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Improved flow and entrained air monitoring for process efficiency improvements through new technology utilizing non-invasive passive arrays

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New technology, based on arrays of passive sensors and SONAR processing algorithms, has spawned new capabilities in flow and entrained air 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 impact on hydrocyclone flow measurements will be illustrated. Its use in the presence of ferromagnetic 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.

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 endeavour for metallurgists and process control engineers using traditional flowmeter technologies such as electromagnetic, differential pressure, and ultrasonic based technologies because of many process influences. These influences include pipe wall scale build-up, the presence or absence of magnetic ore or ferrosilicon, changing process fluid properties, and the changing levels 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. This non-invasive technology provides an accurate flow measurement of practically any fluid within any type of pipe without making contact with the fluid, thus leading to unprecedented reliability.

In addition, density meters are commonly used to help determine the solids content in a slurry stream, but are confounded by the entrained air in the slurry. A secondary measurement that can be provided by this array-based technology is a determination of the amount of air entrained in the form of bubbles that is contained within the slurry or liquid flow. This entrained air measurement is combined with the output of a nuclear density gauge to provide the true density and hence mass content. There are many applications within a minerals processing plant where by process control strategies may be improved and maintenance cost may be reduced by applying this technology.

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 1 500 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 to ensure a set clamping force without requiring torque wrenches or screwdrivers. 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.

Velocity measurement of turbulent flow

Within most industrial processes, the most common flow disturbance is turbulence. 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



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

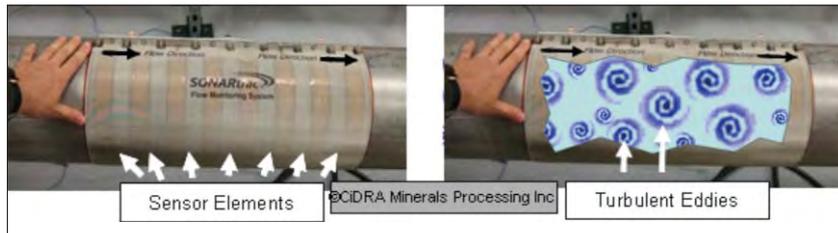


Figure 2. (Left) Passive sensor band wrapped around pipe (right) interior pipe view with illustrated turbulent eddies

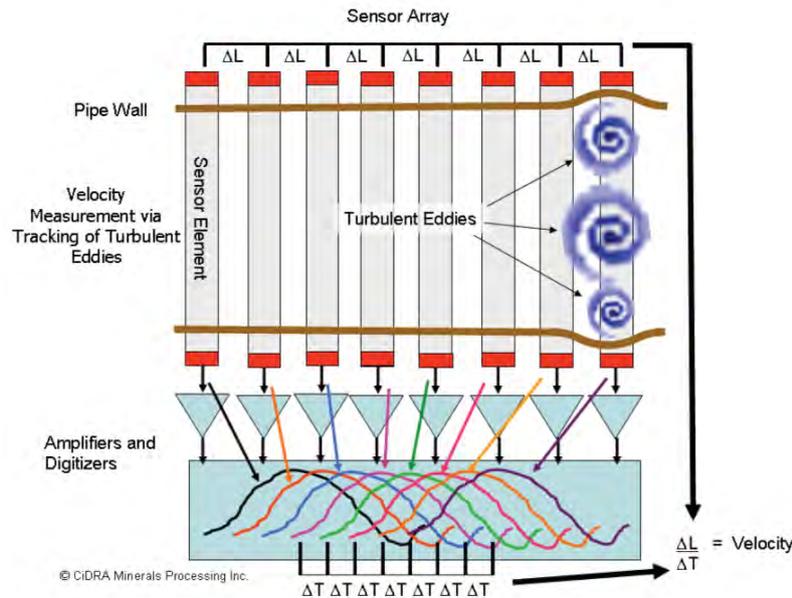


Figure 3. Illustration of strain induced in pipe walls by passing turbulent eddies, resulting in similar signals detected by sensor elements with time or phase differences, leading to velocity measurement

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.

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 to within $\pm 1\%$ of reading. In most applications, a minimum flow rate of 0.9 m/s (3 f/s) is required to measure the flow velocity

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 build-up. A full pipe is required and a determination of the pipe's inner diameter must be done in order to convert the accurate velocity measurement (m/s) produced by this technology into an accurate volumetric flow rate such as m³/h.

