O'KEEFE, C.V., MARON, R., FELIX, J., VAN DER SPEK, A.M., and ROTHMAN, P. Non-invasive passive array technology for improved flow measurements of slurries and entrained air. *The 4th International Platinum Conference, Platinum in transition 'Boom or Bust'*, The Southern African Institute of Mining and Metallurgy, 2010.

Non-invasive passive array technology for improved flow measurements of slurries and entrained air

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Efficient operation of a platinum minerals processing facility requires accurate measurements of critical process parameters such as flow and density. In many cases, the accuracy and noise characteristics of older flowmeter technologies such as ultrasonic Doppler, electromagnetic or Coriolis flowmeters is inadequate for monitoring, control and process improvement purposes. The latest generation of flowmeters, based an array of sensors externally mounted to a pipe, has demonstrated superior noise performance and accuracy relative to other flowmeter technologies. In addition, entrained air bubbles in slurry streams can lead to significant inaccuracies in density measurements thus leading to appreciable offsets in mass balance calculations. Besides measuring flow from the outside of the pipe, the array based technology has demonstrated the ability to measure the volume of entrained air bubbles in a slurry stream. This information has been used to compensate the density measurement from a nuclear density gauge thus enabling the accurate calculation of true mass flow rates. The principle of operation of this technology, the use of both flow and entrained air measurements to determine true mass flow rates, will be detailed. Case studies of applying this technology to minerals processing operations including platinum facilities will be discussed.

Introduction

Accurate, robust measurement of true volumetric flow is necessary for many critical areas of minerals processing. These areas include leak detection in tailings lines or pipelines, control of cyclones, flotation circuit loading, mass balancing, metallurgical accounting, and other aspects of process monitoring and control. Using traditional flowmeter technology such as electromagnetic, ultrasonic Doppler, differential pressure or Coriolis flowmeters to obtain a true flow measurement has proven to be a challenging endeavour for process control engineers 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, calibration drift, 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 whereby process control strategies may be improved and maintenance cost may be reduced by applying this technology. This technology was invented a decade ago for the oil and gas industry, and has experienced high adoption rates in minerals processing over the last five years.

Principle of operation

Array-based flowmeters operate by using an array of sensors and passive sonar processing algorithms to detect, track, and measure the mean velocities of coherent disturbances travelling in the axial direction of a pipe. These disturbances are grouped into three major categories: disturbances conveyed by the flow, acoustic waves in the fluid, and vibrations transmitted via the pipe walls. Each disturbance class travels at a given velocity. For example, the flow will convey disturbances such as turbulent eddies, density variations, or other fluid characteristics at the rate of the fluid flow. 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, travels at velocities that are several times greater than the acoustic waves.

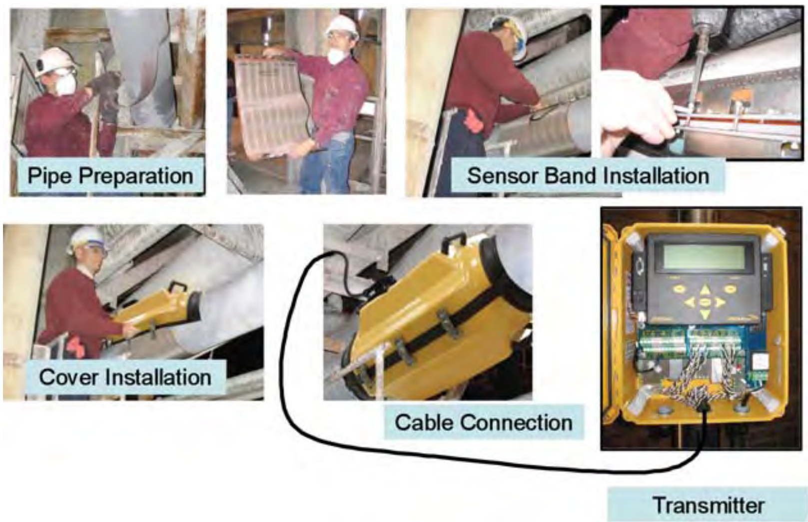

Figure 1. Installation procedure from: (top-left) pipe preparation through cleaning and light sanding of pipe; to (top-middle and top-right) mounting of the flexible, lightweight sensor band to (bottom-left) installation of the sensor cover; and to (bottom-middle and bottom-right) connection of sensor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

