NOVEL PASSIVE TECHNOLOGY FOR ENTRAINED AIR MEASUREMENT IN PIPES AND GAS HOLDUP MEASUREMENTS IN COLUMN CELLS

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Abstract

Measurements of the quantity of entrained air within processes have challenged instrumentation developers for years. This is particularly true in the unique and demanding operating environment and applications seen in minerals processing. In minerals processing applications, entrained air plays a role in errors seen within nuclear density gauge measurements and in pumping efficiency. It is also the major component of flotation processes. The measurement of the quantity of entrained air, known as the gas void fraction, can now be performed from the outside of a process pipe through CiDRA's patented passive sonar array-based technology. Within column cells, the need for a robust, no maintenance, accurate means of measuring the entrained air, known as gas holdup, has resulted in a submersible version of this technology.

CiDRA's meter technology calculates the gas void fraction by first measuring the speed at which naturally occurring sound in the process slurry propagates 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. A known relationship between this speed of sound and the entrained air captured in the form of bubbles within the slurry is then applied in CiDRA's meter to calculate the gas void fraction. This paper will present the measurement technology, its operation, its calibration and its application in a variety of gas void fraction and gas holdup measurement situations such as pumping efficiencies, hydrocyclone operation, external sparging, and column cells.

Introduction

The minerals processing industry faces many unique and challenging process control conditions and environments. In terms of fluid composition measurements, many of these situations are not being properly served by traditional sampling techniques, particularly due to the inaccuracy and expense of manual methods. A new class of instrumentation has been developed that solves these unique measurement problems. This new class of technology utilizes sonar-based processing algorithms and an array of passive sensors to measure not only fluid composition, in particular entrained air levels, but also flow. It does so accurately, reliably and without making contact with the fluid. These measurements are performed on practically any type of fluid within virtually any type of pipe, or within column cells.

Principle of Operation

Sonar array-based flowmeters are ideal for tracking and measuring the mean velocities of disturbances traveling in the axial direction of a pipe. These disturbances generally will convect with the flow, propagate in the pipe walls, or propagate in the fluid or slurry. To calculate the amount of entrained air, we must first measure the velocity of the naturally generated acoustic waves that are propagating in the fluid or slurry. An accurate measurement of this velocity along with a few other process measurements, in particular pressure, will yield an accurate entrained air or gas void fraction calculation.

Array Measurement of Acoustic Waves

In most mineral processing applications, there is an abundance of acoustic waves propagating within the pipes or flotation columns. 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 1 and as can been seen in the figure they can propagate in either direction down the pipe or in both directions.

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

- Acoustic waves are traveling pressure waves, introducing localized pressure changes on the inside of the pipe walls during their cycling from compression to rarefaction and back.
- 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.

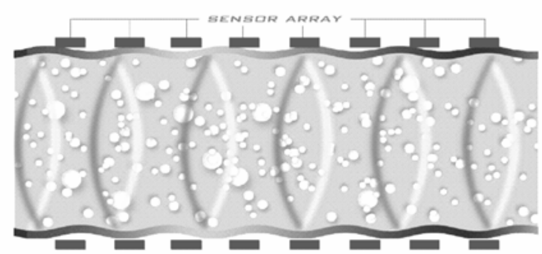

Figure 1 Illustration of Naturally Occurring Acoustic Waves Propagating in Pipe under the Sonar Array Sensors

The challenges of performing this measurement in a practical manner are many. These include the challenges of operating in an environment with flow generated signals and pipe vibrations in which the latter can cause large dynamic straining of the pipe. The impact of these effects is that the dynamic strain due to the acoustic waves is usually smaller than the dynamic strain arising from pipe vibrations. The strength in the array processing algorithm is its ability to isolate and measure the velocities of these different components, thus allowing for an accurate acoustic velocity measurement.

The technology lends itself to the generation of a measurement robustness indicator otherwise known as a quality factor. In the sonar processing algorithm such a quality factor can be generated by comparing the strength of the signal from the acoustic waves against background energy levels. A quality factor ranging from 0 to 1.0 is generated, with any measurement providing a quality factor above 0.1 to 0.2 (depending on the application) having the confidence as being a good measurement. The technology lends itself to measurement on practically any pipe size or type.

