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Process Control Applications in Mining and Metallurgical Plants

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IMPROVED FLOW AND FLOTATION MONITORING FOR PROCESS EFFICIENCY IMPROVEMENTS THROUGH NEW TECHNOLOGY UTILIZING NON-INVASIVE PASSIVE ARRAYS

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ABSTRACT

New technology, based on arrays of passive sensors and SONAR processing algorithms, has spawned new capabilities in flow and flotation monitoring, allowing a higher degree of process efficiency. This new technology, which performs accurate, robust, non-invasive flow measurements, gas volume fraction (entrained air) measurements, and other performance measurements, will be described. Its use in the presence of magnetic ore such as magnetite and pyrrhotite and in flow with entrained air to potentially increase the accuracy of mass balance calculations and enhance hydrocyclone performance will be detailed.

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INTRODUCTION

Accurate, robust measurement of true volumetric flow is necessary for many critical areas of minerals processing. These areas include mass balancing, metallurgical accounting, and process monitoring and control. Obtaining a true flow measurement has proven to be a challenging endeavor for metallurgists and process control engineers because of many process influences. These influences include pipe wall scale buildup, the presence or absence of magnetic ore, changing process fluid properties, and the presence of entrained air bubbles. In most cases, 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 arrays of sensors. In addition, new measurements such as the amount of air bubbles entrained within a slurry or liquid is now possible.

PRINCIPLE OF OPERATION

In essence this measurement principle is based on the use of an array of sensors and passive SONAR processing algorithms to detect, track, and measure the velocity of any disturbance moving in the axial direction of the pipe. These disturbances can be grouped into three major categories: disturbances conveyed by the flow, acoustic waves in the fluid, and vibrations transmitted via the pipe walls. Each of the three classes of disturbances travel within distinct and separate groups of velocities. For example, the flow will convey turbulent eddies, density variations, or other fluid characteristics at the rate of the fluid flow which for liquid based flows rarely exceed 9 m/s. Acoustic waves in the fluid will typically have a minimum velocity of 80 m/s and a maximum velocity of 1500 m/s. The third group, pipe vibrations, travel at velocities that are several times greater than the acoustic waves. Thus by using the differences in velocities, with a gap of velocities between classes of disturbances, the distinct classes can be clearly separated and their velocities can be accurately measured.

Passive Array Hardware

In a commercial embodiment of this measurement principle, a flexible band of passive sensors is wrapped around and tightened onto the pipe. This is a dry fit that does not require gels or couplants since no ultrasonic waves are used. The sensor band is always 50 cm long in the axial direction of the pipe and equal to the circumference of the pipe in the orthogonal dimension. The typical installation procedure and hardware embodiment is outlined in Figure 1. First the pipe is wiped down and any high points are sanded or filed away. Second, the flexible sensor band is wrapped around the pipe and a series of captive screws on the sensor band are used to tighten the band onto the pipe. Each screw uses a stack of spring washers to allow for pipe expansion and contraction, as well as ensure a set clamping force. Third, a protective cover with signal conditioning and diagnostics electronics is installed over the sensor band, and the sensor band is connected to the electronics in the cover. Fourth, the cable from the sensor head to the transmitter is installed and wired to the transmitter. Fifth, the easy to use front panel menu on the transmitter is used to configure the transmitter.