Speed of sound and entrained air bubbles (gas void fraction) measurement

The same array based technology used to measure the velocity of turbulent eddies can be used to measure the velocity of acoustic waves. In most mineral processing processes including slurry 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 itself as it travels 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. The acoustic waves can propagate in either direction down the pipe or in both directions.

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 travelling 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 as seen in Figure 4, 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

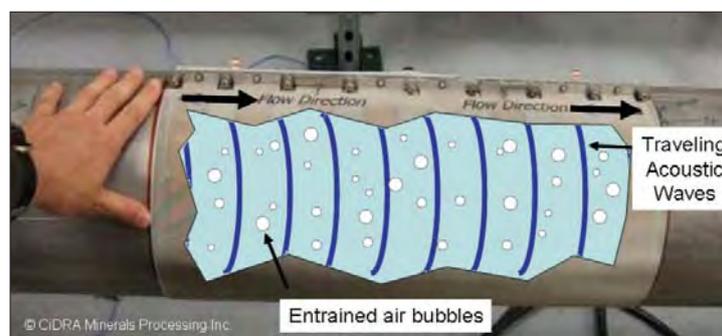


Figure 4. Illustration of naturally occurring acoustic waves propagating in pipe under the array of sensors

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 in order to determine the relationship between the speed of sound and gas void fraction. 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.

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 $\pm 5\%$ of the reading, thus the maximum absolute error is $\pm 1\%$.

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 array based flowmeters these applications include ones with ferromagnetic slurry incorporating material such as magnetite, pyrrhotite, and ferrosilicon; 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.

Measuring volumetric flow in the presence of ferromagnetic ore such as magnetite

Magnetic ore or medium in a slurry line, whether intentional in an iron ore mill or dense medium separation plant, or whether unintentional in mills concentrating other metals, poses a potential problem for electromagnetic flowmeter measurements. Many locations mining copper, gold or other non-ferrous metals have magnetic ore in or near their orebody. The magnetic slurry, even in small quantities, creates both short-term and long-term changes in the outputs of electromagnetic flowmeters. Short-term changes result from perturbations of the magnetic field induced by the magnetic slurry. The magnetic ore, even in small quantities, creates both short-term and long-term changes in the outputs of electromagnetic flowmeters. Short-term changes result from perturbations of the magnetic field induced by the magnetic ore within the electromagnetic flowmeter resulting in over reporting of flow or the introduction of noise in the output. Long-term changes result from an attraction of the ferromagnetic ore to the electromagnetic flowmeter elements resulting in a reduction of the pipe cross section, thus increasing the over reporting of volumetric flow rates. Electromagnetic flowmeter manufacturers have attempted to circumvent the impact of magnetic ore with a third coil, with magnetic field measurements, and with manual offset adjustments based on laboratory samples of the typical slurry. These methods have resulted in mixed results. Many times the calibration or offset changes depend on the quantity of magnetite present.

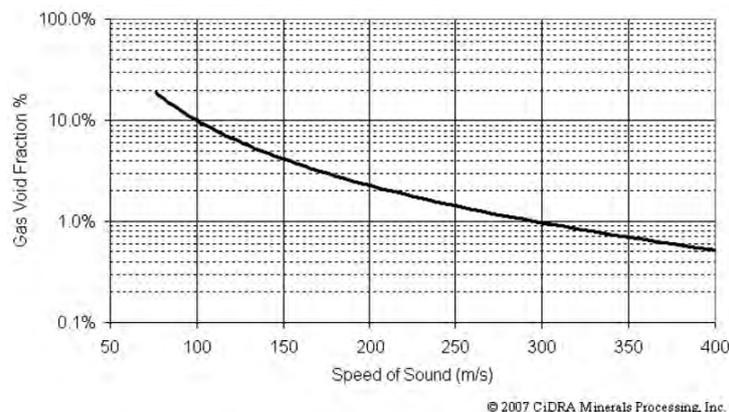


Figure 5. Example of relationship between gas void fraction (entrained air bubbles) and speed of sound

A more robust solution is to use a flowmeter technology that is not affected by the presence of magnetic ore. A passive array based flowmeter does not rely on the use of any magnetic fields. It is totally impervious to the effects of magnetic ore. An example of this is illustrated in Figure 6 in which an array flowmeter is compared to an electromagnetic flowmeter. In the figure, one can see that during a period of constant flow rate as the amount of the magnetic ore in the slurry increases, the electromagnetic flowmeter erroneously reports a higher flow rate, whereas the array based flowmeter correctly continues reporting no change in the flow rate. The resulting over-reporting in mass flow rate is directly proportional to the over-reporting of flow rate by the electromagnetic based flowmeter, as seen in Figure 7.