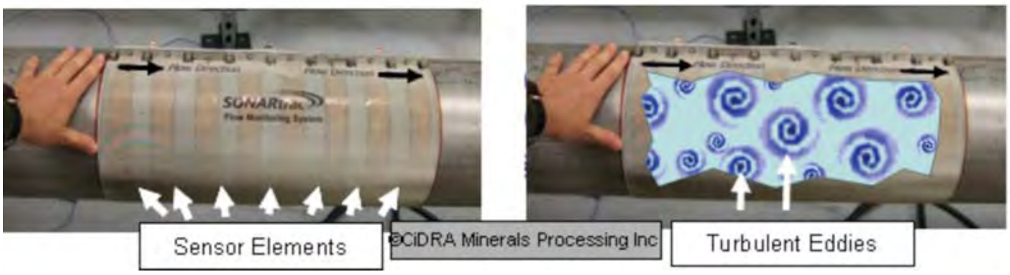

Figure 2. (Left) Passive sensor band wrapped around pipe. (Right) Interior pipe view with illustrated turbulent eddies

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 without requiring torque wrenches or screwdrivers. Third, a protective cover containing signal conditioning and diagnostics electronics is installed over the sensor band, and the sensor band is connected to these electronics. Fourth, a cable from the sensor head to the transmitter is connected. Fifth, the easy to use front panel menu on the transmitter is used to configure the transmitter.

Velocity measurement of turbulent flow

Flow velocity may be determined by focusing on the disturbances that are conveyed by the flow. These disturbances can be density variations, temperature variations, turbulent eddies, or others. 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. The overall mean velocity of the disturbances is equal to the flow velocity. These eddies are 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 for the largest vortices and by viscous forces for the smallest vortices. 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 in turbulent flow or density variations in paste type core annular flow is obtained. The sequence of events that occur to make this measurement possible is as follows:

- The passage of the turbulent eddies or paste induced density variations creates a small pressure change on the inside of the pipe wall.

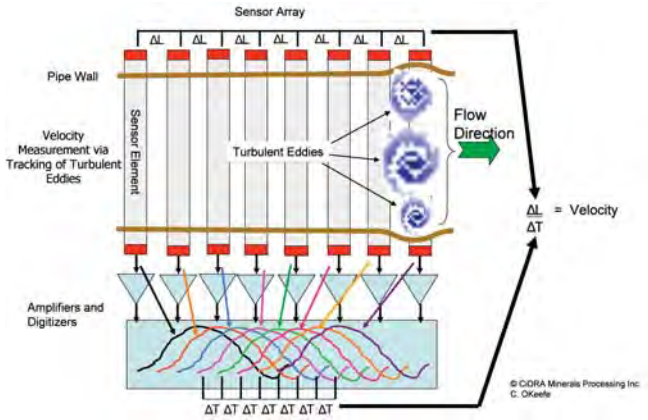

Figure 3. Illustration of strain induced in pipe walls caused by passing turbulent eddies, resulting in similar signals detected by sensor elements with time or phase differences, leading to velocity measurement

- 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 ± 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 in turbulent flow or density variations in paste type core annular flow 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. Like most other flowmeters, 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 m^3/h.

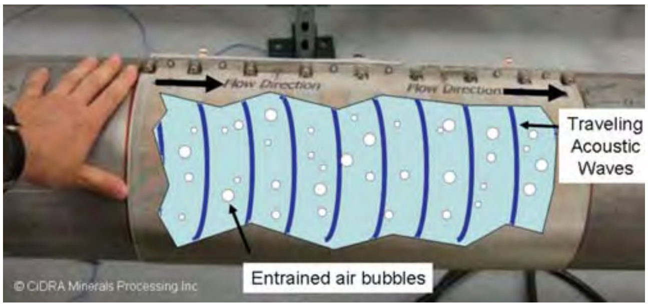

Figure 4. Illustration of naturally occurring acoustic waves propagating in pipe under the array of sensors

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 and the density of the slurry mixture. Both the compressibility and the density are influenced by air content, thus the speed of sound is heavily influenced by the air content. An example of the resulting

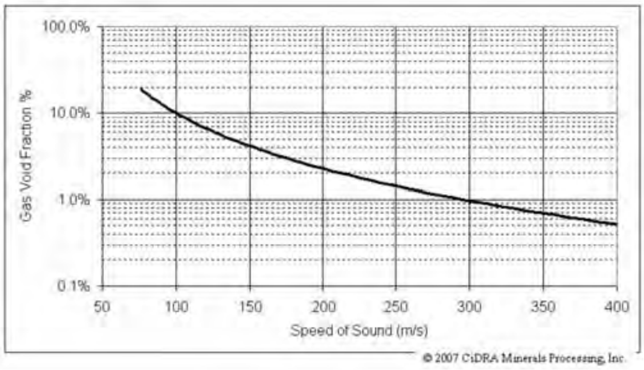

Figure 5. Example of relationship between gas void fraction (entrained air bubbles) and speed of sound