The fluid in which these acoustic waves propagate can be multiphase, or multicomponent single phase. In a multicomponent 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:

$$c_M = \phi_1 c_1 + \phi_2 c_2 \quad \text{(Wang and Nur 1991)}$$

where $\phi_{1,2}$ are the phase volume fractions
$c_{1,2}$ are the acoustic velocities of the phases

Using ϕ_2=1-ϕ_1 this can be rearranged to give:

$$\phi_1 = \frac{c_M - c_2}{c_1 - c_2}$$

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.

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 2.

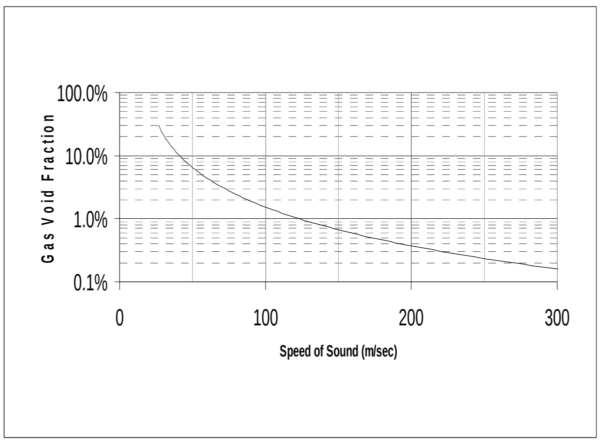

Figure 2 Example of Relationship between Gas Void Fraction and Speed of Sound

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.

Implementation of Technology

Implementation of the gas void fraction measurement has taken place in two forms: instrumentation external to the pipe and instrumentation internal to a flotation column. The external instrumentation uses the same sensor head hardware as the volumetric flowmeter instrument. Pictures of the meters and installation procedures for the external instrumentation are shown in Figure **3** and Figure 4.

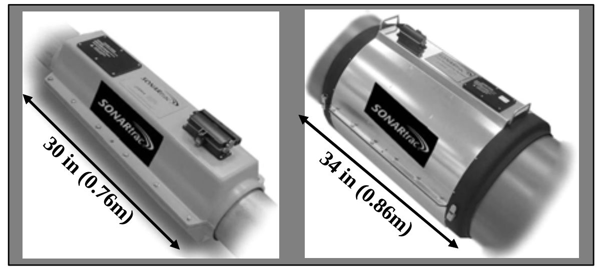

Figure 3 Pictures of External Gas Void Fraction Meters for Installation on Outside of Pipes. Left-For Pipe Sizes up to 16 Inches. Right-For Pipe Sizes from 18 Inches and larger.