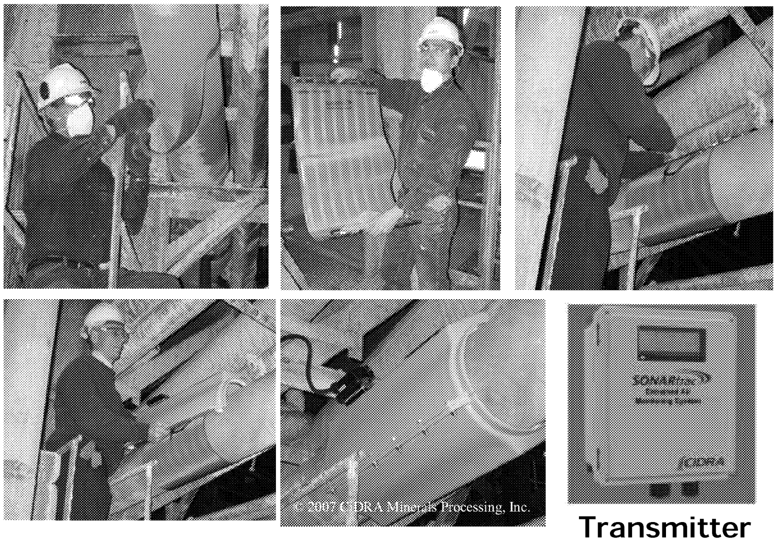

Figure 1 - Installation procedure from (top-left) pipe preparation through cleaning and light sanding of pipe to (top-middle and top-right) mounting of the flexible, lightweight sensor band to (bottom-left) installation of the sensor cover and to (bottom-middle and bottom-right) connection of sensor cover to transmitter via water tight cable

Velocity Measurement of Turbulent Flow

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 are conveyed with the flow. An illustration of these turbulent eddies is shown in the right hand side of Figure 2. These eddies are being continuously created. Once created they break down into smaller and smaller vortices, until they become small enough to be 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 bracketed by the diameter of the pipe on the largest vortices and by viscous forces on the smallest vortices. On the average, these vortices are distributed throughout the cross section of the pipe and therefore across the flow profile. Thus the average velocity of the fluid can be determined by tracking the average axial velocities of the entire collection of vortices.

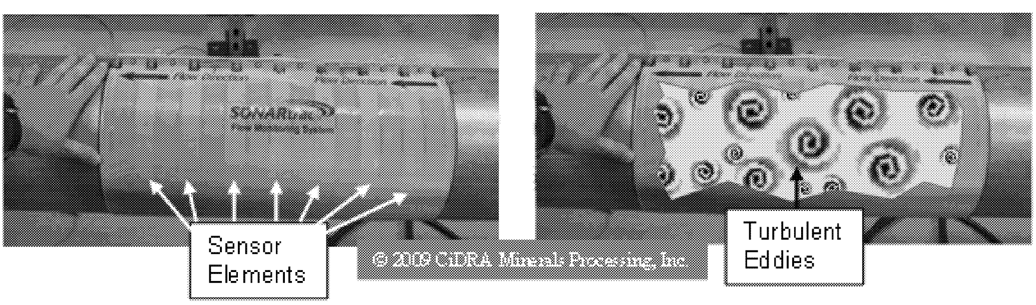

Figure 2 - (Left) Passive sensor band wrapped around pipe (Right) Interior pipe view with illustrated turbulent eddies

Through the combination of an array of passive sensors and the sonar array processing algorithms, the average axial velocities of a collection of vortices 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 3 exaggerates)
- The mechanical dynamic strain signal is converted to an electrical signal through a passive sensor wrapped partially or fully around the pipe – no coupling 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. In most applications, a minimum flow rate of 0.9 m/s (3 f/s) is required to measure the flow velocity

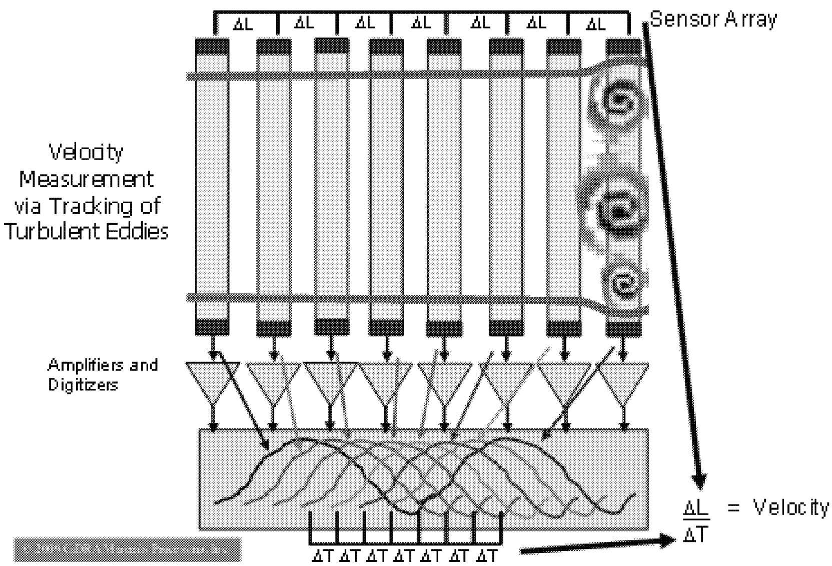

Figure 3 - Illustration of strain induced in pipe walls by passing turbulent eddies, resulting in similar signals detected by sensor elements with time or phase differences, leading to velocity measurement

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 strains in the pipe wall as discussed earlier. 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 fluid conveyed 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).