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 analogue 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.

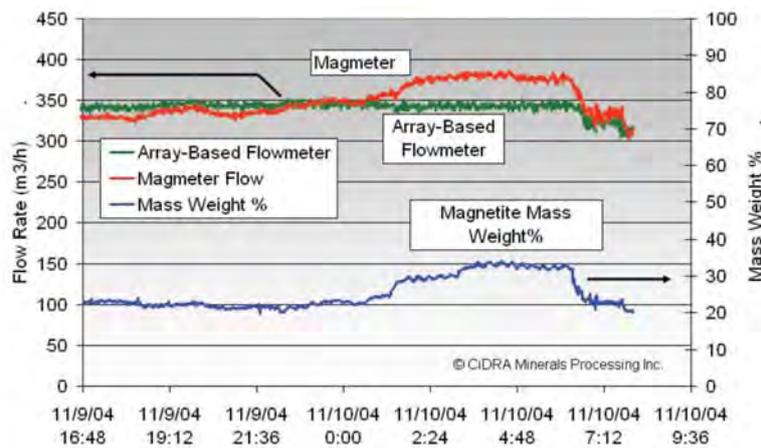


Figure 6. Electromagnetic flowmeter erroneously respond to magnetite whereas array flowmeter accurately reports flow

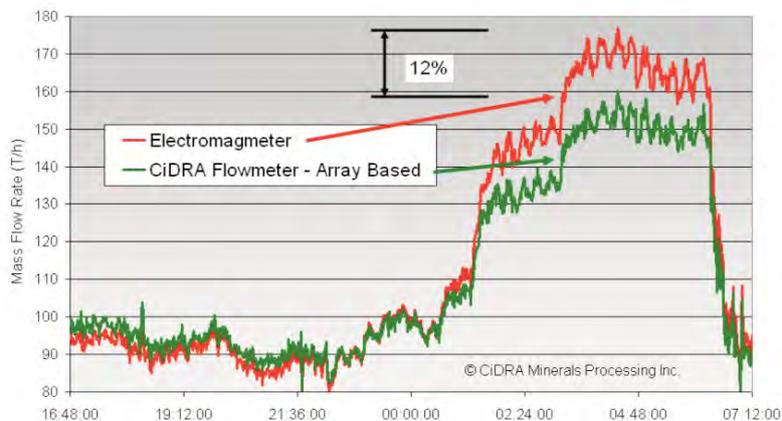


Figure 7. Impact of ferromagnetic slurry on mass flow rate, showing over-reporting by electromagnetic based flowmeter versus array based flowmeter

As an example data are shown in Figure 8 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, and 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 covered by this data-set. The data from a array-based flowmeter are 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.

Hydrocyclone 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 exhibits a strong linear component if operational conditions such as slurry density, viscosity, and sump level are kept constant. In Figure 9 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, represented by the dark dash lined, differs significantly from both the pump power and the array-based flowmeter output. 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.

