SONAR FLOW MONITORING: FIRST FIVE YEARS OF EXPERIENCE IN THE MINERAL PROCESSING INDUSTRY AND FUTURE DIRECTIONS

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ABSTRACT

Sonar array-based flow measurement technology was introduced into the mineral processing industry five years ago, and has since demonstrated significant usefulness and value in many difficult and critical flow monitoring applications. This robust non-invasive technology has become the standard for many companies in certain applications.

Presented here is a summary of application experience, lessons learned, and best practices from installations world wide. Highlighted applications include: cyclone feed flow measurement, measuring aerated flows for mass balance correction, stratification and sanding detection in horizontal slurry lines, slurry pipeline flow monitoring and leak detection.

It will be shown how the basic volumetric flow rate, combined with the unique additional measurement of entrained air volume and the proper positioning of multiple meters can enable novel solutions to monitoring and control problems that are not possible with other flow technologies.

Recent product development work will be presented showing how the same fundamental sensor technology can be used to obtain robust, high quality acoustic signals which can be used to monitor and control key flow related process equipment in the beneficiation process, and improve process performance. Results of in-plant tests will be presented.

INTRODUCTION

Since its introduction to the mining industry five years ago, sonar array based technology has achieved rapid and widespread acceptance, achieving approximately 1,000 installations in over 150 mine sites in 26 countries. This has happened because using traditional flowmeter technology such as electromagnetic, ultrasonic Doppler, differential pressure, or Coriolis to obtain true flow measurement has proven to be a challenge for process control engineers because of many process influences. These influences include changing process fluid properties, calibration drift, pipe wall scale buildup, presence of magnetite, and the presence of entrained air. It is now possible to perform accurate flow measurements in the presence of these influences through the use of the latest generation of flow measurement technology based on the use of arrays of passive acoustic sensors. This report will present the basic operating principles, and then review some application examples from the first five years of commercial use and the lessons learned.

BASIC OPERATING PRINCIPLES

Volumetric Flow Measurement – Basic Operating Principle

Through the combination of an array of passive sensors and sonar array processing algorithms, the average axial velocities of a collection of vortices or density variations is obtained [1]. The sequence of events that occur to make this measurement possible is as follows (see Figure 1).

- The passage of the turbulent vortices 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
- 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.

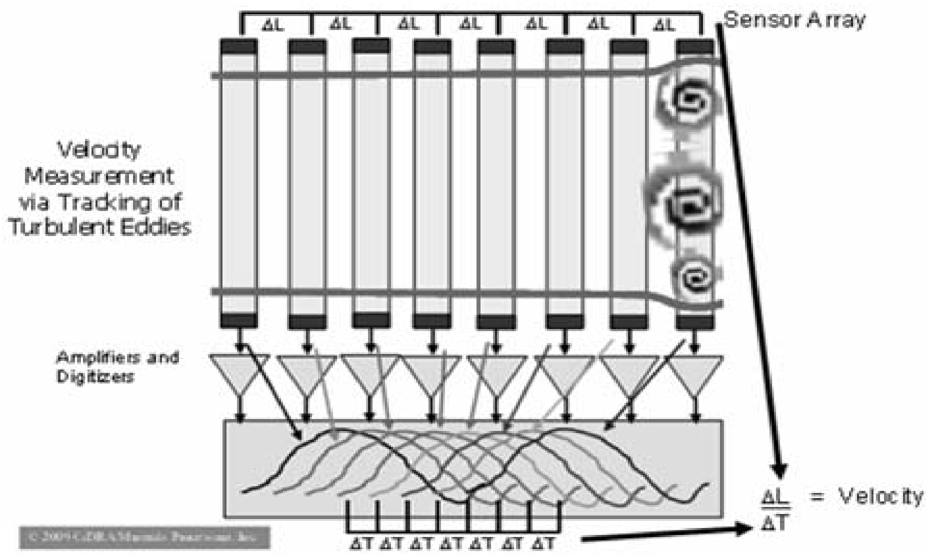

Figure 1: Basic operating principle. Tracking velocity of vorticle pressure fields straining pipe wall.

