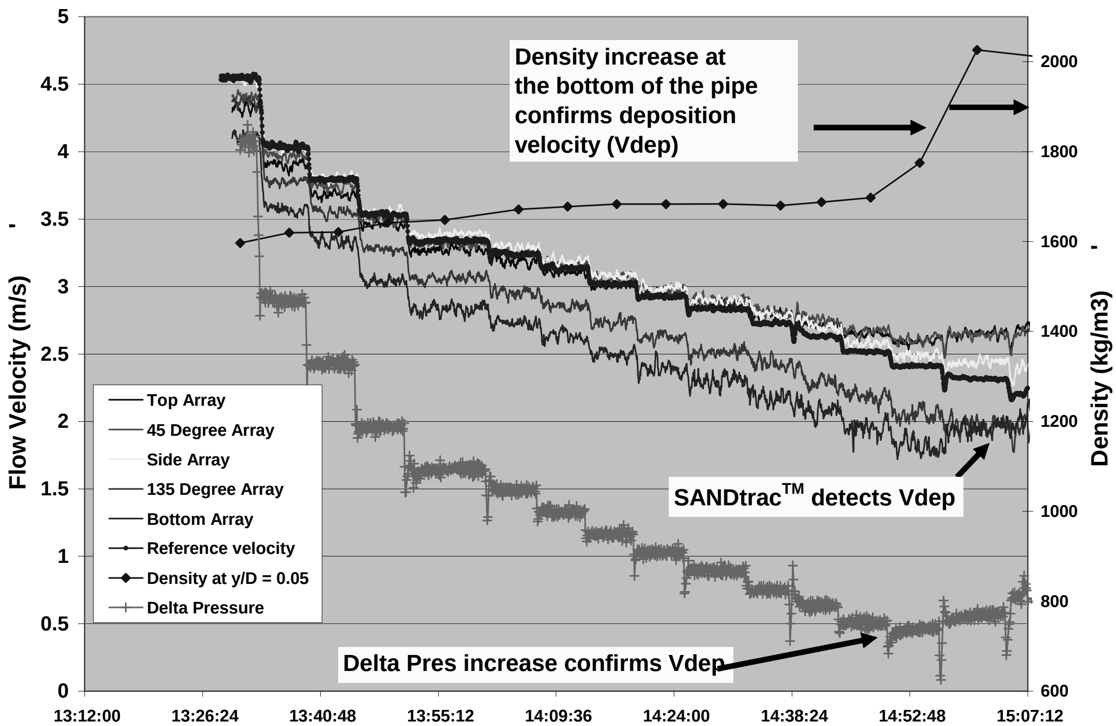


Figure 9: 186 μm Slurry solid deposition detected by sonar meter, densitometer, and delta-pressure

The velocity profile versus reference flow velocity is shown in Figure 10, and Figure 11 shows a normalized plot where all velocities are normalized to the center velocity. The Figure 11 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. 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 causing an apparent "velocity inversion" between the bottom and 135 arrays.