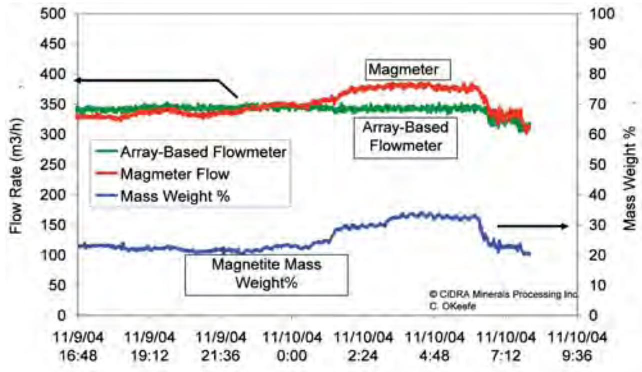

Figure 6. Electromagnetic flowmeter erroneously responds to magnetite while array flowmeter accurately reports flow

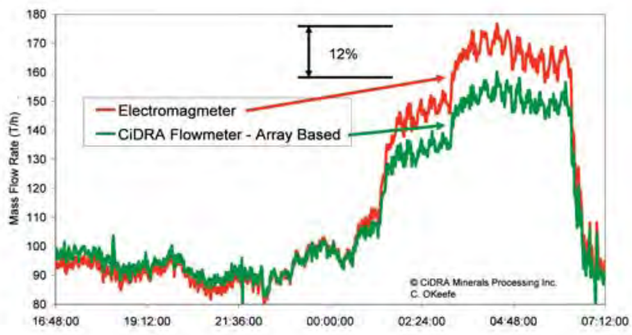

Figure 7. Impact of ferromagnetic slurry on mass flow rate, showing overreporting by electromagnetic based flowmeter versus array based flowmeter

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 ± 5% of the reading, thus the maximum absolute error is ± 1%.

Use of array-based flowmeters

Each flowmeter technology has a sphere of applications in which it provides clear value to the customer. For the 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 requiring high measurement accuracy; 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 applications will be discussed here.

Impact of magnetic ore or magnetic dense medium on traditional flow measurements: case study

Magnetic ore or magnetic dense medium such as pyrrhotite, magnetite or ferrosilicon found 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 companies mining copper, gold or other non-ferrous metals have magnetic ore in or near their ore body. The magnetic slurry, even in small quantities, creates both short-term and long-term changes in the outputs of electromagnetic flowmeters. 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 causing 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 causing an 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 provided mixed results. Many times the calibration or offset changes depending on the quantity of magnetite present.

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 overreporting in mass flow rate is directly proportional to the overreporting of flow rate by the electromagnetic based flowmeter, as seen in Figure 7.

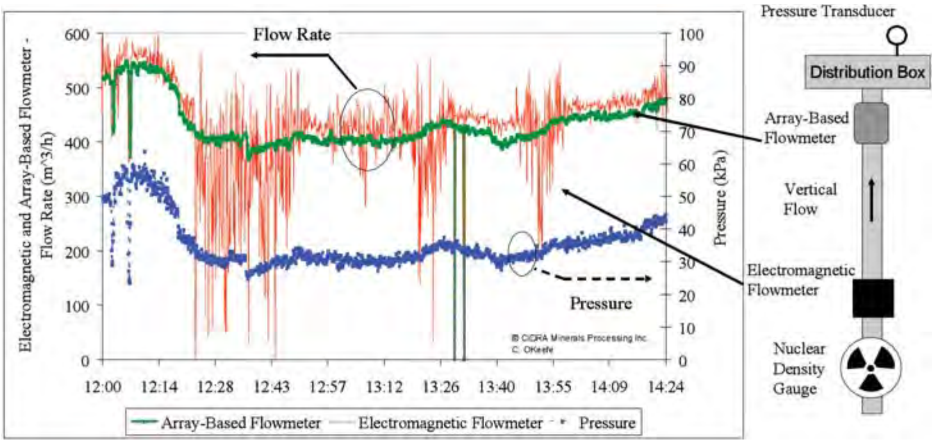

Figure 8. Comparison of readings from array-based flowmeter (top trace with low noise); electromagnetic flowmeter (top trace with high noise); and pressure transducer (bottom trace)

