Application of Non-Invasive Passive Array Technology for Entrained Air and Flow Measurements along with Mass Balance Calculations at Mineral Processing Facilities

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ABSTRACT
Efficient operation of each key process stage in minerals processing facility requires accurate information of process production rate. That information is based on measurement of flow and density. In many cases, the accuracy and noise characteristics of older flowmeter technologies such as ultrasonic, electromagnetic or Coriolis flowmeters is inadequate for monitoring, control and process improvement purposes. The latest generation of flowmeters, based on arrays 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 will be discussed.
Keywords: measurement, flow, entrained air, slurries, mineral processes, optimization

Introduction

Accurate, robust measurement of true volumetric flow is necessary for optimal run of each critical stage in 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 over a decade ago for the oil and gas industry, and has experienced high adoption rates in minerals processing over the last eight years.

1. 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 traveling 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 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 1500 m/s. The third group, pipe vibrations, travels at velocities that are several times greater than the acoustic waves. Based on different propagation velocities each disturbance class may be clearly identified by it velocity and accurately measured.

1.1 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 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.

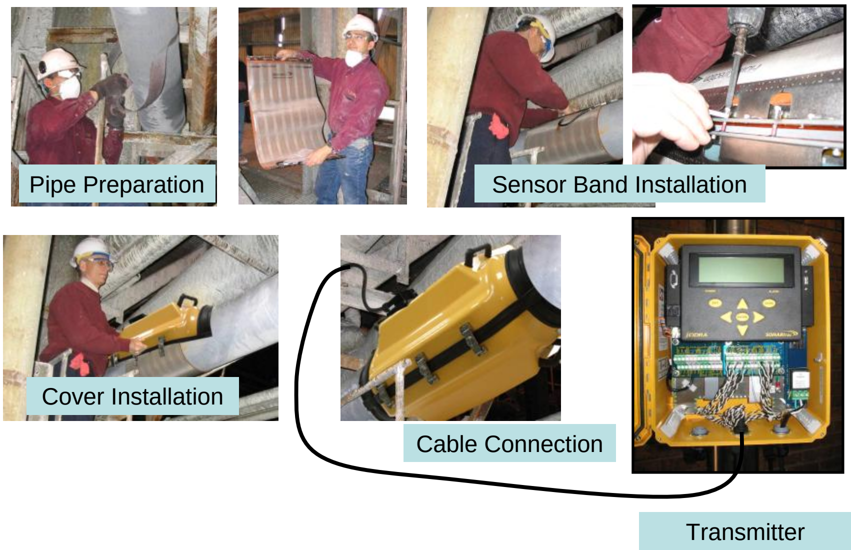

Figure 1 - Installation procedure from (top-left) pipe preparation through cleaning and light sanding of pipe to (top-middle and top-right) mounting of the flexible, lightweight sensor band to (bottom-left) installation of the sensor cover and to (bottom-middle and bottom-right) connection of sensor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

1.2 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 and 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. 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

- The mechanical dynamic strain signal is converted to an electrical signal through a passive sensor wrapped 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. To reach that accuracy the flow rate in most cases should be 0.9 m/s to ensure turbulent flow model. With slower flows the accuracy can be affected by the changes in the flow model with slow flow velocities.

