APPLICATION OF NON-INTRUSIVE SONAR TECHNOLOGY TO FLOW MEASUREMENT AND CONTROL IN MINERAL PROCESSING PLANTS

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ABSTRACT

In this presentation, CiDRA's patented technology platform and its applications will be described. CiDRA's non-invasive, passive sonar array-based flow meter technology provides the volumetric flow rate of single or multiphase fluids by measuring the speed at which naturally occurring structures such as turbulent eddies or density variations convect with the flow past an axial array of sensors. These sensors are incorporated in a band that is wrapped around the outside of the pipe, resulting in no process downtimes for installation and unprecedented reliability. This technology has resulted in a unique ability to measure the flow rate of most fluids – clean liquids, high solids content slurries, pastes, and liquids and slurries with entrained air. Unique and difficult minerals processing flow measurement problems and their solutions will be described, such as high solids content abrasive slurries, pastes, and liquids and slurries with entrained air. These applications are located in concentrator plants, hydrotransport lines, and tailings lines.

Recent developments in extending this technology to solve other unique minerals processing measurement problems will also be presented. Applications to be discussed include; non-invasive slurry velocity profiling, and sanding detection which make use of the unique ability to measure localized velocities within a slurry pipe; valve movement detection which uses the unique ability to measure overall frequency selectable sound levels within a process pipe to provide acoustic condition monitoring.

En esta presentación se describe la plataforma tecnológica de CiDRA para medición de flujo. Basado en un arreglo de sensores tipo sonar pasivo, se realiza dos mediciones independientes en flujos de uni y multi-fase; flujo volumétrico, y velocidad de sonido (fracción de gas por volumen). Primeramente, el medidor entrega la velocidad de flujo midiendo la velocidad a la que los remolinos turbulentos convectan con el flujo. En segundo lugar, entrega velocidad de sonido midiendo velocidad a la que las ondas acústicas de frecuencia baja se desplazan en el fluido. La cabeza de sensor es no-invasivo, y no requiere detención del proceso para instalación. Es insensible a presencia y porcentaje de sólidos; y mide desde líquidos puros hasta pulpa con alta concentración de sólidos. Se presentará la aplicación de esta tecnología a varias aplicaciones difíciles en beneficio de minerales y hidrotransportes.

INTRODUCTION

The minerals processing industry encounters many unique and difficult process measurement and control conditions and environments. With respect to flow measurement, many of these applications are not being adequately served by traditional flowmeter technologies such as ultrasonic, electromagnetic, turbine, vortex, Coriolis, venturi, and orifice plate. To address these needs, a new class of flowmeter technology has been developed that operates well in many of these unique situations, thus solving many of these difficult flow measurement problems. This new class of flowmeter technology utilizes an array of passive sensors and sonar-based processing algorithms[1] to measure not only flow, but also fluid composition. It does so reliably, accurately, and without making contact with the fluid. These measurements can be made on practically any type of fluid and any pipe material.

PRINCIPLE OF OPERATION

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), propagation in the fluid or slurry (mid-range velocity), and propagation in the pipe walls (fast velocity). The sonar array-based meters separate the three main propagation modes from each other through a combination of frequency and velocity differences. First let us focus on the disturbances that convect with the flow. These disturbances can be turbulent eddies, density variations, temperature variations, or others. Within most industrial processes, these will be turbulent eddies for turbulent flow and density variations for core annular flow. Either type provides an excellent means of measuring the flow rates.