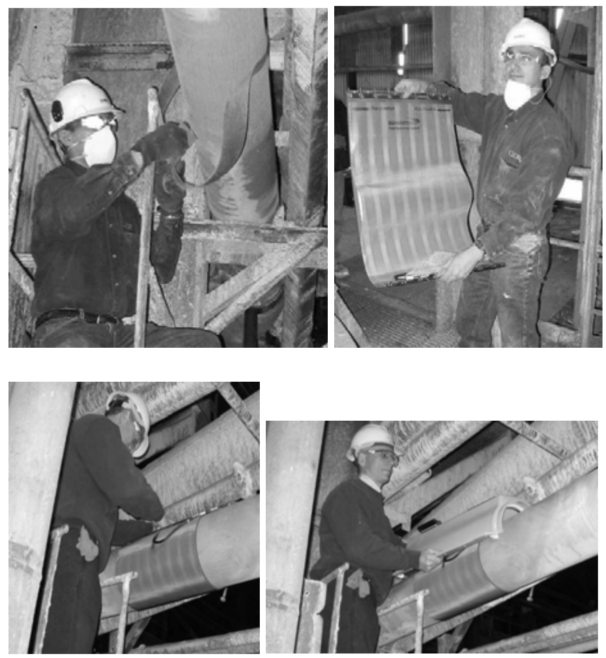

Figure 4 Installation Procedure for Externally Mounted Gas Void Fraction Meter

For measurement of the gas void fraction, commonly known as gas holdup, within a column cell, a submersible version of the instrument was created. This instrument, termed the gas holdup meter, consists of the sensor array installed onto a four inch diameter pipe and a water tight cover especially designed to withstand years of service in a column cell. A picture of the gas hold sensor head is shown in Figure 5. The design along with the vertical orientation of the meter allows for bubbles to enter the bottom of the pipe and pass through the pipe. The meter can be moved around in a column or can be permanently attached.

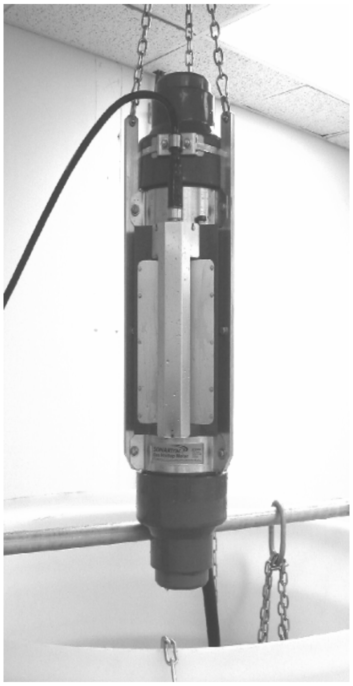

Figure 5 Picture of Gas Holdup Meter Sensor Head for Submersible Application in Column Cells

Calibration and its Maintenance

Since the acoustic velocity measurement and hence calibration are not dependent on the absolute values of any analog signals, they will not drift with time or temperature. Maintenance of the calibration from meter to meter as well as from temperature effects and aging is dependent on maintaining the spacing between the sensor elements and maintaining the stability of the clock used in the digitizer. The spacing between the sensors is set in the factory where they are bonded to a stainless steel sheet and cannot be adjusted by the customer. Pictures of the lightweight sensor band are shown in Figure 6.

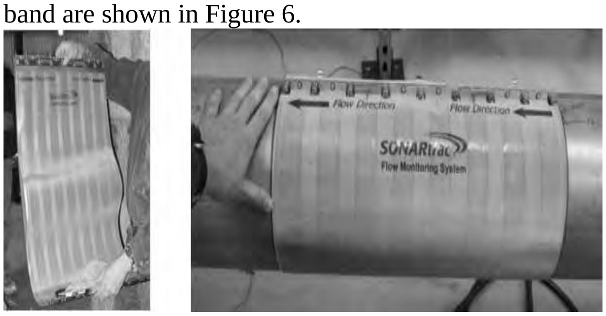

Figure 6 Pictures of the Sensor Band with Drift-Free Sensor Elements

The clock stability is better than 0.01% and thus is 50 times better than needed to maintain the meter's typical accuracy. As a result, the impact of clock stability can be neglected.

The accuracy of the gas void fraction derived from the acoustic velocity measurement has been verified through a variety of means including differential pressure measurements, and mixture volumetric changes.

Figure 7 Mini-Column Cell Calibration Fixture

Calibration for the gas void fraction externally mounted instrument was performed by mounting the sensor head on a clear PVC vertically oriented pipe. Spargers at the bottom of the pipe were used to add air to the column, while a combination of volume displacement and differential pressure measurements were used to verify the perform of the gas void fraction technology. Results from three test runs, using differential pressure measurements are shown in Figure 8. In that figure, the gas void fraction was held to values typically seen within pipes and as can be seen from the graph, the repeatability and accuracy were quite good.

