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The impact of entrained air and enhanced flow measurements at Eland Platinum concentrator

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Abstract

Volumetric flow and mass flow are two of the critical process parameters needed to understand and control flotation processes, with others being levels, densities, and metal analyses. Both volumetric flow and density measurements can be adversely influenced by entrained air, which will result in artificially high flow readings and artificially low mass flow calculations. Array-based instrumentation has been used successfully to accurately measure both volumetric flow of aerated slurry and the quantity of air entrained within the slurry. The latter measurement has been used to correct density measurements, thus providing an accurate mass flow calculation. A case study involving the use of this technology to measure both flow rates and air entrainment levels at Eland Platinum processing facility (concentrator) will be covered in detail. In addition, with certain traditional flow meters such as electromagnetic meters, erroneous volumetric flow rates can be recorded in the presence of paramagnetic or ferromagnetic material. The use of this array technology to avoid spikes in measurements due to steel fragments passing through the pipe will also be discussed.

Introduction

Most concentrators require accurate metal analyses and mass flow calculations to optimize their operations and to provide accurate metal accounting figures. Calculation of mass flow requires accurate measurement of feed tonnage and assays, or accurate measurement of slurry density and flow rates. Both of these latter measurements are susceptible to errors induced by entrained air, which is commonly found within flotation plant slurries. Entrained air can potentially introduce two major errors into flow measurements. Firstly, depending on the measurement technology being used, the overall flow measurement may be subject to significant errors or lapses in reliability. Secondly, the overall flow rate measured will be artificially high due to the additional volume introduced by the entrained air. Conversely, with density measurements, entrained air results in a lower density reading than the actual density

of the non-aerated slurry. Therefore, the resulting mass flow calculation will under-report the true mass flow. Both measurement problems have been overcome by using array-based instrumentation to measure both the volumetric flow and the gas void fraction (that is, the percentage volume of entrained air within the slurry).

Principle of operation

Array-based flow meters 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. A coherent disturbance is one that retains its characteristics for an appreciable distance, which in this case is the length of the array of sensors or longer. These coherent 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 75 m/s and a maximum velocity of 1500 m/s. The third group, pipe vibrations, travel at velocities that are several times greater than the acoustic waves. Thus each disturbance class may be clearly segregated based on its velocity, as seen in Figure 1, allowing its velocity to be accurately measured.

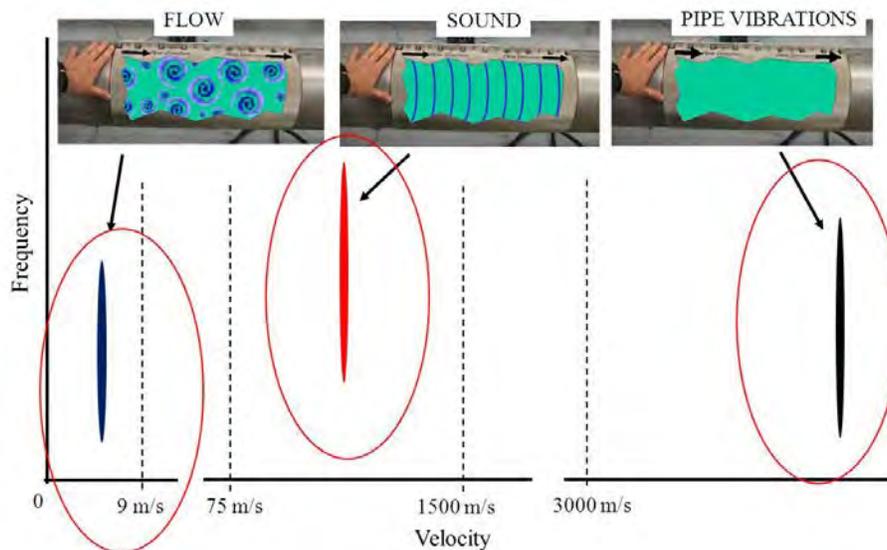


Figure 1. Classes of coherent disturbances conveyed down pipe

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 for pipes that are smaller than 1 m diameter, and equal to the circumference of the pipe in the orthogonal dimension. The typical installation procedure and hardware embodiment is outlined in Figure 2. The pipe is first wiped down and any high points