Flow Velocity Measurement using Turbulent Eddies

Turbulent flow is composed of eddies, also known as vortices or turbulent eddies, which meander and swirl in a random fashion within the pipe but with an overall mean velocity equal to the flow, that is they convect with the flow[2]. An illustration of these turbulent eddies is shown in Figure 1. These eddies are being continuously created. Once created they break down into smaller and smaller vortices, until they become small enough such that they are dissipated as heat through viscous effects of the fluid. For several pipe diameters downstream, these vortices remain coherent retaining their structure and size before breaking down into smaller vortices. The vortices in a pipe have a broad range of sizes, which are limited by the diameter of the pipe for the largest vortices and by viscous forces for the smallest vortices. On the average, these vortices are distributed throughout the cross section of the pipe and therefore across the flow profile. The flow profile itself is a time-averaged axial velocity of the flow that is a function of the radial position in the pipe with zero flow at the pipe wall and the maximum flow at the center as seen in Figure 1. In turbulent flow, the axial velocity increases rapidly when moving in the radial direction away from the wall, and quickly enters a region with a slowly varying time-averaged axial velocity profile. Thus if one tracks the average axial velocities of the entire collection of vortices, one can obtain a measurement that is close to the average velocity of the fluid flow

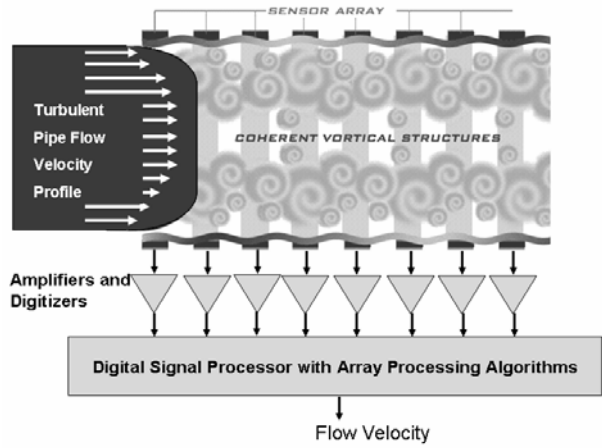


Figure 1 Diagram of pipe with turbulent flow showing fully developed flow profile and turbulent eddies

Flow Velocity Measurement using Density Variations in Slurry and Paste

High volumetric solids content slurries can have viscosities large enough to quickly dissipate any turbulent eddies that may be formed. Fortunately, many of these slurries are shear thinning in which the viscosity decreases as the fluid shears. This results in a core of coarse particles with zero or low settling velocity due to the low shear rate in the center of the pipeline resulting in a high viscosity in this region. Between this core and the pipewall, there is a high shear rate region, resulting in a low apparent viscosity, thus forming a core-annular flow profile. This shear thinning behavior is advantageous for high solids content slurries transport[3] providing for a lower pressure gradient along the pipeline with its reduced pumping and energy requirements, while presenting a sufficiently high yield stress at the disposal location for proper disposal slopes and stabilities. The core-annular flow profile has non-uniform density variations and ripples at the core to annular interface as seen in Figure 2. This ripples or waves remain coherent for a distance sufficient for tracking through the array of passive sensors.

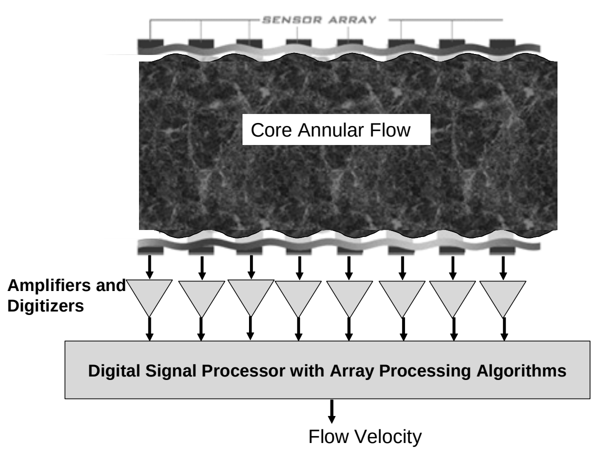


Figure 2 Diagram of pipe showing core annular flow with density variations and waves at core to annular interface

Flow Velocity Measurement With Array Sensing And Processing

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

- The passage of the turbulent eddies or density variations creates a small pressure change on the inside of the pipe wall
- This small pressure change results in a dynamic strain of the pipe wall itself (Figure 1 exaggerates)
- The mechanical dynamic strain signal is converted to an electrical signal through a passive sensor wrapped partially or fully around the pipe – no couplant gels or liquids are required
- This electrical signal 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 resulting electrical signal from each sensor element is interpreted as a characteristic signature of the frequency and phase components of the acoustic waves under the sensor.
- An array processing algorithm combines the phase and frequency information of the characteristic signature from the group of sensor array elements to calculate the velocity of the characteristic signature as it propagates under the array of sensors[4].