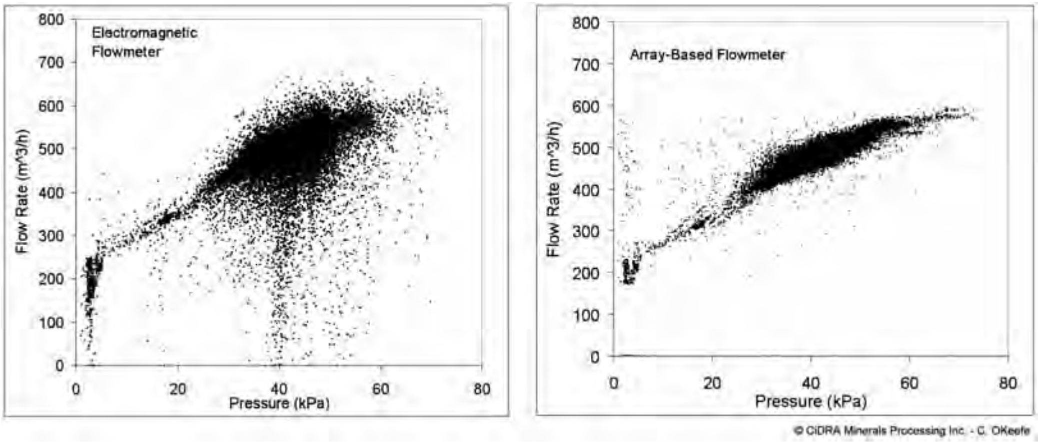

Figure 9. (Left) Cross-plot of electromagnetic flowmeter readings versus pressure. (Right) Cross-plot of array-based flowmeter readings versus pressure

Platinum plant case study: feed to hydrocyclone battery and screen: comparison of array-based flowmeter and electromagnetic flowmeter vs. 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 300 mm polyethylene pipe as illustrated in the right side of Figure 8. 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.

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 9. 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 9. After application of heavy filtering (120 second first order filter) to the electromagnetic flowmeter output data, an overall trend relative to the readings from the pressure transducer and array-based flowmeters can be seen in Figure 10. The electromagnetic exhibits a poor correlation to the pressure readings. In contrast, the array-based flowmeter exhibits excellent agreement with the pressure reading.

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, previous generations of flowmeter technologies do not have the ability to compensate for the air content. The array based technology can accurately measure flow

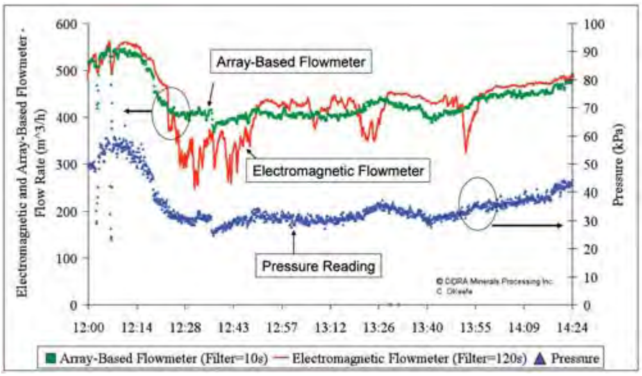

Figure 10. Comparison of readings from array-based flowmeter (green top trace) and pressure readings (bottom trace) along with filtered reading from electromagnetic flowmeter (red top trace with first order filter of 120 seconds applied to electromagnetic flowmeter and first order filter of 10 seconds applied to array-based flowmeter)

rates in the presence of air bubbles while quantitatively determining the amount of entrained air.

Entrained air bubbles can come about from a myriad of sources including low sump levels, comminution processes, pump leaks, flotation cells or tanks, 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 red trace at the top of the figure is a measurement of the mixture volumetric flow rate. The blue trace at the bottom of the figure 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 green trace between the other two traces is the true volumetric flow rate of the slurry as calculated from the total volumetric flow (red trace) and the gas void fraction (blue trace) via a simple linear correction (Equation [1]).

[1]

where: $Q_{corrected}$ = Corrected volumetric flow rate
$Q_{uncorrected}$ = Uncorrected volumetric flow rate (from a volumetric flowmeter)
φ_{gas} = phase fraction of gas (percentage of entrained air, GVF, or gas void fraction)

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. The equation used to correct the density in order to obtain the density of only the solids/liquid mixture is given by:

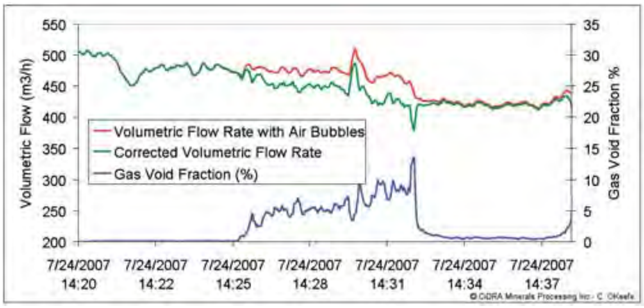

Figure 11. Detection of entrained air bubbles (bottom trace) and compensation of flow measurement. Uncorrected flow (top trace) and corrected flow (middle trace)

[2]

where: ρ_m = density of mixture (as measured by nuclear density gauge)
ρ_{SL} = density of slurry without air (solids/liquid mixture)
ϕ_G = percentage of volume occupied by air (gas void fraction)

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 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%.