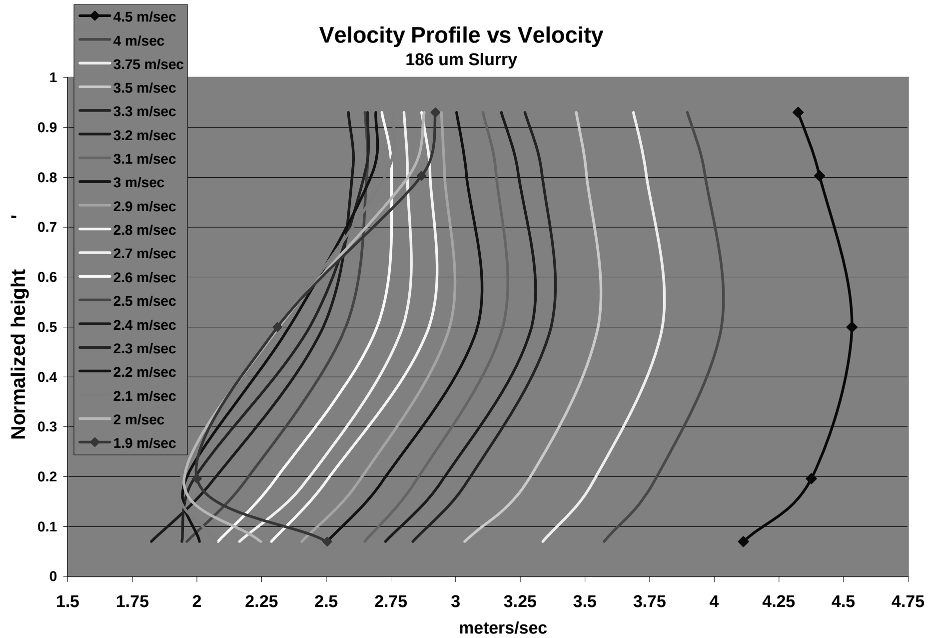


Figure 10: Velocity profiles vs. reference velocity

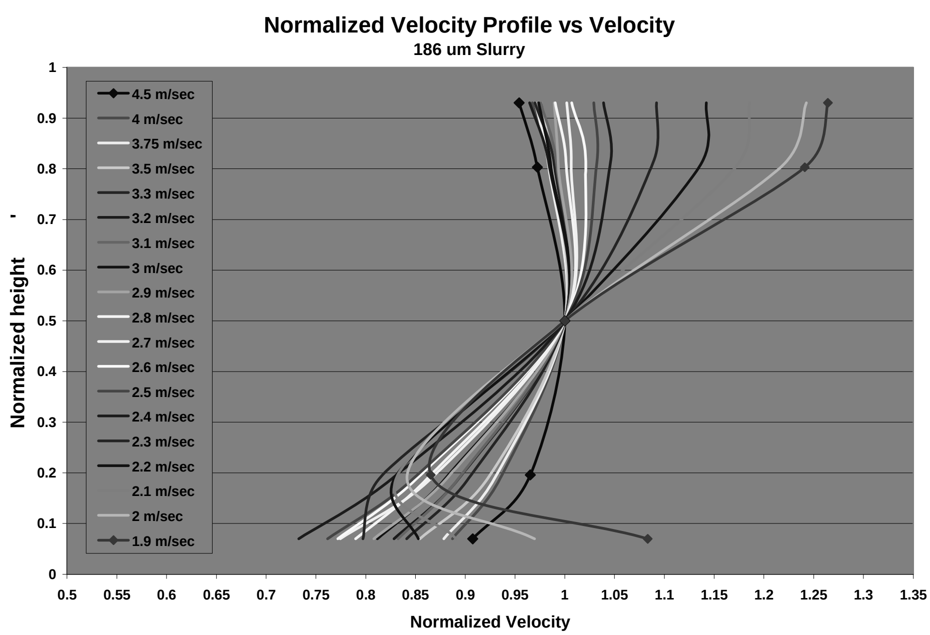


Figure 11: Velocity profiles (normalized to pipe center velocity) vs. reference velocity

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 12.

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. 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.

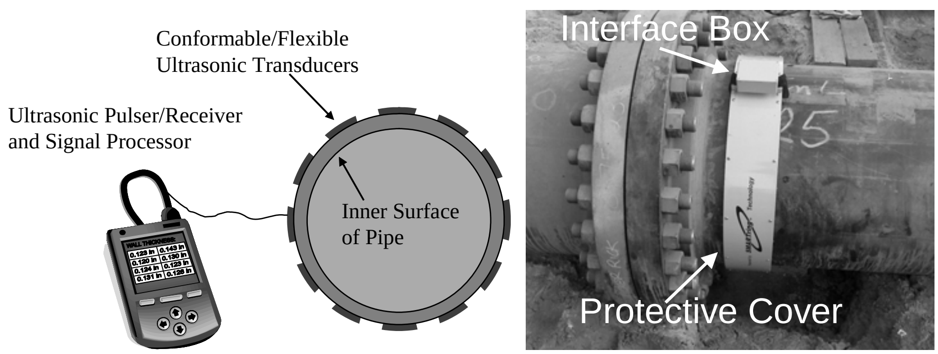


Figure 12: Conceptual layout of HALO™ system and picture of system in operation at a customer site

Comparison to Conventional Ultrasonic Thickness Measurement Instrumentation and Techniques

The current baseline pipewall thickness measurement technique consists of a handheld ultrasonic transducer and a portable pulser/receiver. One comparison between the HALO™ system and a sophisticated handheld ultrasonic pipewall thickness measurement tool revealed similar results. Measurements taken at the same points were not possible since the HALO™ 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 13.