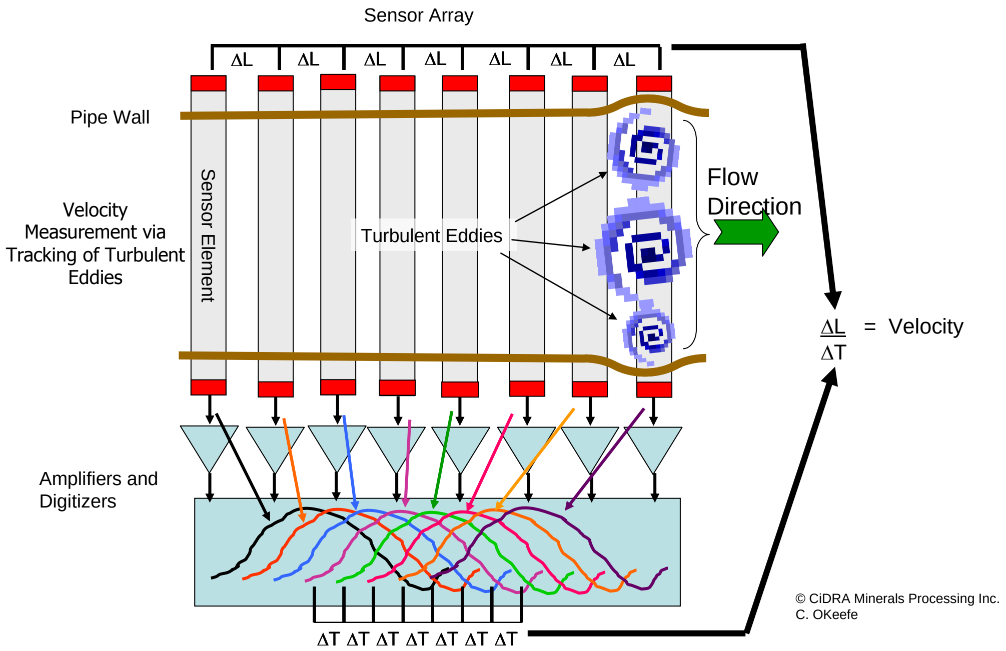

Figure 2 - Illustration of strain induced in pipe walls by passing turbulent eddies, resulting in similar signals detected by sensor elements with time or phase differences, leading to velocity measurement

The 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. 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 m3/h.

1.3 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. 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 in the audible frequency 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 3. The acoustic waves can propagate in either direction down the pipe or in both directions.

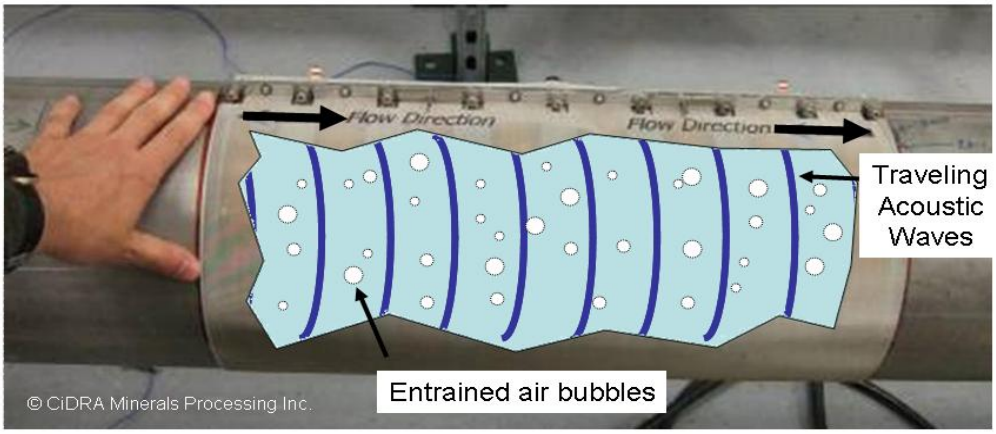

Figure 3 - Illustration of naturally occurring acoustic waves propagating in pipe under the array of sensors

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 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 3, 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 4. 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.

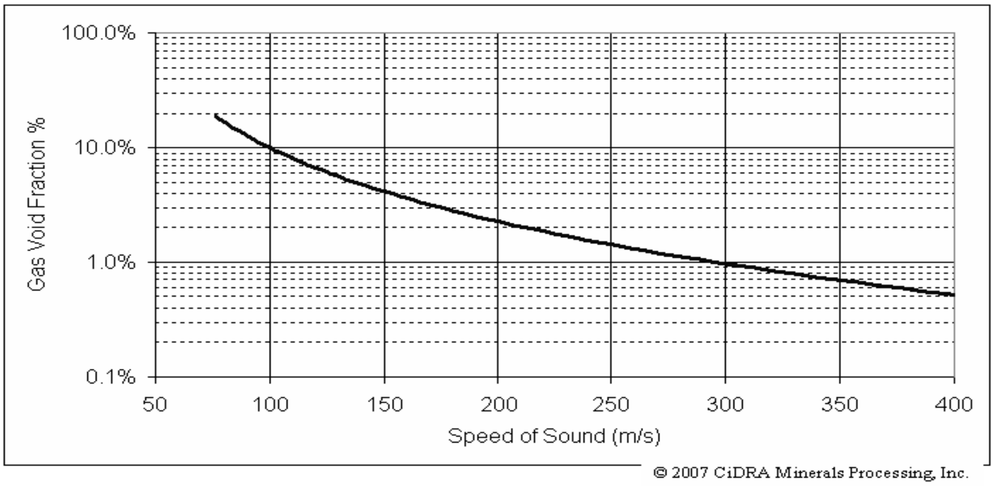

Figure 4 - Example of relationship between gas void fraction (entrained air bubbles) and speed of sound

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, thus the maximum absolute error is +/- 1%.