Gas Volume Fraction Determination Based on Speed of Sound Measurement – Basic Operating Principles

The array based technology may also be used to track commonly occurring acoustic waves travelling in the fluid. These acoustic waves are generated naturally from a variety of sources, including pumps, flow-through pipe geometry changes and bubbles within the fluid that 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 and the pipe diameter.

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 volume 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 volume 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 [2] [3]. The values outlined by the curve in this figure are influenced by other factors, particularly pressure. Thus pressure at the location of the array based instrument must be measured or calculated. Once pressure is determined, the array based instrument is used to accurately measure the speed of sound, and the relationship between speed of sound and entrained air content is used to accurately quantify the amount of entrained air.

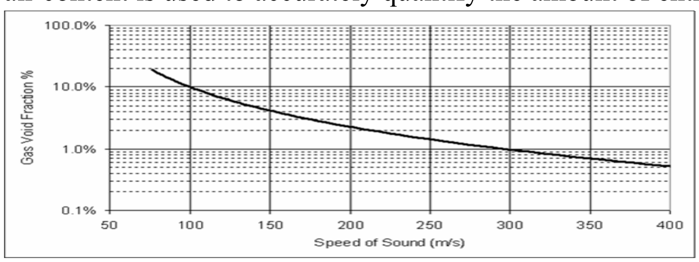

Figure 2: Relationship between gas volume fraction and speed of sound

OPERATIONAL CASE STUDIES - LESSONS LEARNED

Feed to Hydrocyclone Battery and Screen: Comparison of Array-Based Flowmeter and Electromagnetic Flowmeter to Pressure Readings

At a recent minerals processing installation site, the array-based flowmeter was compared to an electromagnetic flowmeter for accuracy and noise performance. Both flowmeters were installed on a vertical section of a 300mm polyethylene pipe as illustrated in the right side of Figure 3. The flow passed through both flowmeters and then up into a distribution box that was instrumented with a pressure transducer. The readings from the two flowmeters, the pressure transducer, a nuclear density gauge, a sump level sensor, and pump speed were recorded at five second intervals. During the data acquisition period, the density and sump level were fairly constant, thus the outputs of the flowmeters were compared only to the pressure and pump speed. Since the flow discharged from the distribution box through a series of valves to atmospheric pressure, the readings from the pressure transducer were used as a form of differential pressure flow measurement. The pressure is a function of the number of valves open and their position, the density of the slurry, and the square of the velocity. With constant valve conditions and density, the pressure is assumed to vary only as a function of the square of the velocity.

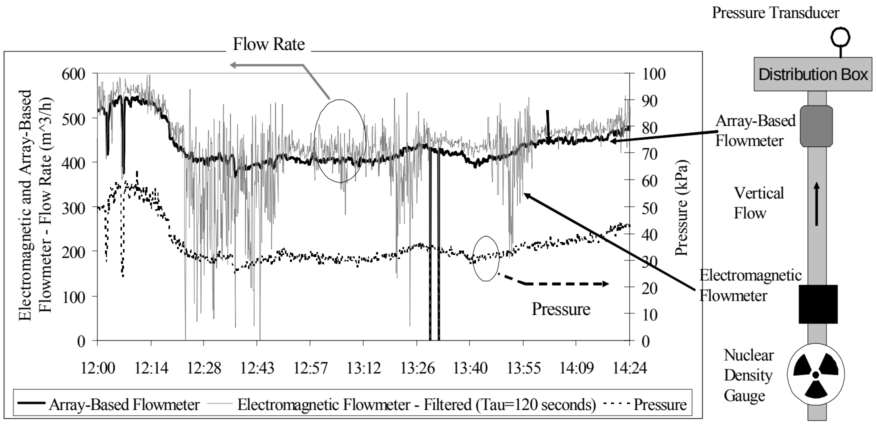

Figure 3: Comparison of readings from array-based flowmeter, electromagnetic flowmeter and pressure transducer.