Mass flow correction: platinum plant case—flotation overflow to recleaner

Flotation is a commonly used process to concentrate ore containing metals and minerals such as platinum for smelting or leaching. Within a flotation circuit air is introduced and chemicals are used to create small, stable air bubbles. These are necessary for efficient flotation separation of metals and minerals, but they create measurement problems with most flow instruments and

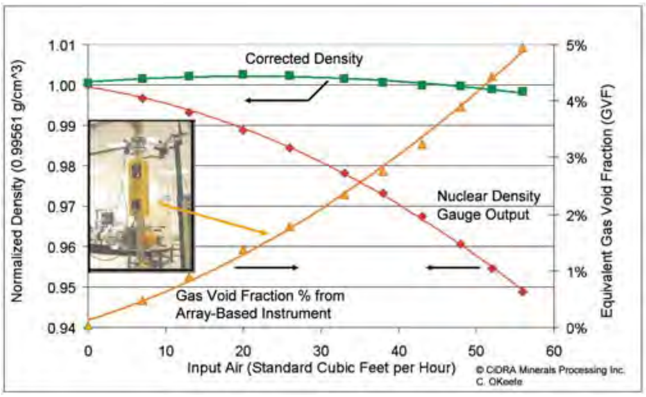

Figure 12. Nuclear density gauge correction using array-based meter

with density gauges. As a minimum, the volumetric flow rate of the solids and liquid components of the slurry will be over reported while the slurry density and the weight fraction of the solids portion will be under reported as outlined in the previous sections. When these three values are used to calculate mass flow rate, the errors from the entrained air partially cancel but a large residual error is still present. This residual error increases with decreasing specific gravity of the solids, liquid and entrained air slurry mixture.

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. As the relative specific gravity approaches one, the resulting mass flow calculation error will increase in the presence of entrained air. The simplified equation for this error is given by:

[3]

where: ρ_m = density of the slurry with entrained air (as measured by density gauge)
ρ_L = density of the carrier liquid (usually water so $\rho_L \approx$ 1 000 kg/m^3 but can be higher for brines and dense mediums)
SG_m = relative specific gravity (ρ_m/ρ_L)
ϕ_G = percentage of volume occupied by air (gas void fraction

As an example, in Figure 13 calculations of the errors in the mass flow rate as a function of the relative specific gravity and percentage of entrained air or gas volume fraction are seen.

At a platinum concentrator, the array-based instrument was installed on the output of a pump that was transferring concentrate from within the flotation circuit to the cleaner portion. The slurry was de-aerated in the sump leading to the pump, thus the entrained air levels were lower than typically seen within flotation circuit transfer lines. During a 20 day test period, the gas void fraction ranged from 0% to 1.8% (excluding any spurious spikes in the data) with an average value of 0.76%. Nonetheless, the slurry was fairly dilute with an average specific gravity of 1.083 over the test period. The density typically varied from 1.083 to 1.091 with some spikes extending to 1.135% and some excursions

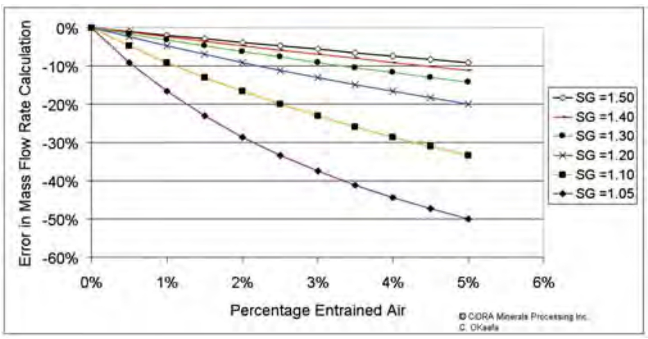

Figure 13. Error introduced by entrained air in mass flow rate calculations as a function of slurry relative specific gravity (SG)

to 1.0. The relatively small variations in entrained air content were of insufficient magnitude to greatly impact the density but due to the low mixture density, these variations were sufficient to significantly affect the solids mass flow rate calculations. A one-day subset of the density and the gas void fraction data are shown in Figure 14, in which, excluding the spike in both density and gas void fraction, the density varied typically from 1.085 to 1.09 and the gas void fraction from 0.21% to 0.98%.