are sanded or filed away to ensure good mechanical contact. The flexible sensor band is then wrapped around the pipe and a series of captive screws on the sensor band is 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. 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. The cable from the sensor head to the transmitter is installed and wired to the transmitter. Finally, the front panel menu on the transmitter is used to configure the transmitter.



Figure 2. Installation procedure from (top left) pipe preparation through cleaning and light sanding of pipe; (top middle and top right) mounting of the flexible, lightweight sensor band; (bottom left) installation of the sensor cover; and (bottom middle and bottom right) connection of sensor cover to transmitter via watertight cable

Flow velocity measurement

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 other types of disturbance. In 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 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 dynamic pressure change on the inside of the pipe wall
- This small pressure change results in a dynamic strain of the pipe wall itself (exaggerated in Figure 3)
- The mechanical dynamic strain signal is converted into 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 at precisely a 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 disturbance under the sensor
- An array processing algorithm combines the phase and frequency information of the characteristic signature from the group of sensor array elements to calculate the velocity of the characteristic signature as it propagates under the array of sensors. In most applications, a minimum flow rate of 0.9 m/s (3 feet per second) is required to measure the flow velocity.

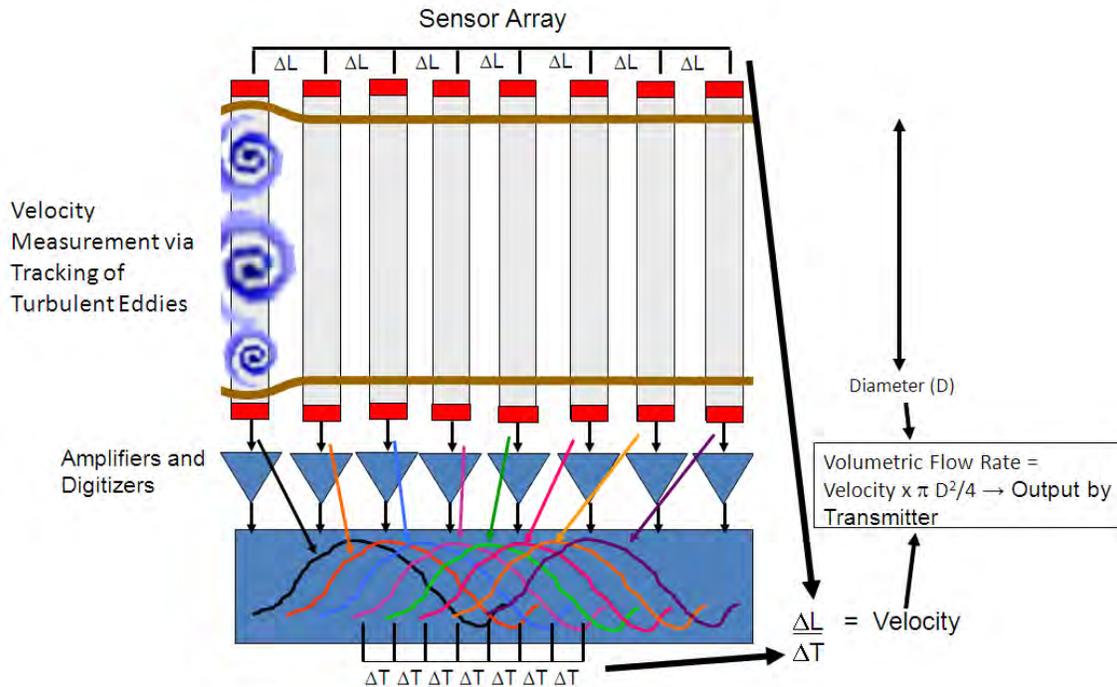


Figure 3. Illustration of strain induced in pipe walls by passing turbulent eddies, resulting in similar signals detected by sensor elements with time or phase differences, leading to velocity measurement