The challenges of performing this measurement in a practical manner are many. These include the challenges of operating in an environment with large pumps, flow generated acoustics, and vibrations all of which can cause large dynamic straining of the pipe. The impact of these effects is that the dynamic strain due to the passive turbulent eddies or density variations is usually much smaller than the dynamic strain arising from pipe vibrations and acoustic waves propagating in the fluid. The strength in the array processing algorithm is its ability to isolate and measure the velocities of these different components, including the weak signal from the convecting turbulent eddies or density variations and the strong signals from the acoustic waves and vibrations. The velocity of the acoustic waves is used to calculate the fluid composition or the amount of entrained air (gas void fraction).

The technology lends itself to the generation of a measurement robustness indicator otherwise known as a quality factor. Most other flowmeters do not provide an indication of the quality of the measurement. Conversely, in the sonar processing algorithm such a quality factor can be generated by comparing the strength of the signal from the flow against background energy levels. A quality factor ranging from 0 to 1.0 is generated, with any flow measurement providing a quality factor above 0.1 to 0.2 (depending on the application) having the confidence as being a good measurement.

Currently this technology can report the volume flow rate on liquids and slurries with flow velocities extending from 3 (0.9 m/s) to several hundred ft/sec. The technology lends itself to measurement on practically any pipe size, as long as the flow is turbulent, and for some non-Newtonian fluids, even without turbulence and at velocities below 3 ft/sec. The pipe must be full to give an accurate volumetric flow rate but it can have entrained air in the form of well mixed bubbles. This technology works on practically any type of fluid within virtually any type of pipe including lined pipes and pipes with scale buildup.

Fluid Composition Measurement

In most mineral processing processes including paste or thickened tailings applications, there is an abundance of acoustic waves propagating within the pipes. These acoustic waves are generated naturally from a variety of sources, including pumps, the flow-through devices, and the flow-through pipe geometry changes. Even bubbles within the fluid will generate acoustic waves through their natural oscillations. These acoustic waves are low frequency (in the audible range), and travel in the pipe's axial direction, with wavelengths much longer than the entrained gas bubbles. An illustration of these acoustic waves in a pipe is shown in Figure 3 and as can been seen in the figure they can propagate in either direction down the pipe or in both directions.

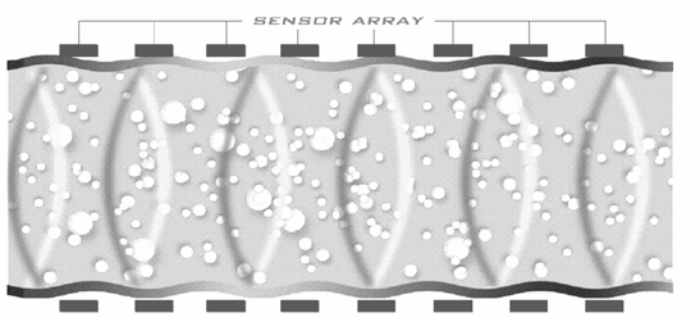


Figure 3 Illustration of naturally occurring acoustic waves propagating in pipe under the sonar array sensors

Through the same array of passive sensors used to measure the flow velocity and similar sonar array processing algorithms, the average axial velocities of a collection of acoustic waves is obtained. Since acoustic waves are traveling pressure waves, they introduce localized pressure changes on the inside of the pipe walls during their cycling from compression to rarefaction and back. These pressure changes strain the pipe walls and are tracked in a similar manner as for the turbulent eddies or density variations.