These velocity measurements have been demonstrated on many types of pipes with a wide variety of liners. The pipes include steel, PVC, HDPE, and fiberglass. The pipes can be lined or unlined. When lined, this has been demonstrated on rubber, urethane, cement, and Teflon lined pipes, as well as pipes with scale buildup.

Speed of Sound and Entrained Air Bubbles (Gas Void Fraction) 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, 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 4 and, as can been seen in the figure, they can propagate in either direction down the pipe or in both directions).

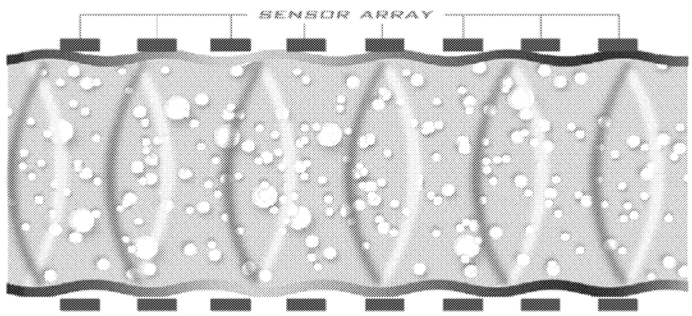

Figure 4 - Illustration of naturally occurring acoustic waves propagating in pipe under the array of sensors

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 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).

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 5. The particular 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.

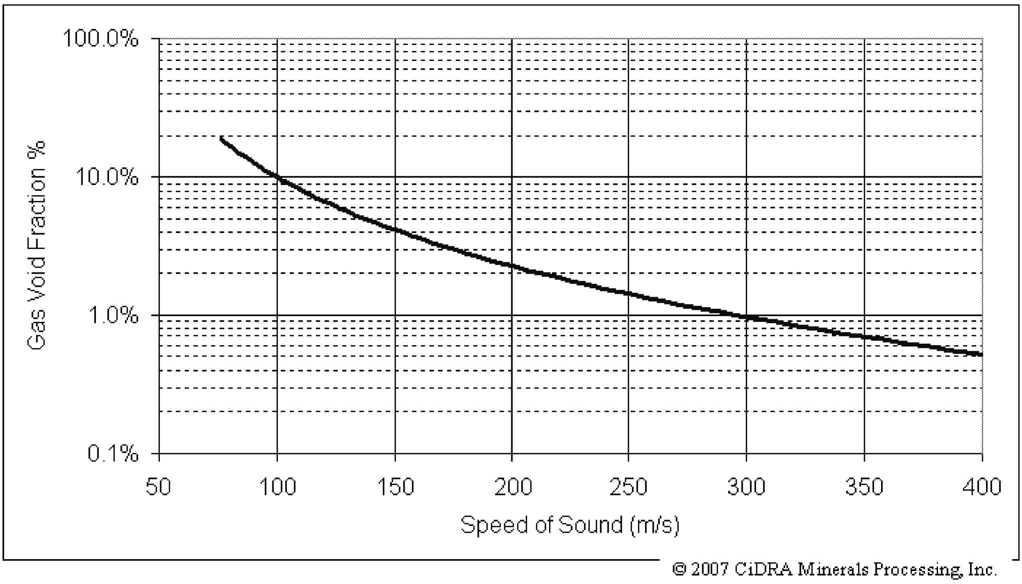

Figure 5 - Example of relationship between gas void fraction (entrained air bubbles) and speed of sound

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.

OPERATIONAL USE OF ARRAY-BASED FLOWMETERS

Each flowmeter technology has a sphere of applications in which it provides clear value to the customer. For passive flowmeters these applications include ones with magnetic ore such as magnetite, pyrrhotite and arsenopyrite; situations with scale build up; abrasive or corrosive flows; slurry flows; liquids or slurries with entrained air; situations in which it is not desirable to shut down the flow; high pressure lines; operations needing long term accuracy; and situations where leaks can result in a safety issue. Some of these will be discussed here.