When the raw density data were used to calculate the weight fraction of solids in this one-day data-set, the weight fraction varied from 11.2% to 13.1% with an average of 11.5%. This was termed the uncorrected weight fraction and is shown by the red line in Figure 15. By applying the gas void fraction measurement to the density data before calculating the solids weight fraction, the corrected weight fraction is calculated as shown by the green line. The corrected weight fraction increased to an average of 12.3%, an increase of 7% in solids weight fraction. When the same analysis was applied to the entire 20-day data-set, the differences between the corrected weight fraction and the uncorrected weight fraction was 10.1%

The solids mass flow rate such as tons per hour or kg per hour is directly proportional to the product of the weight fraction, density and volumetric flow. Both the corrected and uncorrected solids mass flow rates are shown in Figure 16. The average of the difference in solids mass flow rate

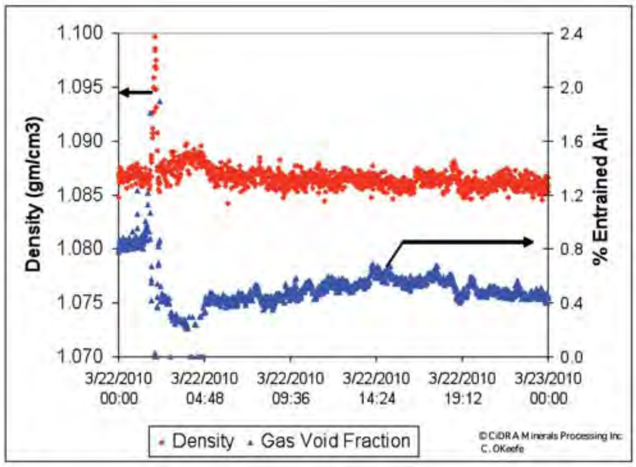

Figure 14. Uncorrected density (top trace) and gas void fraction (bottom trace)—24 hour data-set

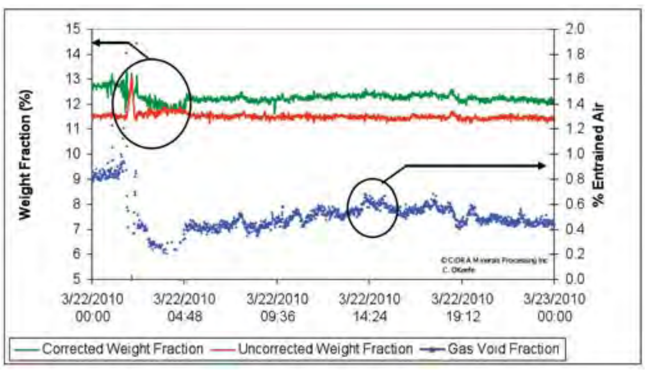

Figure 15. Solids weight fraction corrected (top trace) for entrained air content (Gas void fraction is in bottom trace) and uncorrected weight fraction (middle trace)

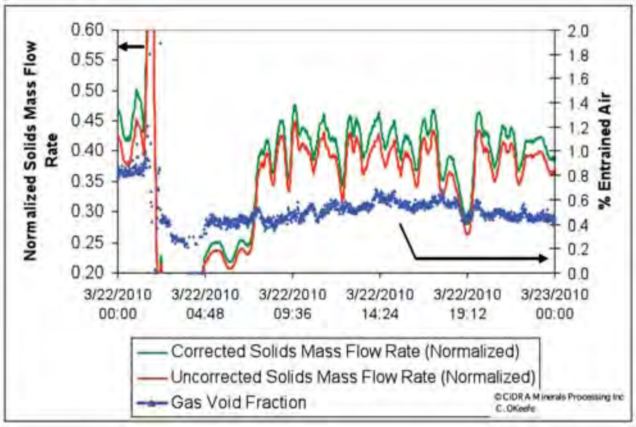

Figure 16. Solids mass flow rate corrected for entrained air impact (top trace) and uncorrected for entrained air (middle trace). Both have been normalized to an arbitrary mass flow rate. Gas void fraction is given by the bottom trace

between the corrected and uncorrected solids mass flow rates for the 20-day test period is the same as for the weight fraction, which is 10.1%.

Performance and condition monitoring of slurry pumps

Monitoring of the performance and condition of critical slurry handling equipment in the mining industry, over extended periods of time, has been limited by the reliability of instrumentation. Techniques such as real-time pump curve monitoring, commonly applied in other industries such as power generation, have rarely been used in mining, in part due to limitations of flow measurement instrumentation. The introduction of accurate, reliable, non-invasive, array-based sonar flow measurement, combined with existing plant instrumentation, now makes it possible to produce non-dimensional pump (head vs. flow) and efficiency (efficiency vs. flow) curves that can be used to monitor performance and condition of centrifugal slurry pumps over extended time periods. During the course of this test, the invasive electromagnetic flowmeter did not exhibit the proper accuracy nor repeatability for this analysis as seen on the left hand side of Figure 17, whereas