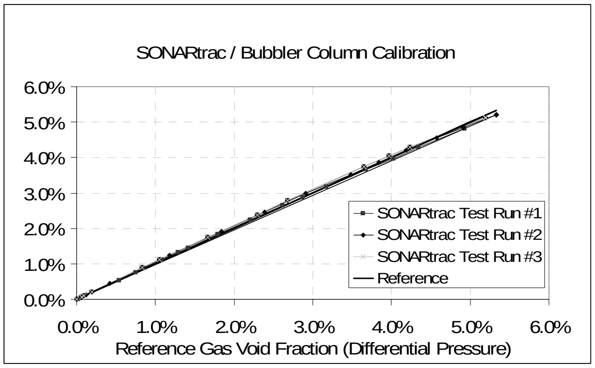

Figure 8 Verification Test Results for Gas Void Fraction Meter on Calibration Column

Gas Void Fraction (Entrained Air) and Gas Holdup Measurement

In the mineral processing application area, fluid composition measurement typically entails using the sonar based flowmeter to determine the amount of air entrained within the slurry. In most cases, plant engineers are unaware of the amount of air entrained within their slurry. Despite the best care in plant design, air can enter the slurry through a variety of sources including leaks on the suction side of pumps, low sump levels, discharge into a sump, from hydrocyclones, and from mills.

Entrained air can impact a process by causing errors in the measurements performed by nuclear density gauges and flowmeters. It can also impact the operation and life of pumps. In other cases, entrained air is beneficial and is intentionally injected into a pipe to assist in the separation of materials such as bitumen from the sand in the oil sands industry, or metals from ores via an external sparging system in a flotation column. In all these cases it is necessary to measure the amount of entrained air or gas void fraction. In some of these processes, the amount of entrained air is controlled with defoamers where the use of a gas void fraction meter is needed to properly control the dosing of the defoaming agent, thus ensuring the proper reduction of air bubbles while saving money.

When varying or even moderate levels of entrained air are present within slurry, older generation flowmeters including Coriolis meters, electromagnetic meters and ultrasonic meters are adversely affected by this air. As a minimum, they cannot provide the true liquid or slurry flow, while in many cases the entrained air will cause a large increase in flow meter noise or a total loss of flow readings. The ability of the array based technology to measure flow in the presence of high levels of entrained air as well as the entrained air level itself leads to better control of the process. Nuclear density gauges and Coriolis meters when used for density measurements will also be adversely impacted by the presence of entrained air. In summary, it is necessary to measure the entrained air or gas void fraction in order to compensate the outputs of the nuclear density gauges and flowmeters, to operate pumps more efficiently and with reduced wear, to properly dose defoamers, or to ensure that the correct amount of air is being injected into a process. Some of these entrained air situations and the use of the array based technology to resolve these measurement and control problems by simultaneously performing flow and entrained air measurements are given in the following sections.

Measurement of Air Entrained within the Slurry on Hydrocyclone Feedlines

In Figure 9, an example is given for the measurement of both flow and gas void content in a 24-inch hydrocyclone feed line. In this case the customer was unaware of the presence of the air and the resulting nuclear density gauge and flowmeter errors.

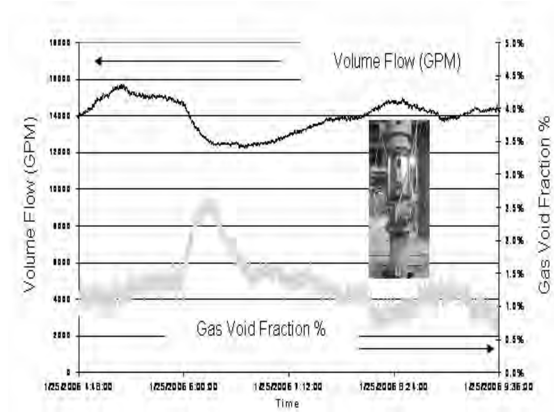

Figure 9 Flow and Gas Void Fraction in a Hydrocylone Feed Line

The benefits of knowing the gas void fraction in a hydrocyclone feed line include the determination of true volumetric flow rate of the slurry, ability to set an alarm condition if the air content becomes too high, and most importantly correcting the nuclear density gauge. Since one of the key control parameters for hydrocyclone based classification is the specific gravity of the slurry, this parameter must be accurately measured and any errors in this measurement must be corrected.