Measurement in the Presence of Scale Buildup

Scale buildup has two major impacts on flowmeter instrumentation – pipe interior diameter changes and ability to provide a flow velocity reading. For velocity based flow measurements, which encompasses most flow meters used in minerals processing, the scale buildup will affect the conversion of the measured velocity to the desired volumetric flow rate measurement. This is due to the reduction of the open section of the pipe interior with the buildup of scale. Like other velocity based flowmeters, the volumetric flow rate reported by the array-based flowmeter will be impacted by this inner cross-sectional area change. The impact of this change can be mitigated by modeling the scale buildup and/or an occasional measurement of the pipe interior. Unlike traditional flowmeters, the array-based flowmeter will continue to accurately measure the velocity in the presence of scale buildup. This is not true for electromagnetic flowmeters or ultrasonic flowmeters. Thus the operation is never operating blindly and unplanned maintenance actions for cleaning electromagnetic flowmeter electrodes are avoided. In addition, the labor and cost associated with cleaning electromagnetic flowmeters is avoided.

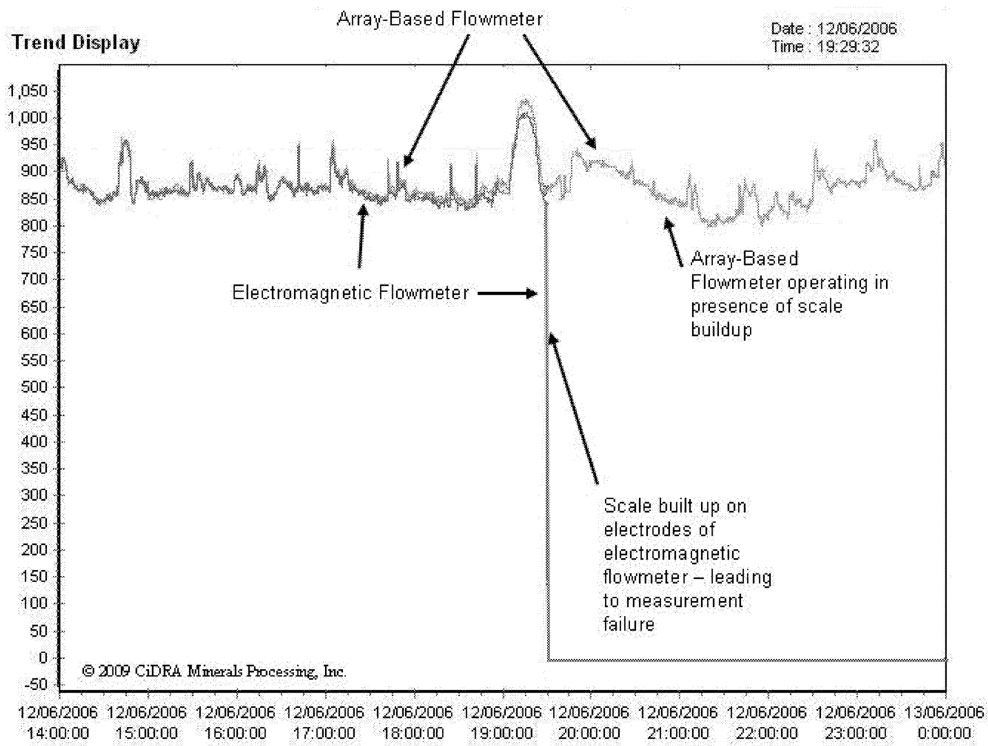

Figure 6 - Comparison of measurement reliability of electromagnetic flowmeter and array-based flowmeter in the presence of scale buildup

Accurate, Drift Free Measurements for Long Term Monitoring Control and Accurate Mass Balance

There are many cases where the measurements provided by flowmeters cannot be verified through an accurate gold standard test such as a tank fill or draw down calibration. Most flowmeters will drift with time and temperature resulting in a change in the signal that is not noticed or cannot be verified. As an example, electromagnetic flowmeters rely on the stability of analog electronics that can drift with time and temperature, the absence of magnetic particles in the ore, and/or clean electrodes to accurately report flow. When any of these conditions are not met, which happens frequently, the operator is not even aware that an error has taken place unless the electromagnetic flowmeter is compared to another meter, or is recalibrated via a gold standard test.