2. Operational Use of Array-Based Flowmeters

Passive array based flowmeters the most beneficial 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 human or environmental safety issue.

2.1 Impact of Magnetic Ore or Medium on Traditional Flow Measurements: Case Study

Magnetic ore or medium such as pyrrhotite, magnetite or ferrosilicon in a slurry line, 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 ore body. 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 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.

A more robust solution is to use a flowmeter technology that is not impacted by the presence of magnetic ore. A passive array based flowmeter is totally impervious to the effects of magnetic ore. An example of this is illustrated in Figure 5 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.

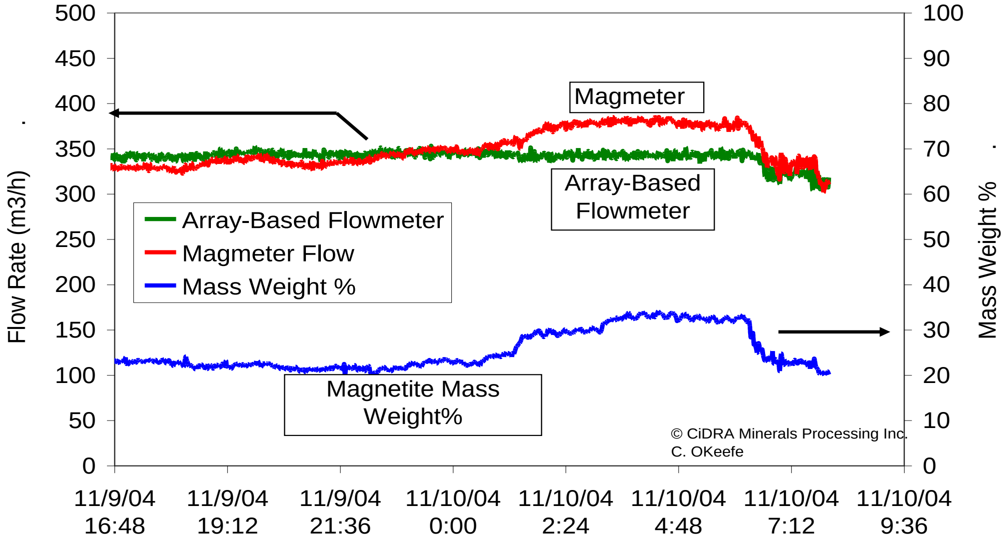

Figure 5 - Electromagnetic flowmeter erroneously respond to magnetite while array flowmeter accurately reports flow

2.2 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. The traditional flowmeter technologies cannot perform an accurate flow measurement in the presence of air bubbles and 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 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 6. In this figure, the red trace is the volumetric flow of all three phases (solid, liquid, and gas bubbles) measured on a concentrate line at a copper/gold/molybdenum concentrator. The blue trace at the bottom of the graph is the 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).

$$Q_{corrected} = Q_{uncorrected}(1-\phi_{gas})$$

Where: $Q_{corrected}$=Corrected volumetric flow rate (1)

$Q_{uncorrected}$=Uncorrected volumetric flow rate (from a volumetric flow meter)

φ_{gas} = phase fraction of gas (percentage of entrained air, GVF, or Gas Void Fraction)