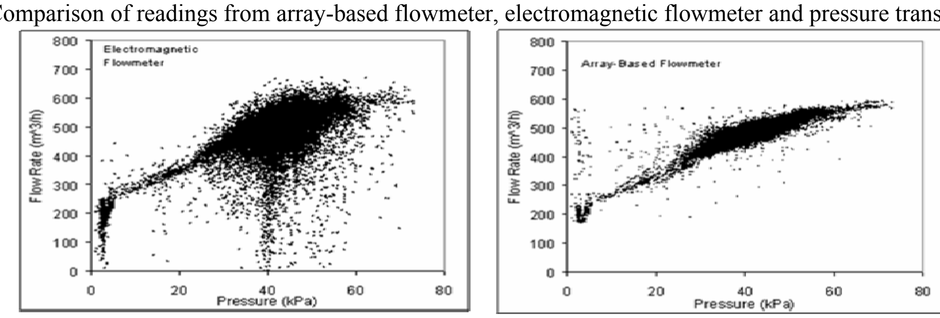

Figure 4 (Left) Crossplot of electromagnetic flowmeter readings versus pressure. (Right) Crossplot of array-based flowmeter readings versus pressure

Likewise the velocity reported by each flowmeter should vary as a function of the square root of the pressure as illustrated by a comparison of the array-based flowmeter readings versus the pressure readings as shown in the right side of Figure 4. Due to the spread in the readings from the electromagnetic flowmeter, this is difficult to see by using the electromagnetic flowmeter readings as seen on the left side of Figure 4. After application of heavy filtering to the electromagnetic flowmeter reading, an overall trend relative to the readings from the pressure transducer and array-based flowmeters can be seen in Figure 5. The resulting erroneous dips in the electromagnetic flowmeter readings cannot be explained by magnetic material passing through the flowmeter or material striking the electrodes. In contrast, the array-based flowmeter exhibits excellent agreement with the pressure reading.

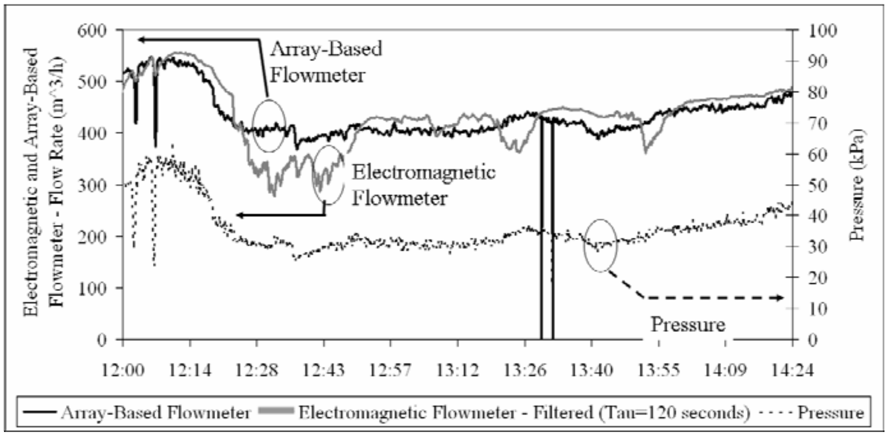

Figure 5: Comparison of readings from array-based flowmeter and pressure readings along with filtered reading from electromagnetic flowmeter (first order filter of 120 seconds applied to electromagnetic flowmeter)

Measuring Aerated Flows for Mass Balance Improvement

The accurate measurement of the percentage of pipe volume occupied by gas bubbles in a liquid also known as gas void fraction can lead to a true volumetric flow measurement, a corrected density measurement and a true solids mass flow rate calculation. Before the introduction of array-based technology, it was not possible to perform this measurement from the outside of the pipe in slurry flows.

Volumetric flow correction for entrained air.