As an example data is shown in Figure 7 from two electromagnetic flowmeters placed in series in close proximity to each other at a gold and copper mill. In that figure the two dark lines are the electromagnetic flowmeter outputs, while the light line between the two dark lines is the array-based flowmeter. The array-based flowmeter was configured using the universal calibration coefficients used for this meter. Here the two electromagnetic flowmeters differ from 2% to 18% during the period of time covered by this data set. The data from a array-based flowmeter is seen to provide a flow reading that is approximately an average of the two electromagnetic flowmeters, but with the confidence that it will not drift with time. Maintenance of the relative accuracy can be verified by moving the array-based flowmeter, without stopping the process, to a location where a tank test can be performed.

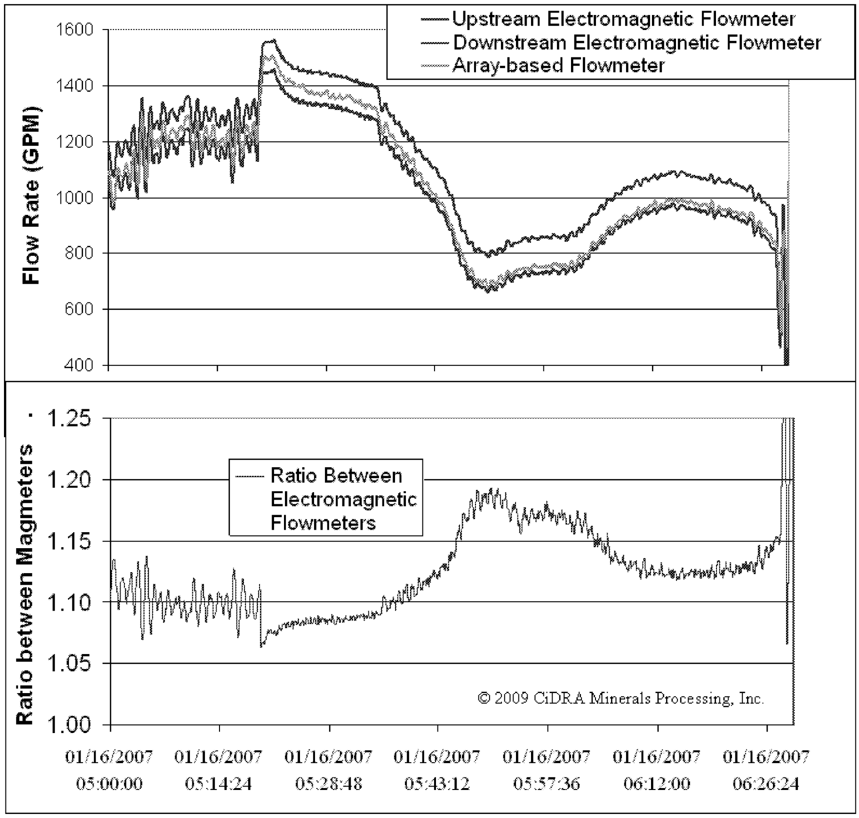

Figure 7 - Two electromagnetic flowmeters in series with array-based flowmeter showing offsets ranging from 2% to 18% between two electromagnetic flowmeters and accurate measurement provided by array-based flowmeter

Control and Monitoring via Repeatable, Linear Flow measurements

An application in which the array-based flowmeter was initially tested due to its reliability and cost effectiveness in high wear rate flow environments was a hydrocyclone feed line. The output of this flowmeter was compared to a new ceramic lined electromagnetic flowmeter and to the pump power. Even though the pump power is a non-linear indication of flow rate, it can be used for short-term comparisons if several conditions are met including keeping the fluid density and the sump level constant. In Figure 8 this comparison of the two flowmeter technologies relative to pump power is seen. The pump power is the dark, solid line which is closely matched by the array-based flowmeter output given by the solid gray line. The electromagnetic flowmeter output, seen as the dark dashed line, fails to respond to many of the flow changes that are detected by both the array-based flowmeter and the pump power. In addition, during steady state conditions at approximately 9:07 and 11:31, where both the pump power and the array-based flowmeter are indicating a relatively stable flow, the output of the electromagnetic flowmeter fluctuates by 6% peak to peak.