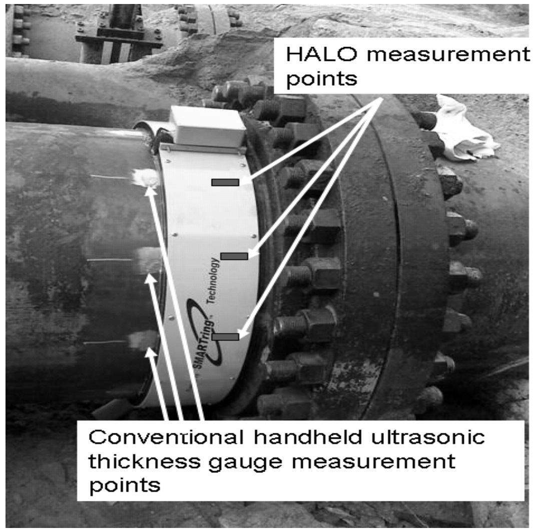


Figure 13: Pipewall thickness measurement points to compare conventional technique with HALO™

Small variations between the conventional ultrasonic technique and HALO™ 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 14 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™ 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.

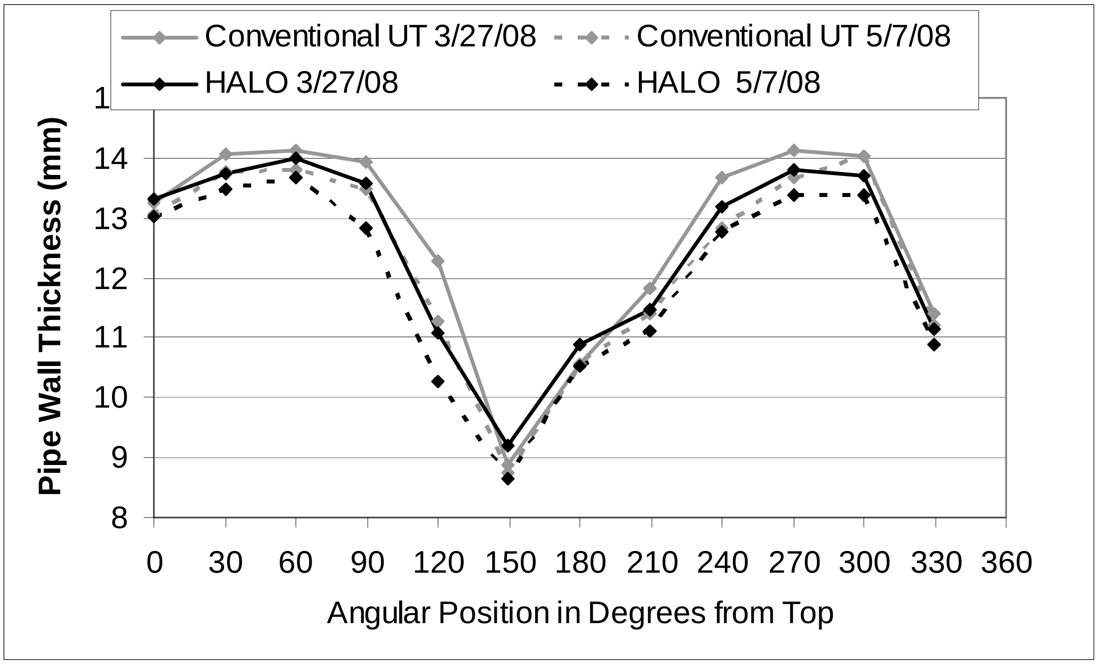


Figure 14: Conventional ultrasonic (UT) pipewall thickness measurement versus HALO™ measurements

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 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 15. The degree of wear is unequivocally seen. In the plot shown in the left side of Figure 15 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 15, 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.