Correction of Nuclear Density Gauges Due to the Presence of 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 instrumented with a nuclear density gauge. As expected, when the air injection rate, shown as standard cubic feet per hour (SCFH) in Figure 10, was increased the nuclear density gauge output seen in the light solid line decreased by 5%. The sonar array-based flowmeter on the same line accurately measured the resulting air content increase of 5% 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%. Our experience has shown that the entrained air content in hydrocyclone feed lines can vary dramatically up to 5% with the resulting impact on d_{50} classification.

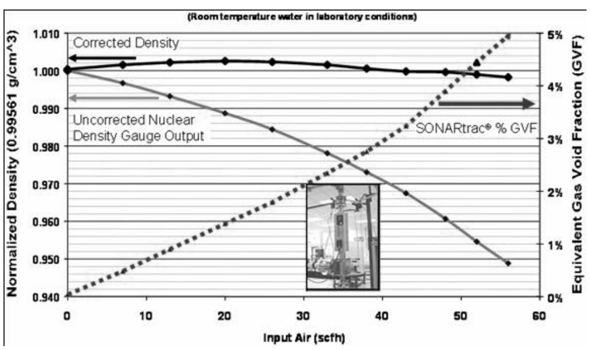

Figure 10 Nuclear Density Gauge Correction using Sonar Array-Based flowmeter

Case Study Flow and Entrained Air Measurement at Kemess Mill

Northgate Minerals uses CiDRA Corporation's sonar array-based (SONARtrac®) technology to not only measure bulk concentrate flows and the feed to the flotation columns at Kemess mine in British Columbia, Canada, as shown in Figure 11 but also the level of entrained air. The non-intrusive technology measures these abrasive slurries accurately with no process downtime due to the no maintenance, non-intrusive design of the flow meter.

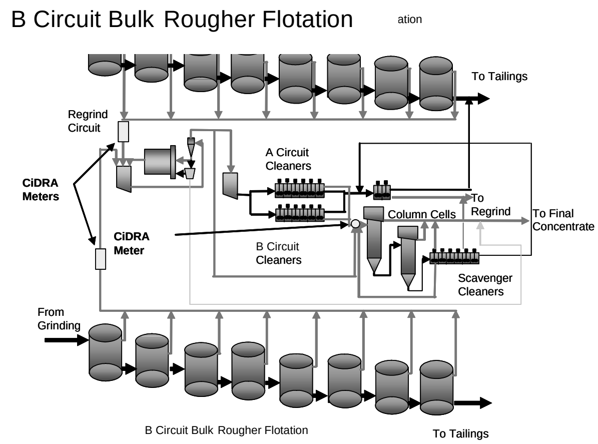

Figure 11 Kemess Mills Flowsheet Showing Locations of Three Sonar Array-Based (CiDRA) Flowmeters

Kemess uses the Gas Void Fraction capability of the sonar array-based meter as a tool to monitor increases of air in these lines. Increased air will cause pump inefficiencies and could lead to pump damage due to cavitations. Knowing the volume of entrained air provides a true volumetric flow rate and provides operators with another tool for process control. In the following figure the step increase of entrained air from approximately 6% to 8% coincides with the decrease in flow from ~2300 GPM to ~1900 GPM. This may indicate that the increased entrained air is impacting the operation of the pump and alert the operator to a condition that needs attention.

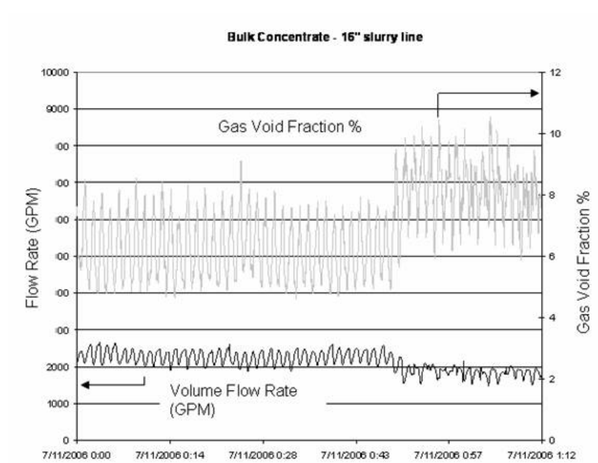

Figure 12 Flow and Entrained Air (Gas Void Fraction%) Measurements Show Impact of Air on Flow Rate

Entrained air levels vary from 8% to 0.1% in flotation feed lines as seen in Figure 13. The ability of sonar array-based technology to measure flows with large amounts of entrained air over varying conditions improves the accuracy and reliability of the flow measurement. It is likely that the varying air content of the feed will affect the gas holdup within the flotation process itself.