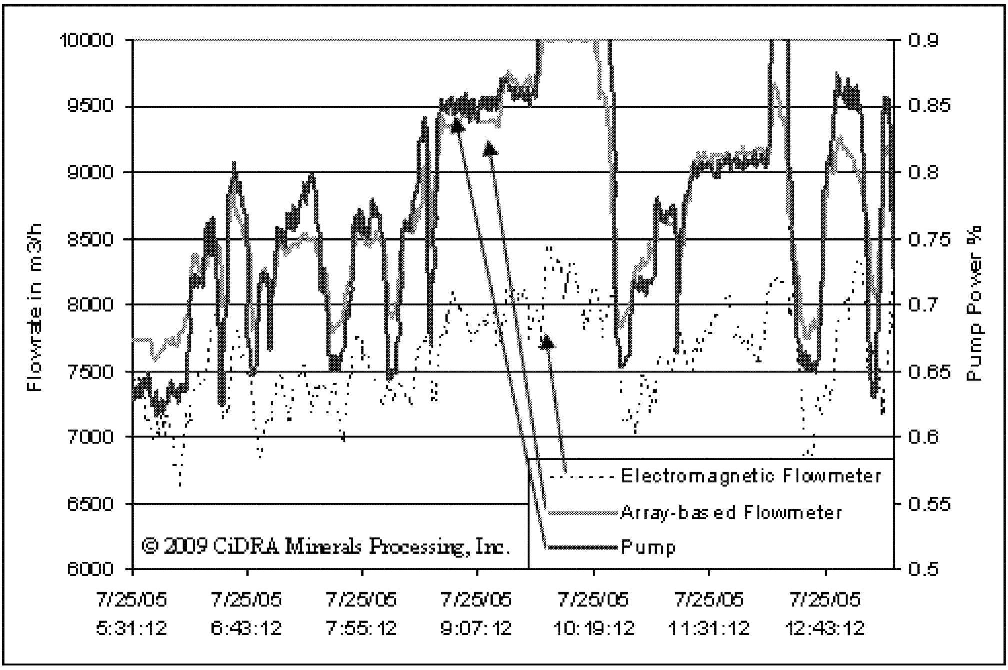

Figure 8 - Comparison of array-based flowmeter and electromagnetic meter to pump power on hydrocyclone feed line

When the flow rate indicated by the two different technologies is compared to the pump power, another indication of the repeatability of the two flowmeter technologies can be seen. If certain key process parameters are kept constant, then for the same pump power, the flow rates reported should have a minimal spread around an average for each level of pump power. In Figure **9,** the electromagnetic flowmeter output is shown by the dark points, whereas the array-based flowmeter output is shown by the gray points. A normalized standard deviation of the flow rates for the respective technologies can be taken in which the standard deviation of the flow rate is divided by the average of the flow rate at each pump power level. This will provide a quantitative indication of the amount of spread in the outputs of the flowmeters with a lower normalized standard deviation indicating less spread and hence better precision (repeatability). The resulting calculations reveal that the electromagnetic flowmeter has a normalized standard deviation of 9.1% whereas the array-based flowmeter has a normalized standard deviation of 5.7%.