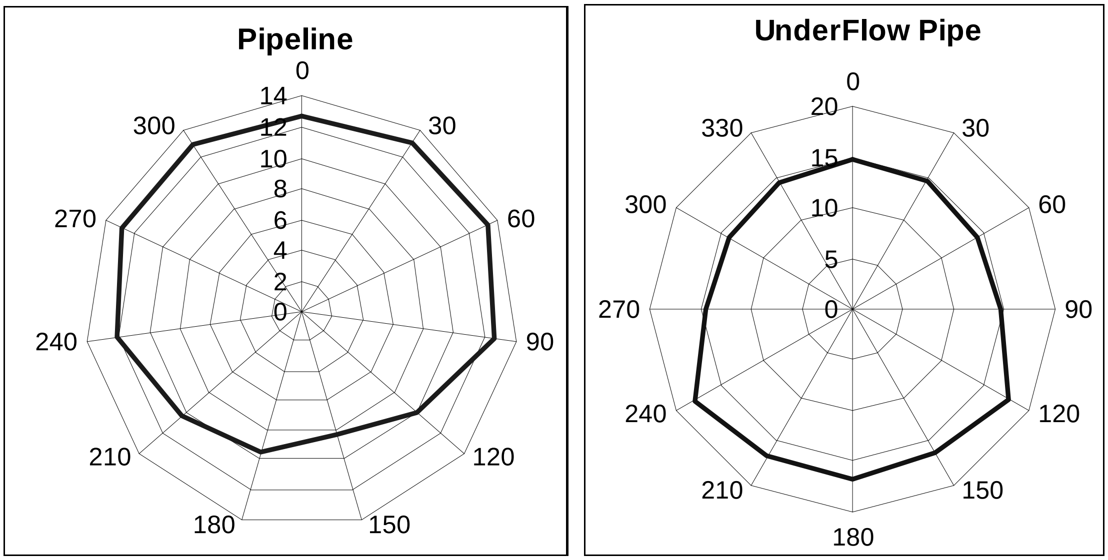


Figure 15: Pipe wall thickness in millimeters as a function of angular position from top of pipe as shown on two different pipes at a customer site

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 16.

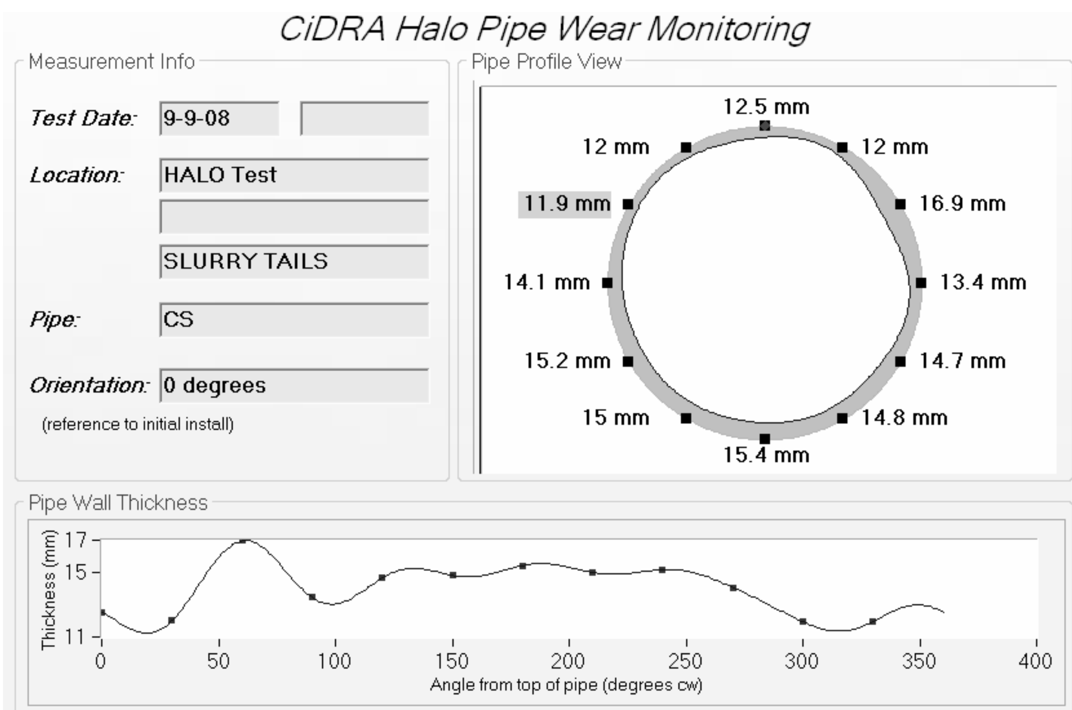


Figure 16: HALO™ pipe wall thickness visualization software output

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 17. 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.