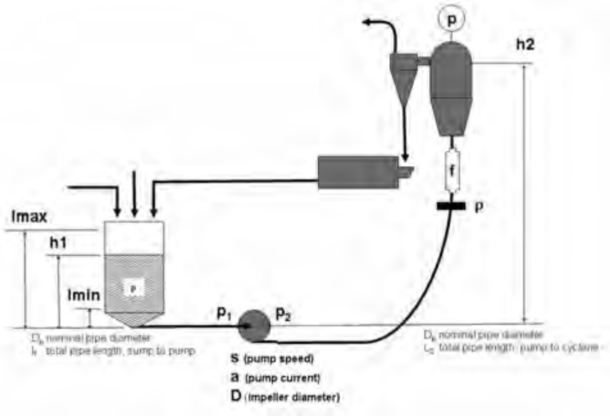

Figure 18. Measurements required to calculate pump performance

the array-based flowmeter exhibited the required accuracy and low noise as seen on the right hand side of Figure 17. The technique can be used with any flow measurement instrument; however, an essential requirement for long-term monitoring is instrument repeatability and reliability which is difficult to obtain with invasive flow measurement instruments used in severe duty, abrasive slurry flows. The methodology and application of this technique over an extended period (248 days) is shown below.

For variable-speed centrifugal slurry pumps, standard plant measurements (e.g. pressure, flow rate, density, pump speed) combined with configuration information (piping sizes, lengths, elevation differences) as shown in Figure 18 can be used to obtain a non-dimensional pump curve (non-dimensional head vs. non-dimensional flow). In the pump industry, the data for non-dimensional head (CH) vs. non-dimensional flow (CF) is typically fit to a quadratic equation. As a result, the relationship for efficiency vs. non-dimensional flow will be a cubic relationship, which permits analytical determination of the point of maximum efficiency—best efficiency point or BEP.

The methodology involves use of six dimensionless numbers which serve to better represent important pump metrics, and permit the use of data from variable speed

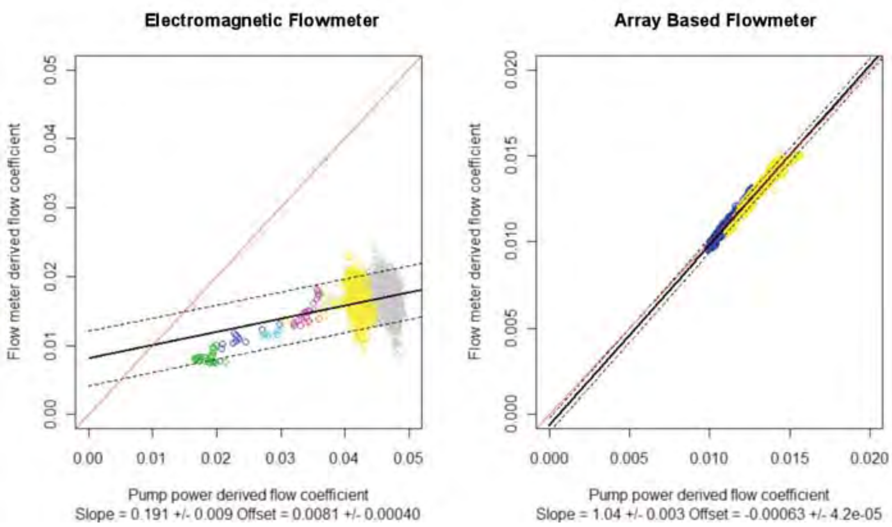

Figure 17. Flowmeter coefficient versus pump power coefficient for electromagnetic flowmeter and array-based flowmeter