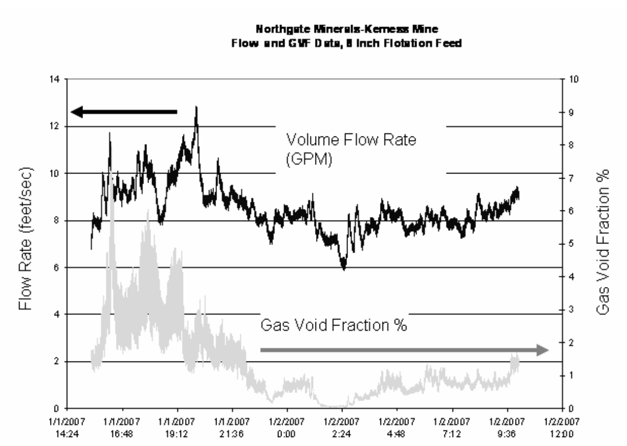

Figure 13 Flotation Feed Line and Varying Air Levels Measured by Sonar Array-Based Instrumentation

Case Study: Volume Flow and Entrained Air Measurement in High Air Content Flotation Overflow Lines at Newmont Facility

The flotation process, by its very nature, will always introduce large amounts of air into the overflow line. The amount of air can change quite dramatically with operating conditions thus making it difficult to determine the true slurry flow rate. A sonar array based flowmeter was used in this application to robustly measure the quantity of entrained air (gas void fraction %) as well as the flow rate. This is illustrated in Figure 14.

In this case the impact on pumping efficiency could be seen. From the data it can be seen that the amount of air changed by a significant amount. This occurred during periods of high pumping speeds, even with constant sump levels. The corresponding drop in flow rate was explained by the increase in entrained air, which in turn affected the pumping efficiency.

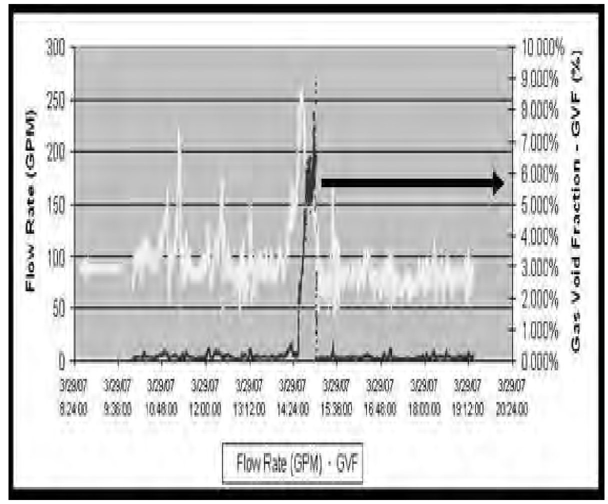

Figure 14 Problems Measuring Both Flow and Gas Void Fraction in a Flotation Overflow Circuit is Solved. Effect on Pumping Efficiency and Resulting Drop in Flow Rate can now Determined by Measurement of Gas Void Fraction (Entrained Air)

Accurate Non-Invasive Flow Measurement of Slurries with Flashing Gas

Many industrial processes transport hot single and two phase (solid and liquid) slurries from one stage of the process to another. In many cases the line pressure varies as a function of back pressure or head level of a collection tank. If the slurry contains dissolved gases there will be conditions where the gas will come out of solution and become entrained. Traditional in-line flow devices will not account for this entrained gas and will report erroneous flow readings during these temporary or prolonged events. Devices that use polymer based liners may suffer from gas diffusion problems where the liners back away from the flow tube and become separated from the device. The sonar meter is not affected by this entrained gas. In fact the device can measure the amount of entrained gas. This measurement may then be used to correct the flow reading for the voids caused by the gas. It may also be used to adjust other system parameters, such as pump speed or sump levels, in order to eliminate the out gassing event. Figure 15 shows an example of some data collected at an alumina refinery. There is a period of about eight minutes where the gas volume fraction increases from 0% to 14% and then back to about 1%.