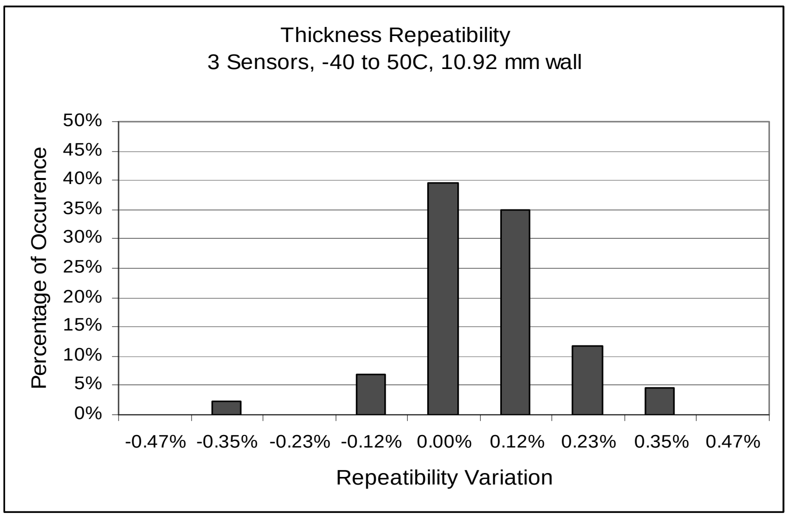


Figure 17: Small spread in data over 90C temperature range and over three sensors is shown

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 18 , the wear rate in a high wear rate environment shows the rapid decrease of wall thickness over a period of 23 weeks.

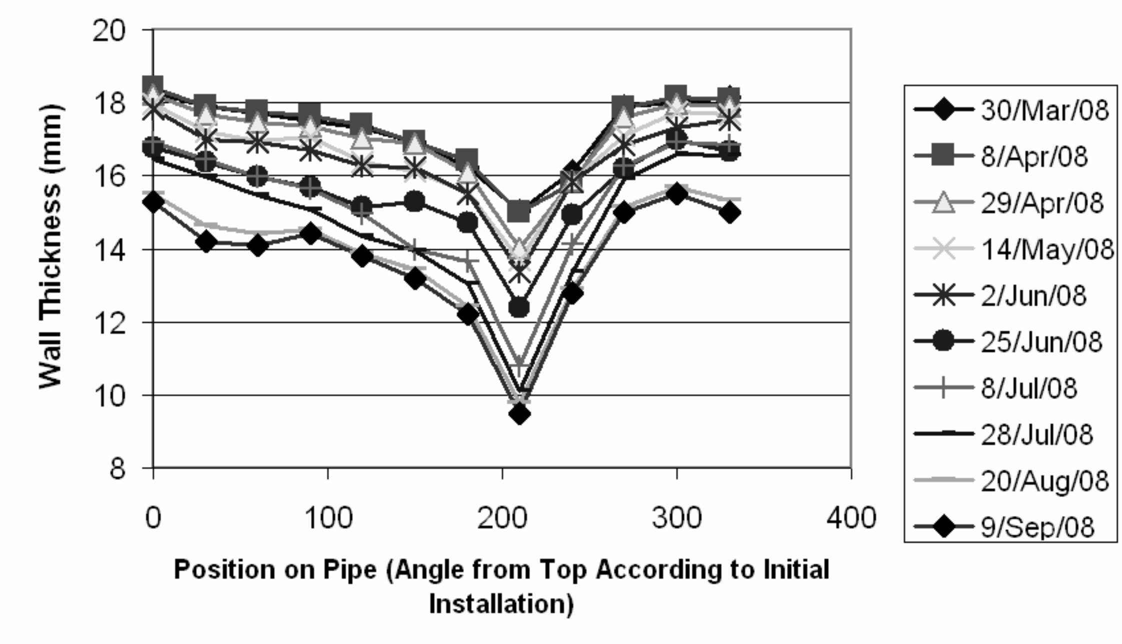


Figure 18: Measurement of pipe wall thickness as a function of angular position and time is shown

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. Three of these surfaces are shown in Figure 19.