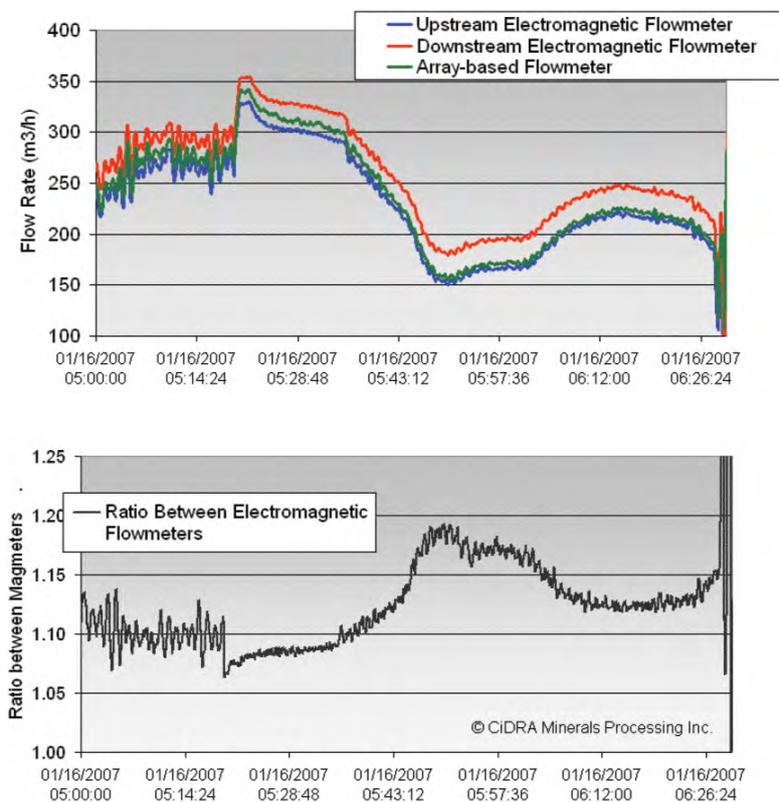


Figure 8. Two electromagnetic flowmeters in series with array-based flowmeter showing offsets ranging from 2% to 18% between two electromagnetic flowmeters and accurate measurement provided by array-based flowmeter

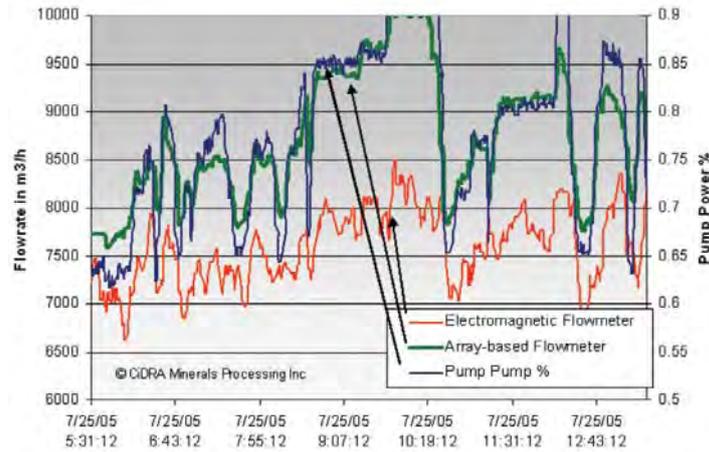


Figure 9. Comparison of array-based flowmeter and electromagnetic meter to pump power on hydrocyclone feed line

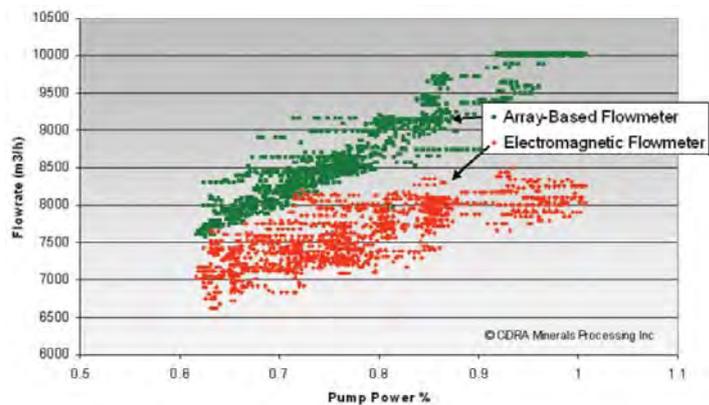


Figure 10. Flow rate reported by array-based flowmeter and electromagnetic flowmeter relative to pump power (as percentage of maximum power)

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 10, the electromagnetic flowmeter output is indicated by the dark points, whereas the array-based flowmeter output is represented 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%.

Correction of volumetric flow due to entrained air bubbles

To achieve a stable processing system with higher levels of efficiencies, accurate and repeatable volumetric flow measurement of the liquid or liquid/solids (slurry) phases is necessary. Slurries tend to entrain air bubbles. Most traditional flowmeter technologies cannot perform an accurate flow measurement in the presence of air bubbles. In addition, the older generations of flowmeter technologies do not have the ability to compensate for the air content. The array based technology robustly measures flow in the presence of entrained air and quantitatively determines the amount of entrained air.