Several steps in a process require the accurate measurement of volumetric flow rates. Examples include cyclone feed rates for control of separation and sharpness of cut, and flotation feed rates for control of flotation residence times. In many cases, both expected and unexpected, gas in the form of entrained air bubbles can enter into a pipe conveyed slurry stream. This entrained air occupies space within the pipe thus leading to an overall volumetric flow rate that is the sum of both the gas volumetric flow rate and the slurry flow rate which is the combined solids and liquid volumetric flows. Assuming that the air bubbles and the slurry travel at the same velocity, which is a valid assumption for horizontal flows, and for vertical flows in the case of small bubbles or high slurry velocities, the total volumetric flow rate can be expressed in the form of the phase fraction of the air or gas component

$$Q_T = Q_G + Q_{SL} \tag{1}$$

where Q_T is the total volumetric flow rate; Q_G is the gas volumetric flow rate; and Q_{SL} is the slurry volumetric flow rate. Using the phase fraction of the gas component, φ_G, also known as the gas void fraction or GVF and solving for Q_{SL} we obtain a straightforward linear equation for the correction.

$$Q_{SL} = (1-\varphi_G)Q_T \tag{2}$$

Slurry density correction for entrained air

Measurement of slurry density is used for both control and monitoring purposes including cyclone control to maintain the separation and sharpness of the cut, and in thickener underflows to control the discharge rate. As with volumetric flow, entrained air bubbles will cause an error in the required measurement when this measurement is performed by commonly employed nuclear density gauges or less frequently by Coriolis meters. The particular impact of entrained air bubbles on the mixture is as follows.

$$\rho_m = \varphi_G\, \rho_G + \varphi_{SL}\, \rho_{SL} \tag{3}$$

where as before φ_G is the volumetric phase fraction of the gas; ρ_G is the density of the gas component; φ_{SL} is the volumetric phase fraction of the slurry; and ρ_{SL} is the density the slurry without air. Now since by definition $\varphi_G + \varphi_{SL} = 1$, and since $\rho_G << \rho_{SL}$ we obtain:

$$\rho_m = (1 - \varphi_G)\, \rho_{SL} \tag{4}$$

which can be rewritten as

$$\rho_{SL} = \rho_m \big/ (1 - \varphi_G) \tag{5}$$

Solids weight fraction (Cw) correction for entrained air

It is common to use solids weight fraction when referring to solids content in the slurry and when calculating solids mass flow rates such as ton/hr or kg/hr. Solids weight fraction can be measured directly via a sampling and drying technique but real time determination of solids weight fraction is typically performed by using the density measurement from a nuclear density gauge along with the density of the dry solids to calculate the solids weight fraction. This calculation can be done by a PLC, other control systems or within the nuclear density gauge itself. This calculation is based on a formula similar to the following:

$$C_W = \frac{[\rho_{SL} - \rho_L]}{[\rho_S - \rho_L]} \frac{\rho_S}{\rho_{SL}} \tag{6}$$

where ρ_{SL} is the slurry density (if there is no entrained air then this is the density reported from the density gauge); ρ_L is the liquid density (typically water density); and ρ_S is the dry solids density. If there are air bubbles present then the density reported by the density meter will not be the actual slurry (solids and liquid portion) density (ρ_{SL}), instead it will report the combined air, liquid and solids mixture density (ρ_m), thus C_W will be in error. To obtain the correct C_W equation 5 is combined with equation 6 to obtain:

$$C_{W,Corrected} = \frac{\left[\rho_m \big/ (1 - \phi_G) - \rho_L\right]}{[\rho_S - \rho_L]} \frac{\rho_S}{\rho_m \big/ (1 - \phi_G)} \tag{7}$$

where ρ_m is the density reported by the density gauge and φ_G is the volume phase fraction of the air bubbles

Solids mass flowrate correction for entrained air

When performing metallurgical accounting, mass balancing, dosing of chemicals such as flocculants, it is important to know the solids mass flow rate such tons/hr or kg/hr. The solids mass flow rate is calculated from measurements of mixture density and volumetric flow rate, along with the results from calculating solids weight fraction (C_W).