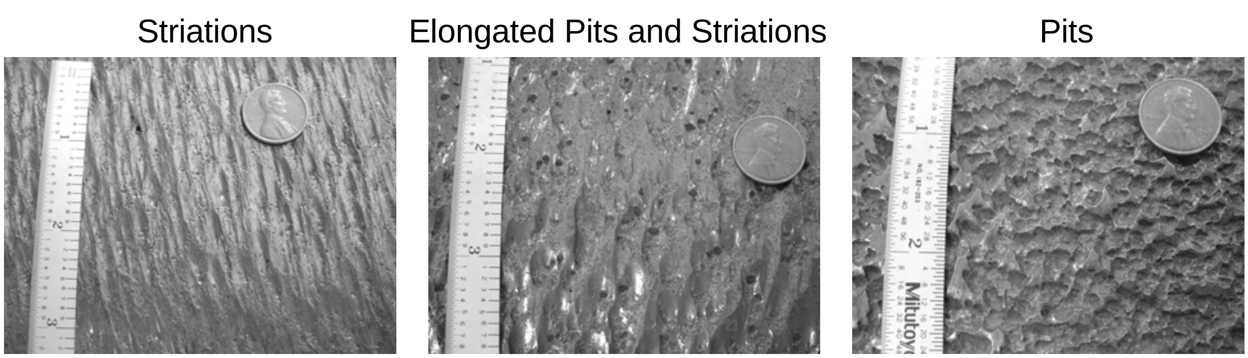
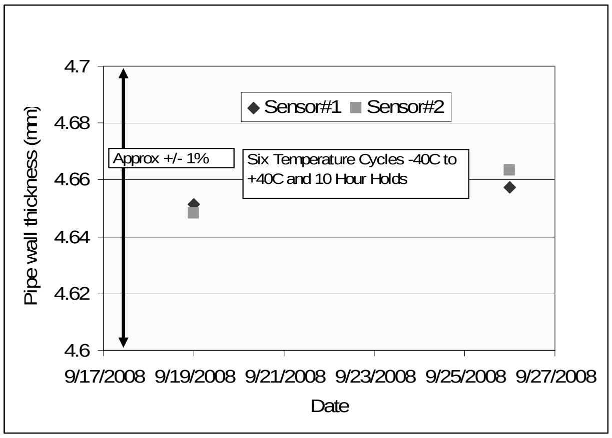


Figure 19: Inner surface irregularities seen on chromium-steel worn pipe

Temperature cycling from -40C to +40C on a semi-permanent style system using ultrasonic gel couplant has been initiated and the results of the first six thermal cycles reveals no discernable difference in pipe wall thickness as seen on the left hand side of Figure 20. 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 the right hand side of Figure 20. A few 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.



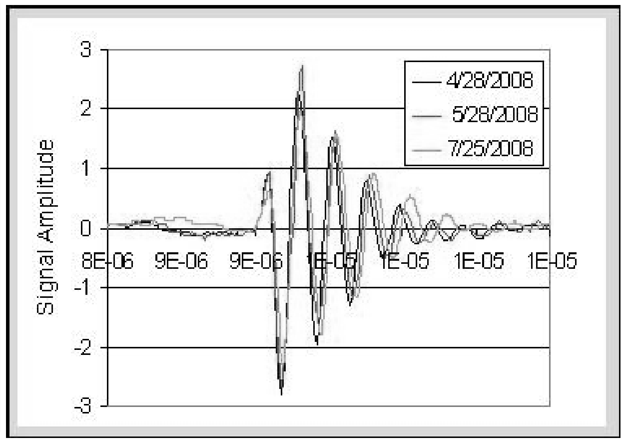


Figure 20: Temperature Cycling and Long Term High Temperature Testing

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.

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