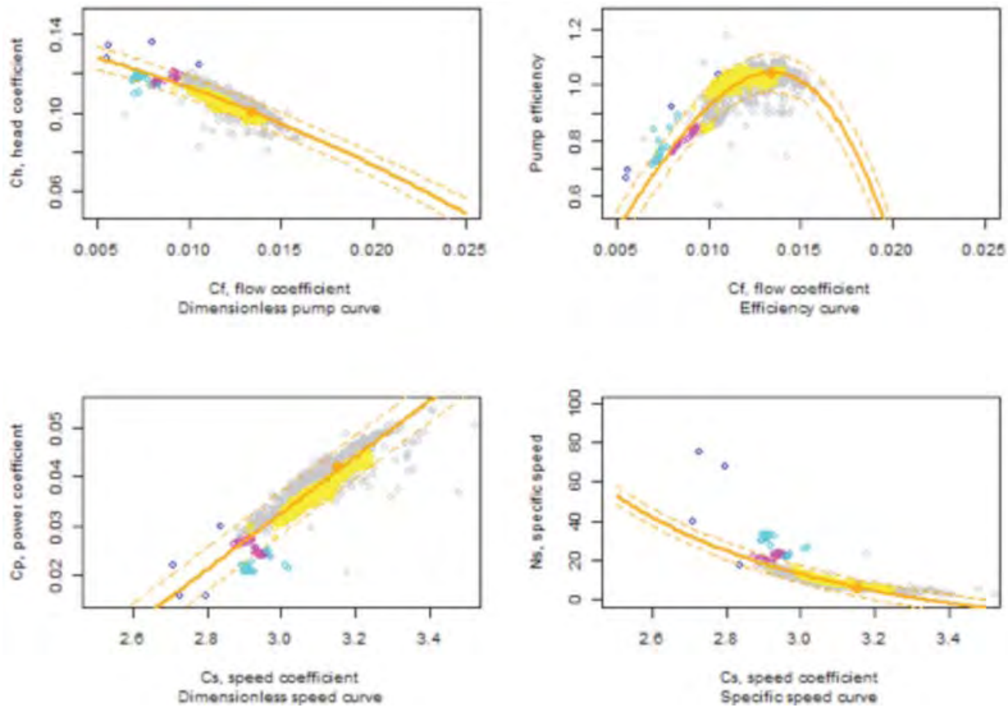

Figure 19. Pump performance curves

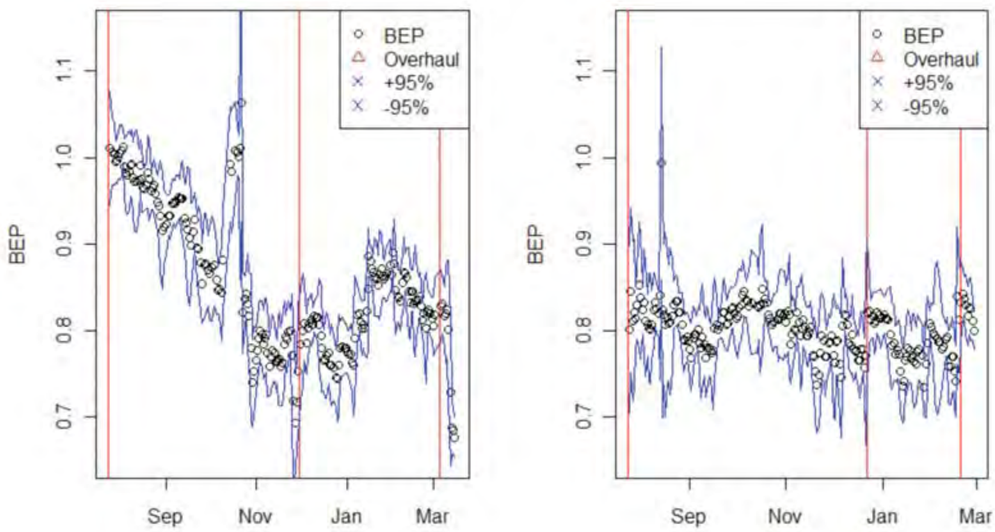

Figure 20. Best efficiency point (BEP) of two pumps as a function of time (includes effects of wear, damage, adjustments and repairs)

pumps. A detailed description of these and all other parameters required, as well as the methodology, can be found in a previous work by the authors. The method is straightforward in theory but in practice it requires detailed attention to data quality. The data-set of 248 days was initially filtered to remove obvious erroneous points (failed sensors, shutdowns, etc). The data-set is broken up in periods of one day. Data from two days is cross-plotted and fit to standard relationships with 95% prediction intervals, forming a four-plot as shown in Figure 19 which presents different views of pump performance, each with its own merit. The BEP is determined from the upper right graph and plotted as a single point on all four graphs. Good data consistency is determined when the BEP point obtained from the upper right graph (black dots) falls on the fitted line in the other three graphs. This cross-plotting is repeated for each pair of days, moving forward in time by one day. Thus the BEP is an average over 2 days.

The result of this analysis for two cyclone batteries is shown in Figure 20, where BEP vs. time is plotted. Vertical dashed lines represent pump maintenance times, and grey lines represent evolution of the 95% prediction interval on the value of BEP. Battery A clearly shows an initial decreasing trend in BHP, whereas Battery B shows no clear trend and relatively lower efficiency. Historical pump maintenance data was not complete, leading to uncertainty in interpretation of results. This represents the first known application of this technique to plant data.

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 ± 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 weight fraction and solids mass flow rate calculations. This technology is currently being used in over 1 000 minerals processing flow monitoring applications within 25 countries.

Acknowledgements

We would like to thank Mototolo JV, Anglo Platinum, and others for their help in applying this technology, acquiring data, and assisting with data analysis.

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