$$\dot{M}_S = C_W\, \rho_{SL} Q_{SL} \tag{8}$$

where ρ_{SL} is the slurry density and Q_{SL} is the slurry volumetric flow rate. If air bubbles are present then the equation should take the gas void fraction into account, resulting in:

$$\dot{\mathrm{M}}_{\mathrm{S,Corrected}} = C_{W,Corrected}\frac{\rho_m}{1-\phi_G}Q_T\left(1-\varphi_G\right) = C_{W,Corrected}\rho_m Q_T \tag{9}$$

Now the gas void fraction does cancel out in part of the equation as shown in equation 9, thus leaving an expression in which the error introduced by the air bubbles is captured within the calculated variable $C_{W,Corrected}$. The full expression is then:

$$\dot{\mathrm{M}}_{\mathrm{S,Corrected}} = \frac{\left[\rho_m/(1-\phi_{\mathrm{G}}) - \rho_L\right]}{\left[\rho_S-\rho_L\right]}\frac{\rho_S}{\rho_m/(1-\phi_{\mathrm{G}})}\rho_m Q_T = \frac{\left[\rho_m-\rho_L(1-\phi_{\mathrm{G}})\right]}{\left[\rho_S-\rho_L\right]}\frac{\rho_S}{\rho_m}\rho_m Q_T \tag{10}$$

If the entrained air is not taken into account we have this expression:

$$\dot{\mathrm{M}}_{\mathrm{S,Uncorrected}} = C_{W,Uncorrected}\rho_m Q_T = \frac{\left[\rho_m-\rho_L\right]}{\left[\rho_S-\rho_L\right]}\frac{\rho_S}{\rho_m}\rho_m Q_T \tag{11}$$

The relative error can be taken by taking the ratio between the uncorrected solids mass flow rate and the corrected solids mass flow rate, and subtracting one from the ratio. With simplification we are left with the following equation

$$\mathrm{Error} = \frac{\dot{\mathrm{M}}_{\mathrm{S,Uncorrected}}}{\dot{\mathrm{M}}_{\mathrm{S,Corrected}}} - 1 = \frac{-\phi_{\mathrm{G}}}{\frac{\rho_m}{\rho_L}-1+\phi_{\mathrm{G}}} = \frac{-\phi_{\mathrm{G}}}{SG_m-1+\phi_{\mathrm{G}}} \tag{12}$$

This error can be expressed in graphical form for measured specific gravities (SG_m) ranging from 1.1 to 2.0 and from gas void fractions (φ_{G}) ranging from 0% to 10% in Figure 6.

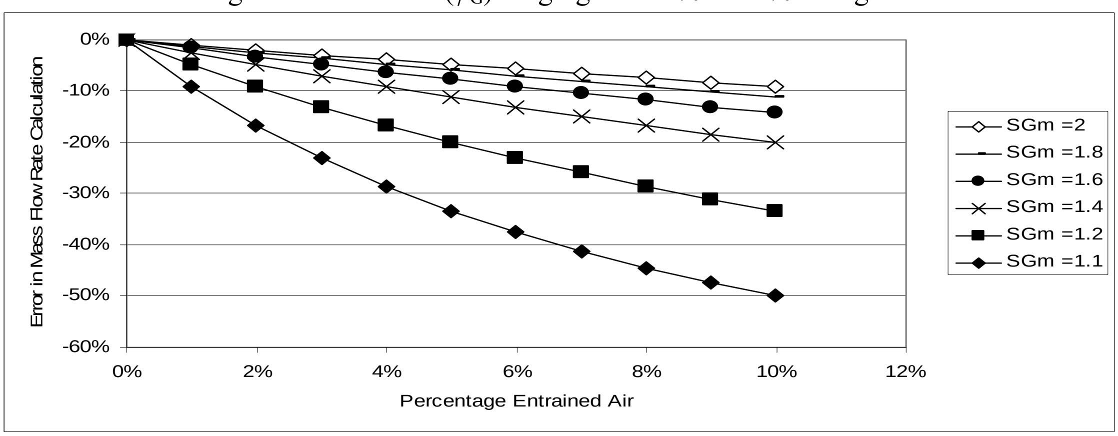

Figure 6: Error in calculation of solids mass flow rate when entrained air bubbles are present and the resulting gas void fraction (percentage of entrained air) is not measured and used in calculation