This fluid can be multiphase, or multicomponent single phase. In a single phase fluid, the acoustic velocity is a function of the ratio and acoustic properties of the two fluids, thus this measurement can be used to determine mixture ratios through application of the simple mixing rule (volume average of velocity). The resulting acoustic velocity c_M can be given by:

$c_M = \phi_1 c_1 + \phi_2 c_2$ (Wang and Nur, 1991) where $\phi_{1,2}$ are the phase volume fractions and $c_{1,2}$ are the acoustic velocities of the phases

Using $\phi_2=1-\phi_1$ this can be rearranged to give: $\phi_1 = \dfrac{c_M - c_2}{c_1 - c_2}$

In multiphase fluids that consist of a gas mixed with a liquid or slurry, the acoustic velocity can be used to determine the amount of entrained gas (gas void fraction) when the gas is in the form of bubbles that are well mixed within the liquid or slurry.[5] [6]
Since the wavelengths of the acoustic waves are much larger than the bubble size, a complex interaction takes place that sets the acoustic velocity to be a strong function of the gas void fraction. The speed of sound is proportional to the square root of the ratio of the compressibility and the density, both of which are heavily influenced by air content. An example of the resulting relationship is shown in Figure 4.

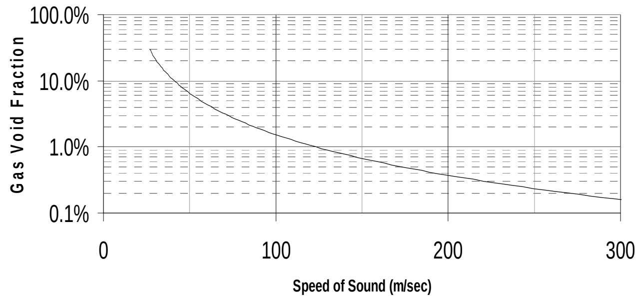


Figure 4 Example of relationship between gas void fraction (entrained air content) and speed of sound

The gas void fraction measurement is used in a variety of different fields and applications. Within mineral processing, it is used for nuclear density gauge correction, flowmeter correction to provide true volume flow, diagnosis of pumping issues, detection of flashing, and air injection applications. It is being successfully used for entrained air applications ranging from 0.01% to 20% gas void fractions with an accuracy of 5% of the reading.

APPLICATION EXAMPLES – FLOW AND ENTRAINED AIR

Non-Invasive Flow Measurement and Leak Detection for High Pressure Pipeline Applications

Due to its non-invasive nature and easy installation, the sonar array-based flowmeter is ideally suited for abrasive and/or high pressure applications.   As an example, there was a need to have a reliable flowmeter to measure flow at the beginning and end of a >50 km pipeline. The requirement was to accurately measure flow in order to detect any leaks, as well as monitor the product transfer rate. The challenge for the plant was to do so without breaking into the pipe due to the high pressures (>1000 psi, >70bar) seen on one flowmeter.

The resulting flow measurements seen in Figure 5 clearly show the two flowmeter signals (dark lines) lying on top of each other. The only way to see the small differences between the two readings is by looking at the ratio of the two outputs (light line). Except where transitions cause a difference in flow between the top and bottom meters due to the transit time of the flow change in the pipeline, the averaged ratio is within approximately +/- 1%, which is within the specifications of the meters and the requirements of the plant.

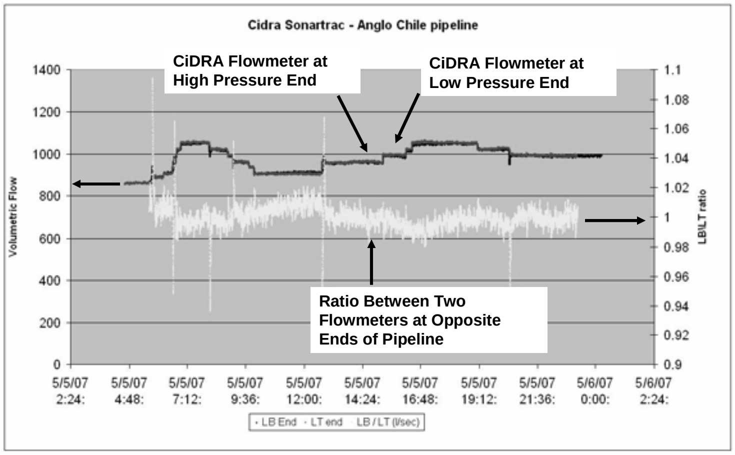


Figure 5 Results of leak detection using sonar array-based flowmeters in which overlapping dark lines are flowmeter outputs and the light line is the ratio between the two outputs.