Entrained air bubbles can come about from a myriad sources including low sump levels, comminution processes, pump leaks, flashing, and others. The ability to measure the entrained air levels results in several major benefits. These benefits include the identification of process and equipment problems, early warning of potential safety issues, and the ability to determine the true volumetric flow of the process fluid/solid phase. Some of these benefits can be seen in the example in Figure 11. In this figure, the dark trace with the triangles is the volumetric flow of all three phases. The three phases consist of solid, liquid, and gas bubbles measured on a concentrate line at a copper/gold/molybdenum concentrator. The dark 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, air has become entrained in the final concentrate slurry, which can lead to a metallurgical balance calculation error. The gray trace with the open circles between the other two traces is the true volumetric flow rate of the slurry as calculated from the total volumetric flow (black trace with triangles) and the gas void fraction via a simple linear correction (Equation [1]).

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

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 12, was increased the nuclear density gauge output seen in the light solid line decreased. The array-based flowmeter on the same

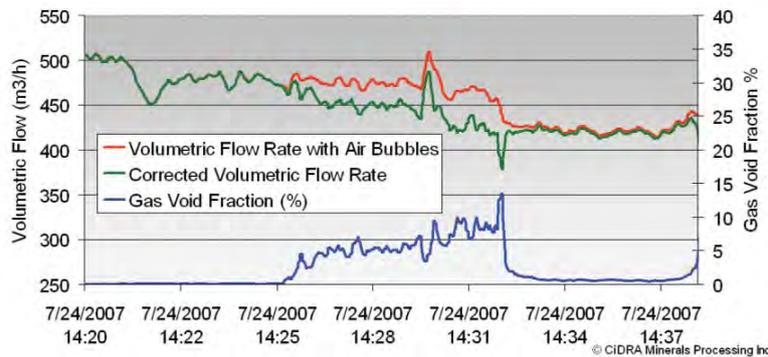


Figure 11. Detection of entrained air bubbles and compensation of flow measurement

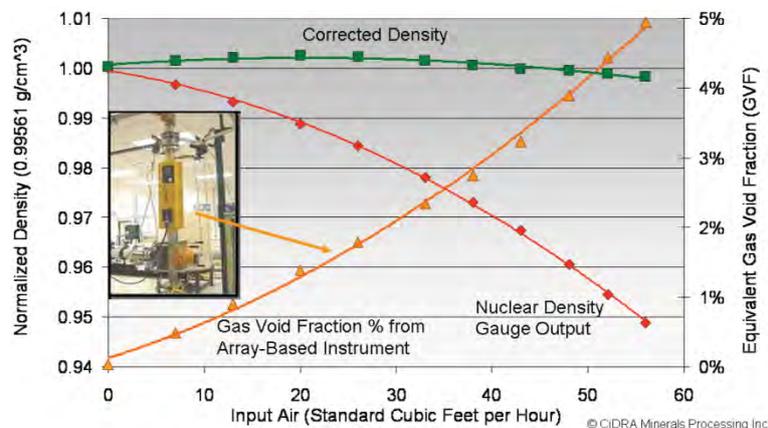


Figure 12. Nuclear density gauge correction using array-based meter

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%.

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 13 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.

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 build-up, in high wear rate or corrosive environments, and in the presence of ferromagnetic slurries. Its accuracy is $\pm 1\%$ in the field but it does require a minimum flow velocity of 0.9 m/s. Its measurement of flow velocity does not drift with time or temperature, allowing for long-term control of processes without adjustment. The use of its entrained air (gas void fraction) measurement has been used to correct both volumetric flow measurements and density measurements of slurries with entrained air bubbles, thus leading to accurate mass flow rate calculations. This technology is currently being used in over 700 minerals processing flow monitoring applications within 22 countries.

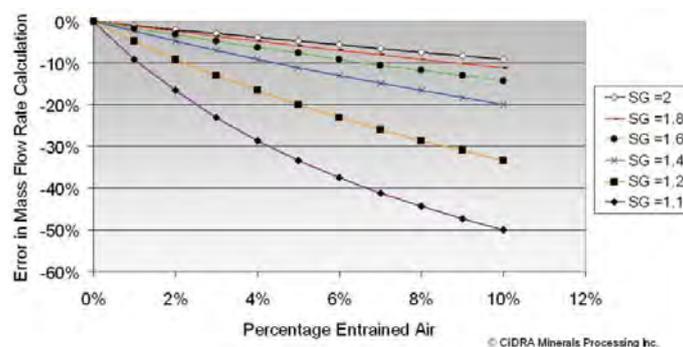


Figure 13. Error introduced by entrained air in mass flow rate calculations as a function of slurry relative specific gravity (SG)