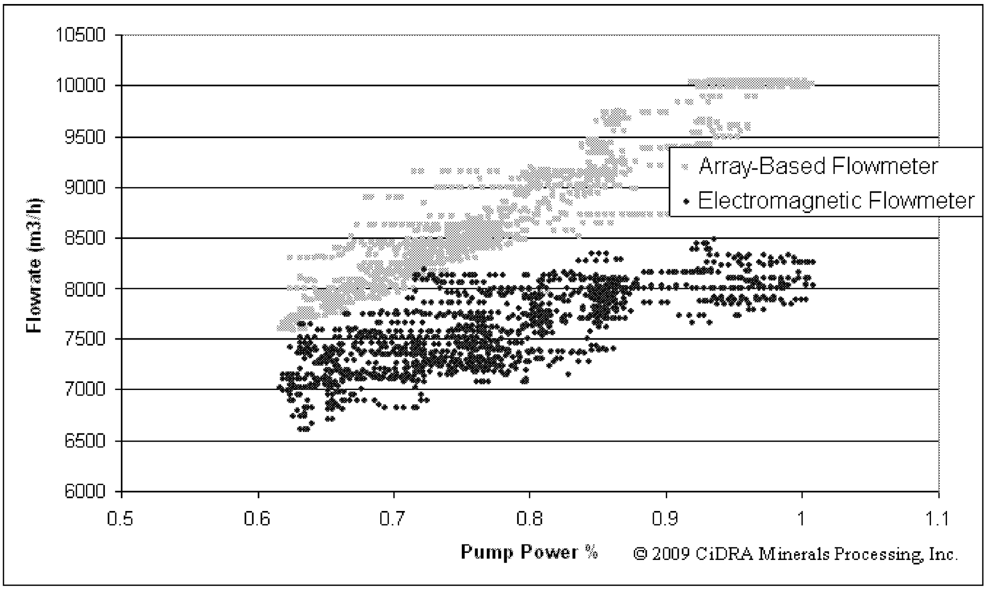

Figure 9 – Flow rate reported by array-based flowmeter and electromagnetic flowmeter relative to pump power (as percentage of maximum power)

Correction of Volumetric Flow Due to Entrained Air Bubbles

To achieve a stable processing system with higher levels of efficiencies, accurate flow rate measurements of the liquid or liquid/solids (slurry) phases are necessary. Unfortunately, when air is trapped within the slurry in the form of the bubbles, this flow measurement was not attainable before the introduction of array-based instrumentation for two reasons. First most traditional flowmeter technologies cannot perform an accurate flow measurement in the presence of air bubbles. Second, none of the older technologies had the ability to compensate for the air content. The array-based technology robustly solves both problems.

Entrained air bubbles can come about from a myriad of sources including low sump levels; flotation processes; pump leaks; flashing; and others. Measuring the entrained air levels has two major benefits. These benefits include the identification of process and equipment problems, early warning of potential safety issues, and the ability to measure true volumetric flow of the process fluid/solid phase. Both of these can be seen in the example in Figure 10. In this figure, the dark trace is the volumetric flow of all three phases: solid, liquid, and gas bubbles. The gray trace at the bottom of the graph is a measurement of the gas void fraction or percentage of volume occupied by the gas bubbles, as measured by the array-based instrument. In this case, flashing has occurred which can lead to both an operational and a safety issue. The gray trace near the top of the graph is calculated from the total volumetric flow (black trace) and the gas void fraction via a simple linear correction (Equation 1).

$$\text{Adjusted Volumetric Flow} = \text{Volumetric Flow} * (1 - \text{Gas Void Fraction \%}) \quad (1)$$

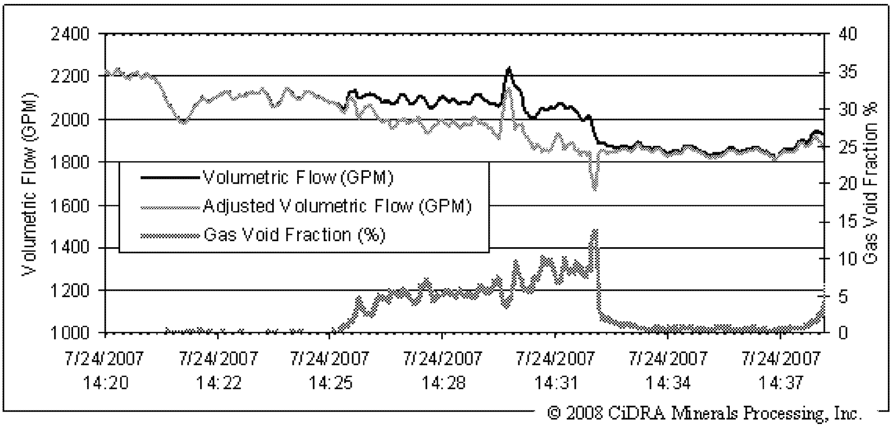

Figure 10 - Detection of entrained air bubbles and compensation of flow measurement

Correction of Nuclear Density Gauges Due to Entrained Air Bubbles

The presence of entrained air bubbles 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, a test was performed in which varying levels of air were introduced into a water flow loop containing a nuclear density gauge. As expected, when the air injection rate, shown as standard cubic feet per hour (SCFH) in Figure 11, was increased the nuclear density gauge output seen in the light solid line decreased. The array-based flowmeter on the same line accurately measured the resulting air content as seen in the dashed line. Using this measurement a simple linear correction was applied to the nuclear density gauge output with the resulting reduction of the error from 5% down to +/- 0.25%.