Correction of Nuclear Density Meter Due To Entrained Air

The presence of entrained air or gas void content will directly reduce the specific gravity reported by a nuclear density gauge. In order to obtain the correct density measurement of the slurry itself, the gas void fraction must be measured and used as a correction factor. To validate this approach, we ran a test in which varying levels of air were introduced into a flow loop containing a nuclear density gauge. As expected, when the air injection rate, shown as standard cubic feet per hour (SCFH) in Figure 6 was increased, the nuclear density gauge output seen (dashed line decreased. The sonar array-based flowmeter on the same line accurately measured the resulting air content as seen in the dashed line. Using this measurement, we applied a simple linear correction of the nuclear density gauge output to reduce the error from 5% down to +/- 0.25%.

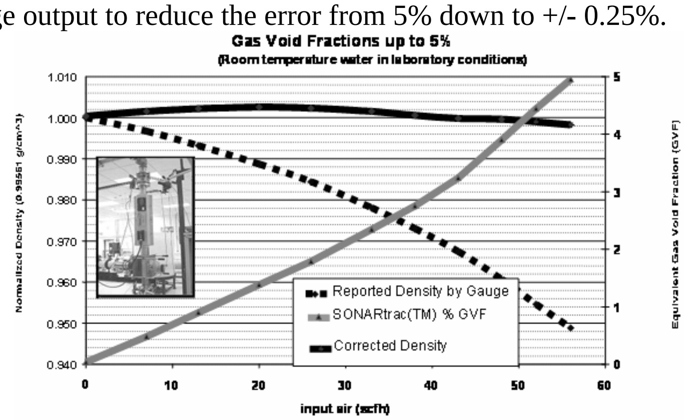


Figure 6 Nuclear density gauge correction using sonar-array based meter

Thickened Tailings Flow

As previously described, the sonar-based flowmeter is also capable of measuring non-Newtonian, shear-thinning slurries. In the mining industry, examples are high-solids content slurries commonly known as thickened tailings and paste. Figure 7 shows an example of a sonar-based flowmeter measuring a thickened tailings flow at low velocities below 1 m/s. As the flow transitions from water at over 2 m/s to slurry, the velocity immediately decreased to 1.2 m/s and then continued a slow additional decrease until the pipe completely plugged at 0.5 m/s. Subsequently, the line was unplugged and cleaned with water flow as shown. This sequence shows that with such slurries, the high density produces a sufficiently high amplitude self-generated coherent pressure field that can be tracked by the sonar-based flowmeter. For this test, conducted for Antofagasta Minerals S.A., Chile, by PSI-JRI Ltda. (both of Chile) the accuracy of the sonar flowmeter was verified by tank-fill tests as shown on the graph.