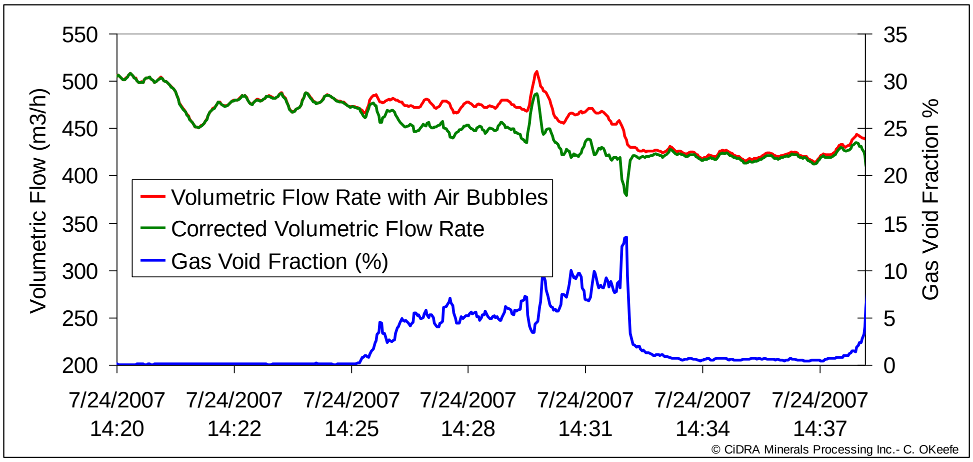

Figure 6 - Detection of entrained air bubbles and compensation of flow measurement

2.3 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:

$$\rho_{SL} = \frac{\rho_m}{(1-\phi_G)}$$

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Where: ρm=density of mixture (as measured by nuclear density gauge)
ρSL=density of slurry without air (solids/liquid mixture)
φG= percentage of volume occupied by air (Gas Void Fraction)

2.4 Mass Flow Correction: Case - Flotation Overflow to Recleaner

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

$$\text{Error} = \frac{-\phi_G}{\frac{\rho_m}{\rho_L} - 1 + \phi_G} = \frac{-\phi_G}{SG_m - 1 + \phi_G}$$

Where: ρm = density of the slurry with entrained air (as measured by density gauge)
ρL = density of the carrier liquid (usually water so ρL ≈ 1000 kg/m3 but can be higher for brines and dense mediums)
SGm = relative specific gravity (ρm/ ρL)
φG= percentage of volume occupied by air (Gas Void Fraction

As an example, in Figure 7 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.

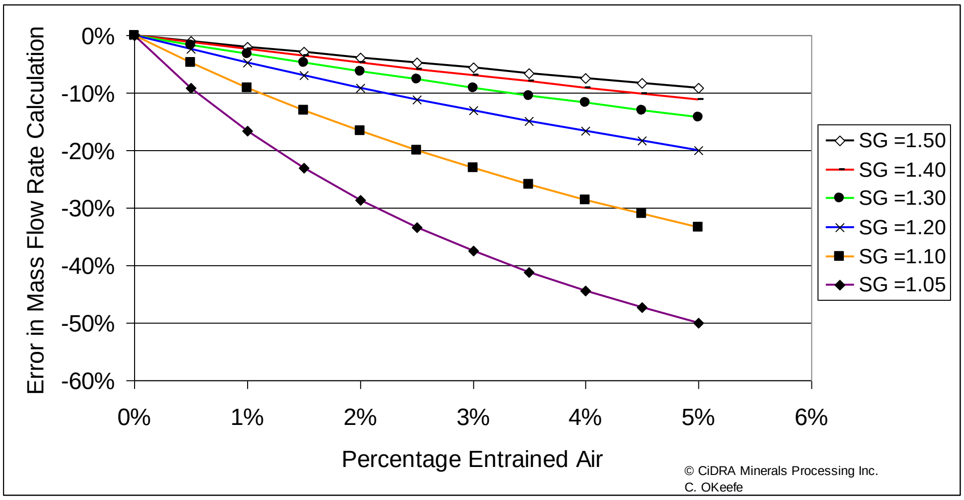

Figure 7 - Error introduced by entrained air in mass flow rate calculations as a function of slurry relative specific gravity (SG)

At this 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 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 impact the solids mass flow rate calculations. A one day subset of the density and the gas void fraction data are shown in Figure 8, 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%.