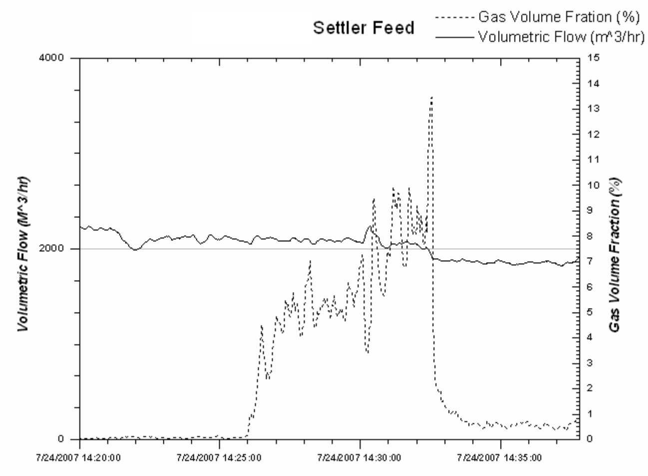

Figure 15 Evidence of Flashing in Alumina Process

Batch Tracking Using Real-time Speed of Sound Measurement

A unique ability of the sonar-based flowmeter is its ability to measure the real-time speed of sound in process piping. Figure 16 shows simultaneous measurements of volumetric flow and speed of sound from two sonar-based flowmeters located 26 km apart on a hydrotransport slurry pipeline. At the start and end of a multi-hour batch run, and sometimes during the batch, water is typically introduced for a short time. The graph shows a clear change in speed of sound between the water and slurry, enabling detection of the water batch at the two meters which have a transit time between them of approximately three hours. The non-invasive nature and insensitivity to pressure of the sonar-based flowmeter allowed installation of one meter at a high-pressure location (~1,000 psi), at the discharge of a large positive displacement pump, without stopping the process.

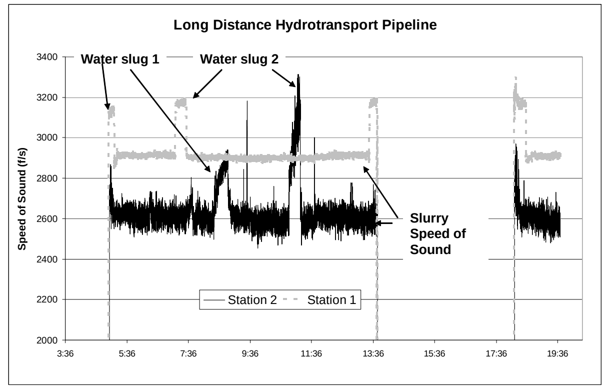

Figure 16 Detection of Water Slugs Separating Batches of Concentrate in Hydrotransport Pipeline at Two Different Locations on Pipeline

Summary

Sonar array-based flow and entrained air measurement instruments are a new class of industrial flow and compositional analyzers leveraging over 60 years of sonar development and utilization. Sonar array-based meters are installed worldwide in many industrial applications and are ideally suited for a wide range of minerals processing applications and provide new measurement insight and quantifiable value to operators. Besides performing flow measurements this technology has the ability to measure speed of sound and thus provide a quantifiable reading of the gas void fraction or gas holdup, as well as other indications of fluid composition.

Acknowledgements

The authors wish to thank our customers for adopting the *SONARtrac*® flow and process meters, providing data and other support. For this paper, these include, but are not limited to Newmont Gold and Kemess Mine. The authors wish to acknowledge the work performed by mineral processing team members at CiDRA including Tim Griffin for analyzing data and performing the nuclear density gauge tests.

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