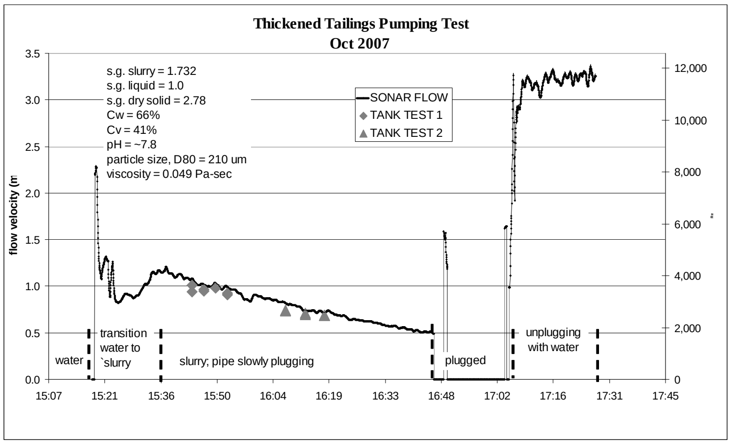


Figure 7 Thickened slurry test for Antofagasta Minerals, Chile, with flow measurements using sonar array-based flowmeter showing accuracy verified through tank fill tests and ability to operate at flow velocities below specifications.

ADDITIONAL MEASUREMENT CAPABILITIES

In addition to the two basic measurements of flow rate and fluid composition previously described, the sonar flowmeter system is able to provide additional measurements that leverage its unique technology capabilities. Some of these new measurement capabilities are described below. They have undergone successful laboratory and field testing where measurement performance has been validated. However because some of these measurements are new to the process control industry, their detailed implementation into the overall process control system must still be determined by the process automation and control community.

Acoustic Monitoring of Process and Pipeline Equipment

During the course of measuring flow, the passive sonar-array based flowmeter developed by CiDRA detects the acoustic levels within the pipe. By monitoring these acoustic levels over selected frequencies, additional information about events occurring in a pipeline or process can be obtained. As an example, valve movement in a pressure reduction choke station corresponds with changes in the acoustic levels during the movement, as well as before and after the movement as the flow is diverted through a different pipe. The flow shown as the dark line in Figure 8 changes by about 8% due to a change in the valve position which directs the flow through a different path in the choke station. The acoustic level changes by a factor of three to four (200% to 300%) during the valve movement and by a factor of three (200%) between valve positions. The combination of the flow measurement and acoustic level provides the necessary information to monitor the valve. This concept can be extended to monitoring of bursting disc events, and for pipeline breaks.

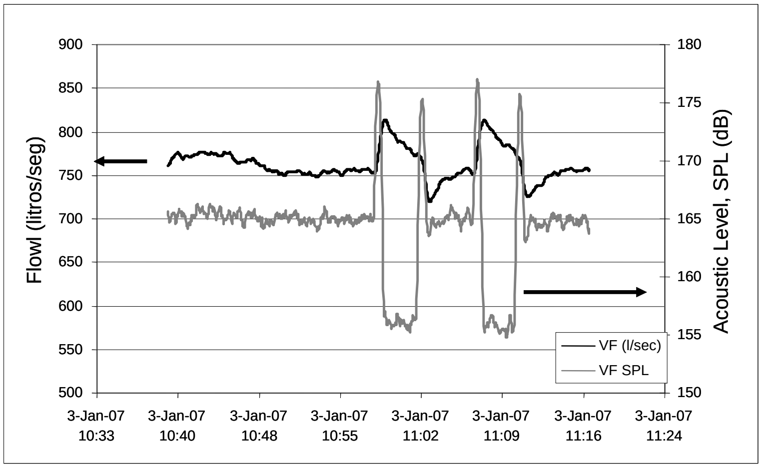


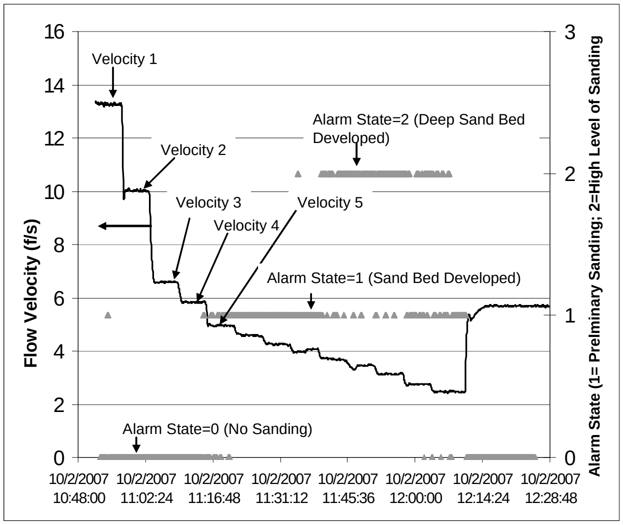
Figure 8 Flow Measurement and Acoustic Level Measurement for Valve Movement Monitoring at Choke Station