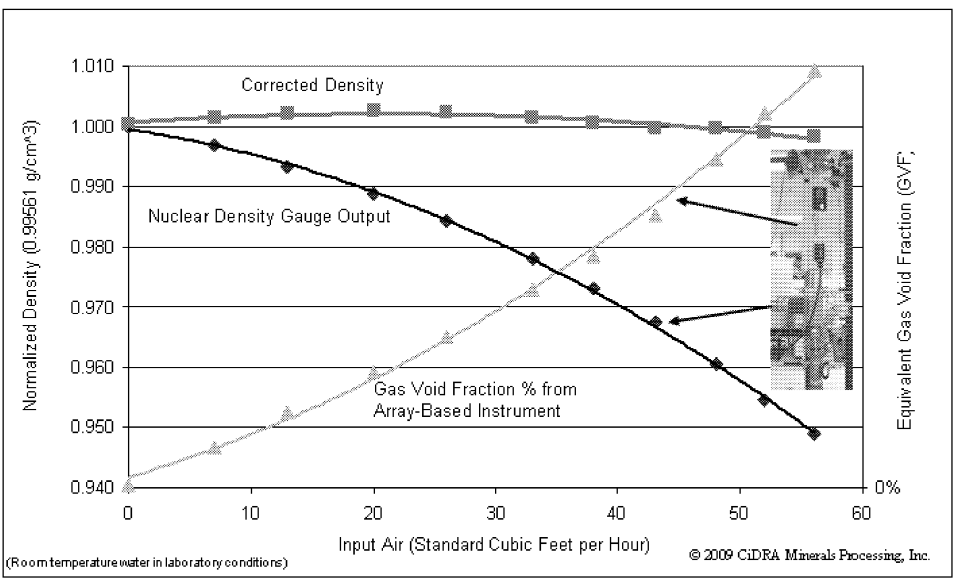

Figure 11 - Nuclear density gauge correction using array-based meter

In the absence of this information on the quantity of air entrained within the slurry, an error can arise in the calculation of the mass flow rate. The extent of the error is dependent on two variables, the amount of entrained air and the relative specific gravity of the slurry. The relative specific gravity is the specific gravity of the slurry divided by the specific gravity of the liquid component. Typically this is water so in those cases the relative specific gravity is the same as the slurry specific gravity. If the carrier fluid is a brine solution then the relative specific gravity will be lower than the slurry specific gravity. As the relative specific gravity approaches one, the resulting mass flow calculation error will increase in the presence of entrained air. As an example, in Figure 12 calculations of the errors in the mass flow rate calculations as a function of the relative specific gravity and percentage of entrained air or gas volume fraction are seen.

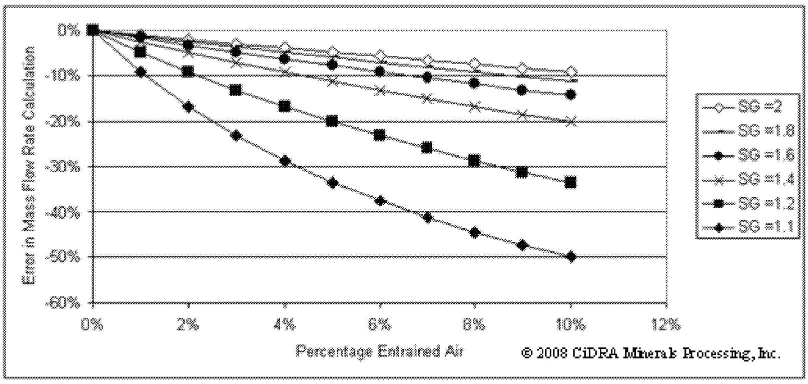

Figure 12 - Error introduced by entrained air in mass flow rate calculations as a function of slurry relative specific gravity (SG)

SUMMARY

The array-based measurement principle has demonstrated the ability to perform accurate volumetric flow measurements and gas void fraction measurements in a variety of minerals processing applications ranging from clean liquids such as water and leach solutions to thick slurries and pastes. It does so with several distinct advantages particularly in mass balance situations, in the presence of entrained air bubbles, under the influence of scale buildup, in high wear rate or corrosive environments, and in the presence of magnetic ores. This technology is currently being used in over 600 minerals processing flow monitoring applications within 21 countries.