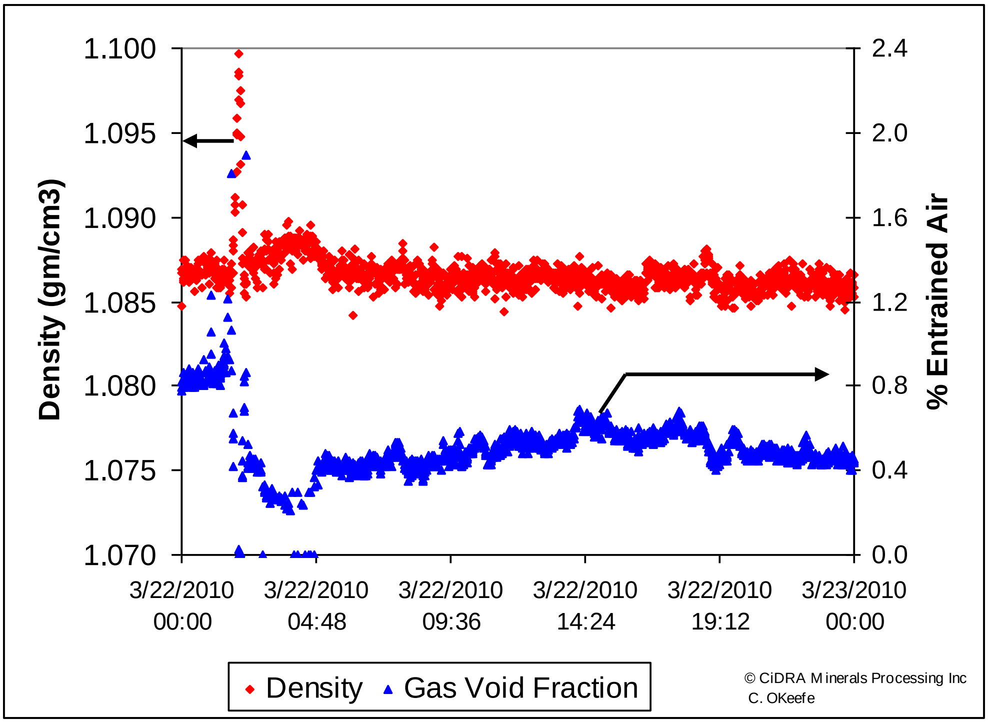

Figure 8 - Uncorrected density and Gas Void Fraction - 24 hour data set

When the raw density data was 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 9. 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%

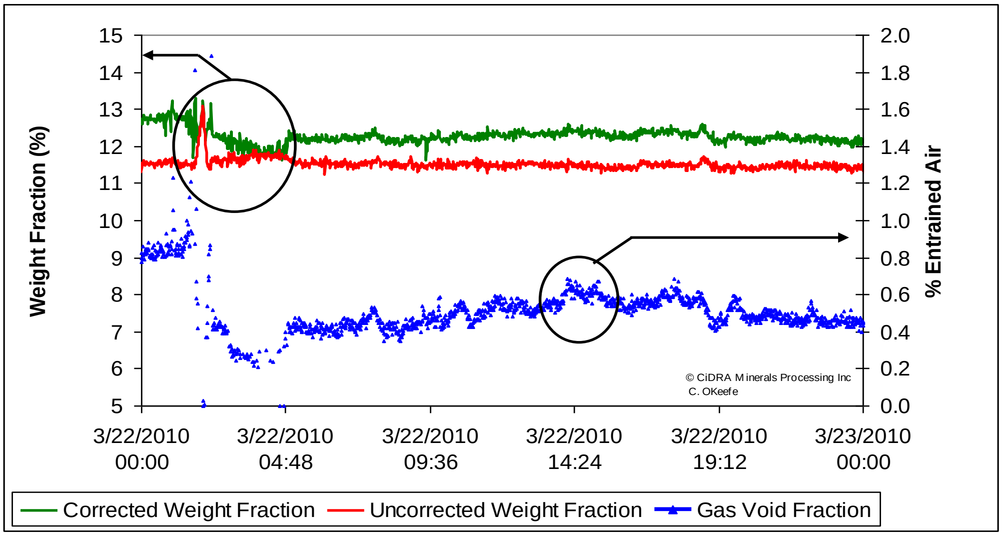

Figure 9 - Solids weight fraction corrected for entrained air content (Gas Void Fraction) and uncorrected weight fraction