Flow Profiling and Sanding Detection

One key problem that continues for operators of hydrotransport pipelines is the possibility that solids material will settle to the bottom of the pipe and lead to a blockage in the pipe. Operators strive to avoid this “sanding out” condition by keeping flow rate above a certain empirically determined or calculated value. Unfortunately, incomplete models and changes in the slurry properties including viscosity, fines content, and particle size distribution changes result in large error bars with either approach.

A better solution is to actively monitor the flow profile in the pipe to see the reduction in flow velocity at the bottom of the pipe as the larger, denser particles settle and approach a very slow velocity. Using a different instrument and a specially engineered sensor, the flow velocity may be determined at locations across the diameter of the pipe. As an example, the flow at the bottom of the pipe may be compared to the flow at the top of the pipe. Results from testing this custom instrument are shown in Figure 9. Here the change in the flow profile due to the stratification of particles is evident in the lower velocities seen near the bottom of the pipe as the “sanding out” condition is approached.

By processing some characteristic features of the flow profile, an alarm condition can be generated. By extending this processing to examine not only the condition where a small level of “sanding out” has occurred but has now reached a higher level in the pipe (>25% of the pipe height) we can set a higher level in the alarm. This is illustrated in the right side of Figure 9.



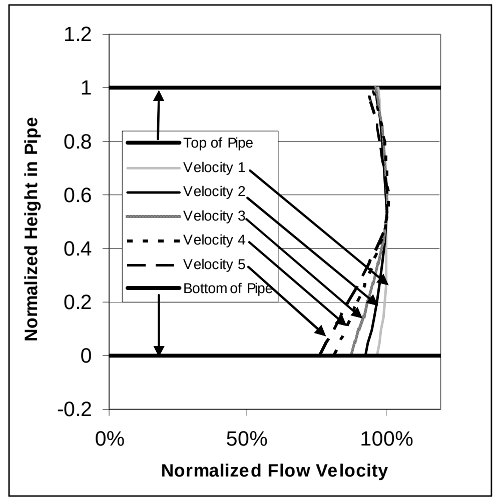


Figure 9 (Left) Normalized velocity profiles at various flow rates showing a drop in velocity at the bottom of the pipe at the lower flow rates. (Right) Flow velocity & alarm condition for low levels of sanding (Alarm level=1) and high levels of sanding (Alarm level-2)

CONCLUSIONS

Sonar-based flow meters are a new class of industrial flow measurement technology well suited to solve many of the long-standing flow measurement challenges in the minerals processing industry. They combine and leverage new sensor technology with over 60 years of sonar development to deliver this technology platform. This technology enables new levels of process control because it is now possible to obtain reliable, high-quality, maintenance-free measurements in applications where measurements were previously unreliable and of poor quality. One example presented was in the measurement of true liquid flow rate in the presence of entrained air, which causes measurement error in the best case, and complete measurement failure in the worst case. Another example is the on-line correction of nuclear density measurement for entrained air.

In addition to the two basic measurements of flow rate and fluid composition described, examples were also presented of extensions of this technology platform that add unique capabilities. One was the ability to monitor process events based on acoustic signature, and thus detect anomalous conditions, such as improper valve actuation. The other was the ability to measure the velocity profile of flowing slurry and thus predict and detect sanding conditions. This ability to make more reliable and accurate common process measurements such as flow rate, combined with the ability to make measurements not previously available such as entrained air, provides the opportunity for improved process measurement and control. The fact that these measurements can now be made in a non-invasive manner, which eliminates constraints due to line pressure, degradation due to abrasive wear, and process shut down for installation, offers the opportunity for improved process measurement and control in both existing and new minerals processing facilities.

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