Slurry Pipeline Stratification and Sanding Detection with three flowmeters

A serious problem in slurry pipelines is the occurrence of highly stratified flow conditions which can quickly lead to solids deposition and a moving or stationary solids bed in the pipe. Early detection of such conditions in real time has suffered from instrumentation limitations. However three sonar flowmeters mounted at strategic locations can provide such information.

The sonar flowmeter has been designed to measure multi-phase flows such as liquid-solid slurries, and therefore is insensitive to large variations in flow profile caused by stratification of solids.

However when stratification becomes severe, and a large fraction of solids are moving slowly near the bottom of the pipe and approaching a sanding condition, the effective pipe cross section area for calculating volumetric flow is reduced, the velocity in the upper portion of the pipe increases, and the sonar meter reports a higher flow rate. Actually, since the sonar meter is fundamentally a velocity meter, it is measuring the velocity first and then calculating a volumetric flow based on an area that is no longer correct. The key to using this effect is to have a reference flow rate to compare against that is not affected by the stratification condition. This can be accomplished by locating two sonar flowmeters at positions where the slurry is known to be well mixed and thus not stratified, and one or more sonar meters at locations where slurry mixing is poor and stratification more likely. Figure 7 shows such a generic pipe configuration, with sonar meters at well-mixed locations at km 0 and km 50. A third sonar meter – the stratification detector – is near km 49.9 has no up-stream feature that would cause mixing, and in fact is at the end of a multi-kilometer straight uphill section where high stratification is more expected due to gravity effects. Figure 7 shows all three meters tracking well at flow rates above 3 m/s. However at approximately 21:00 hours on 29 July 2010, the flow rate is reduced to below 3 m/s at which time the stratification detection sonar meter begins to increase while the other two meters continue to correlate well, indicating a highly stratified flow condition exists at the detection meter. It can also be seen that the density meter begins to trend lower at the same time that the stratification detection sonar flowmeter meter trends higher, indicating that solids are accumulating (or being 'held up') in the uphill section of the pipeline due to stratification, thus causing the density meter at the well-mixed location to report the lower density.

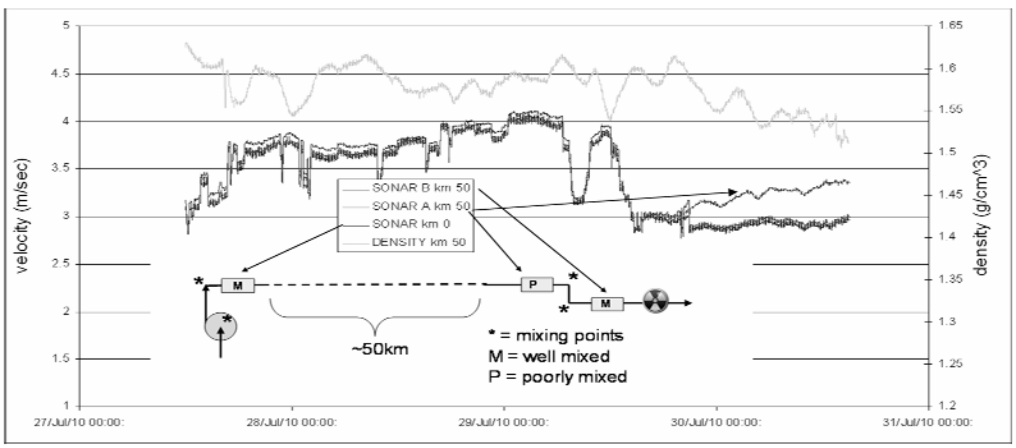

Figure 7: Stratification detection using 3 sonar flowmeters

Slurry Pipeline Leak Detection

Concern over the consequences of slurry pipeline leaks has become increasingly important, as society has become highly intolerant of owners and operators using unsafe practices, and equipment that is not the best technology economically available. Commercial slurry leak detection systems typically rely on two basic methods:

- Mass Balance Leak Detection. Commonly known by this name, in practice it is based on a volume balance. The volume that passes one point should pass through another point, within a certain tolerance; if not, then there is a leak. From an implementation standpoint, the system compares the volumetric flow rates at different locations along the pipeline. The ability to detect smaller leaks requires higher accuracy from the flowmeters used to provide the volumetric flow rate measurements. The ability to determine the leak location along the pipeline is defined by the distance between adjacent pairs of flowmeters.

- Pressure Wave Leak Detection. When a *sudden* leak occurs, a pressure wave is generated that propagates upstream and downstream of the leak location. This wave is detectable with standard pressure sensor instrumentation and data acquisition technologies. Since the wave moves at a known speed (the speed of sound in the fluid), both the existence of the sudden leak and the location can be estimated.

It is important to understand the differences between the two methods and the resulting capabilities and limitations of each. The pressure wave method requires a sudden leak to produce a pressure wave of clearly detectable amplitude. However many leaks start slowly and gradually increase in flow rate, thus never producing a clearly detectable pressure wave, making the leak undetectable. The volume balance method can detect small flow rate changes and slow trends in flow rate, and thus can detect small leaks that are not detectable by the presser wave method. Clearly, a good slurry leak detection system should use both techniques.

However measuring slurry flow rate with accuracy, repeatability and reliability has always been challenging, and too frequently unattainable with commonly used invasive electromagnetic flowmeters. For these devices, highly abrasive flows cause constant wear to flowmeter parts exposed to the flow, and the presence of even small amounts of magnetic material can produce large errors. The sonar meter overcomes these limitations.

Figure 8 shows a comparison between two electromagnetic and two sonar flowmeters on a 50 km tailings line. A sonar and mag meter are located close together at each end of the line. The histograms show that both the absolute difference and the average deviation between similar meters is less for the sonar meter pair.

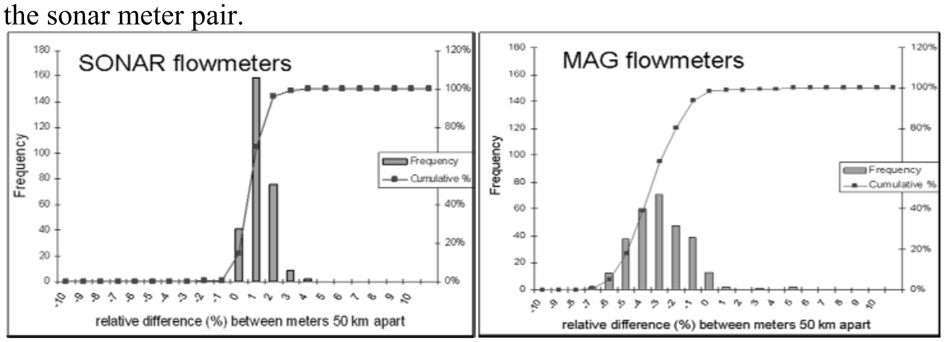

Figure 8: Difference in flowrate between two sonar flowmeters, and difference between two mag meters, all on the same 50 km pipeline. A sonar and mag are located close together at each end of the line.

FUTURE DIRECTIONS

Coarse Material Detection in Hydrocyclone Overflow

A non-invasive acoustic-based passive monitoring system has been developed that provides real-time detection of the presence of large-size coarse particles, (‘rocks’) in the overflow of individual hydrocyclones. The system is in the advanced field test stage, and provides: information that identifies the on-off status of individual cyclones, a qualitative alarm that identifies the severity of rock events detected, and a quantitative measure of the number rocks detected vs time. This previously-unavailable information provides operators with the ability optimize hydrocyclone performance by identifying poorly performing cyclones, and then take corrective action such as shutting off the offending cyclone, and/or adjusting other operating parameters such as changing flow rate, feed density, or battery pressure.