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 10

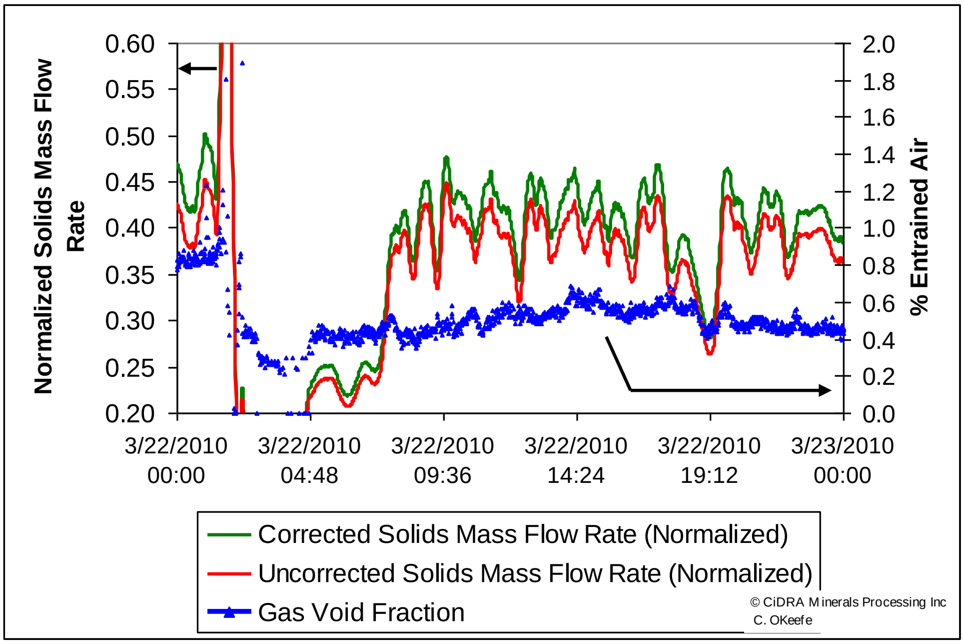

Figure 10 - Solids mass flow rate corrected for entrained air impact (green line) and uncorrected for entrained air (red line). Both have been normalized to an arbitrary mass flow rate.

The average of the difference in solids mass flow rate 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%.

A comparison between magnetic and array based flowmeters installed on same line was done. If production conditions stay relatively stable we can expect that pump power intake would correlate with the variations of actual flow rate. Figure 11 shows the result of comparison of flow meter factor derived from pump power to meter factors derived from electromagnetic flowmeter and array based flow meter. We see that the slope of array based factor comparison is very close to the ideal slope of 1.

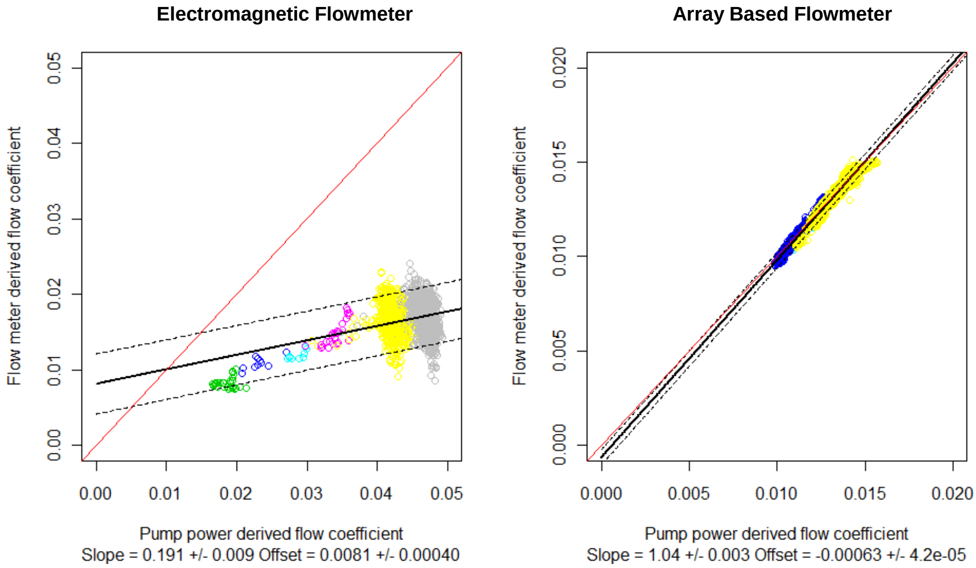

Figure 11 - Flowmeter coefficient versus pump power coefficient for electromagnetic flowmeter and array-based flowmeter

3. 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. 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. This enables the process optimization on stable production control basis throughout the process lifetime. 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 hundreds of minerals processing facilities all over the world.

4. Acknowledgements

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5. References

VAN DER SPEK A.M., MARON R.J., O'KEEFE C.V., and ROTHMAN P.J., Use Of Sonar Flow Measurement for Performance and Condition Monitoring of Slurry Pumps, *MAPLA* 2009, Antofagasta, Chile