Particles smaller than the separation size passing to the overflow will have all the recoverable mineral liberated, thus available for recovery in the flotation circuit. Particles larger than the separation size passing to the overflow will have some unliberated mineral and thus will reduce the recovery of the flotation circuit.

A common problem in hydrocyclone operation occurs when particles ('rocks') much greater than the separation size (at least 10x), are passed to the flotation circuit via the hydrocyclone overflow line. This causes two costly problems; decreased mineral recovery in the flotation circuits, and additional maintenance due to accumulation of large solids in the bottom of flotation tanks.

Figure 9: Oversize detection system on cyclone overflow

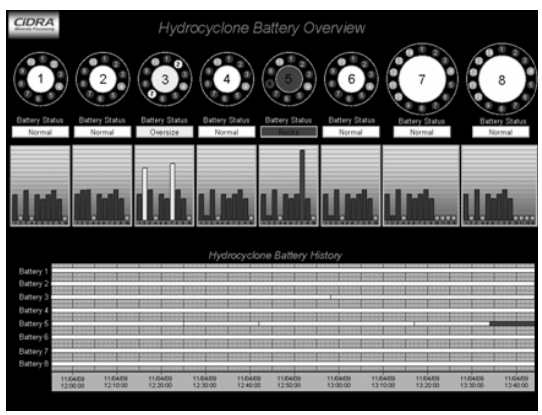

Figure 10: Control room display of real-time cyclone information

The acoustic-based cyclone monitoring system that has been developed is based on passive acoustic principles, and has some similarity to the well-known passive sonar flowmeter. Single and multi-phase flows produce unique acoustic signatures that provide valuable information about the composition of the flow. In multi-phase solid-liquid flows such as slurry flows in grinding circuits, the acoustic signature (amplitude, frequency, and phase) contains information concerning the size of particles being transported. Thus, acoustic analysis techniques can be used to determine the presence of particles in various general size classes, because each size class has a unique acoustic signature. In this way the presence of very large particles, in a size range identified as coarse particles or ‘rocks’, can be clearly detected and quantified based on their acoustic signature.

The system consists of acoustic sensors externally mounted to the overflow pipe as shown in Figure 9. Signals are transmitted via a local amplifier to a processor mounted on the cyclone battery, which then transmits to a PC located in the control room. A graphical user interface shown in Figure 10 provides real-time status for each cyclone, which includes: on-off state, three-state rock event severity (none, moderate, severe), and rock event level trending. It has also been proven that the present technique can be extended to identify an abnormally high fraction of particles larger than the separation size, but smaller than the coarse material or ‘rock’ size, as described above. The potential to monitor the amount of this oversize material in real-time could be highly useful in further hydrocyclone performance optimization, and thus increase overall mineral recovery in the concentrator plant, and reduce energy consumption in grinding.

CONCLUSIONS

Applications were presented where the superior performance of the array-based sonar technology can provide improved levels of process monitoring and control. Flow measurements from an array-based sonar meter and a mag meter were compared in a hydrocyclone feed application. The sonar meter provided significantly better correlation to a pressure signal from which flow can be determined through a well known relationship.

It was shown how the gas volume fraction measurement from the sonar meter can be used to correct several important parameters: volumetric flow rate, slurry density, solids weight fraction (Cw), and solids mass flowrate. Key relationships were presented, and the error effects shown. The error in solids mass flowrate due gas volume fraction is greater at lower slurry densities, and correction for this error can lead to improved mass balance calculations.

Two slurry pipeline applications were presented. The first showed how a group of three sonar meters were used to detect high levels of stratification in a horizontal line. The second showed how the superior performance of a sonar meter enables the reliable use of the mass balance technique for leak detection, which has been extremely unreliable using other technologies.

ACKNOWLEDGEMENTS

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