There are many challenges in performing this measurement in an industrial environment. The most difficult is resolving the relatively low-level strain induced by the vortical disturbances from the relatively high-strain noise levels. This noise includes interfering signals from acoustics and vibrations generated from large pumps and valves. The strength of the array processing algorithm is its ability to isolate and measure the velocities of the low-level vortical components within the flow.

These velocity measurements have been demonstrated on many types of pipes with a wide variety of liners. The pipes include steel, PVC, HDPE (polyethylene), and fibreglass. The pipes can be unlined or lined with various materials, including rubber, urethane, cement, basalt, and Teflon. The measurement system is also effective on pipes with scale buildup.

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

The array-based technology may also be used to track acoustic waves travelling in the fluid. In most mineral processing plants there is an abundance of acoustic waves propagating within the process pipes. These waves are generated from a variety of sources including pumps, the flow through pipe geometry changes, and bubbles within the fluid that generate acoustic waves through their natural oscillations. These acoustic waves are low frequency (in the audible range), and travel in the pipe's axial direction, with wavelengths much longer than the entrained gas bubbles.

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 slurry¹. Since the wavelengths of the acoustic waves are much larger than the bubble size, a complex interaction takes place that sets the acoustic velocity to be a strong function of the gas void fraction. The speed of sound is proportional to the square root of the ratio of the compressibility and the density, both of which are heavily influenced by air content. An example of the resulting relationship is shown in Figure 4. The particular values outlined by the curve in this figure are influenced by other factors, particularly pressure. Thus the pressure at the location of the array-based instrument must be measured or calculated. Once the 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.

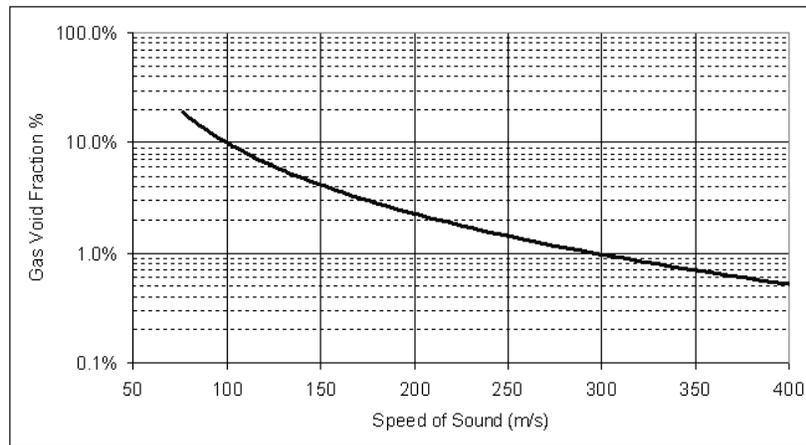


Figure 4. Example of relationship between gas void fraction (entrained air bubbles) and speed of sound

Case studies at Eland Platinum processing facility (concentrator)

Feed to classifier distribution box

Monitoring of feed to classifiers such as screens or hydrocyclones poses certain challenges to traditional flow meters. The presence of larger particles creates conditions for high wear rates on invasive flow meters such as electromagnetic or differential pressure-based flow meters, and these same solids can cause false measurement output spikes in certain flow meters. The passing of paramagnetic or ferromagnetic material such as steel fragments from the mills or magnetite causes spikes in the outputs of electromagnetic flow meters.

An example of these spikes is seen in the comparison of the flow readings given by an electromagnetic flow meter and a passive array-based flow meter installed on the same cyclone cluster feed line. Photographs of the instrumentation configuration and data available for analysis are shown in Figure 5.

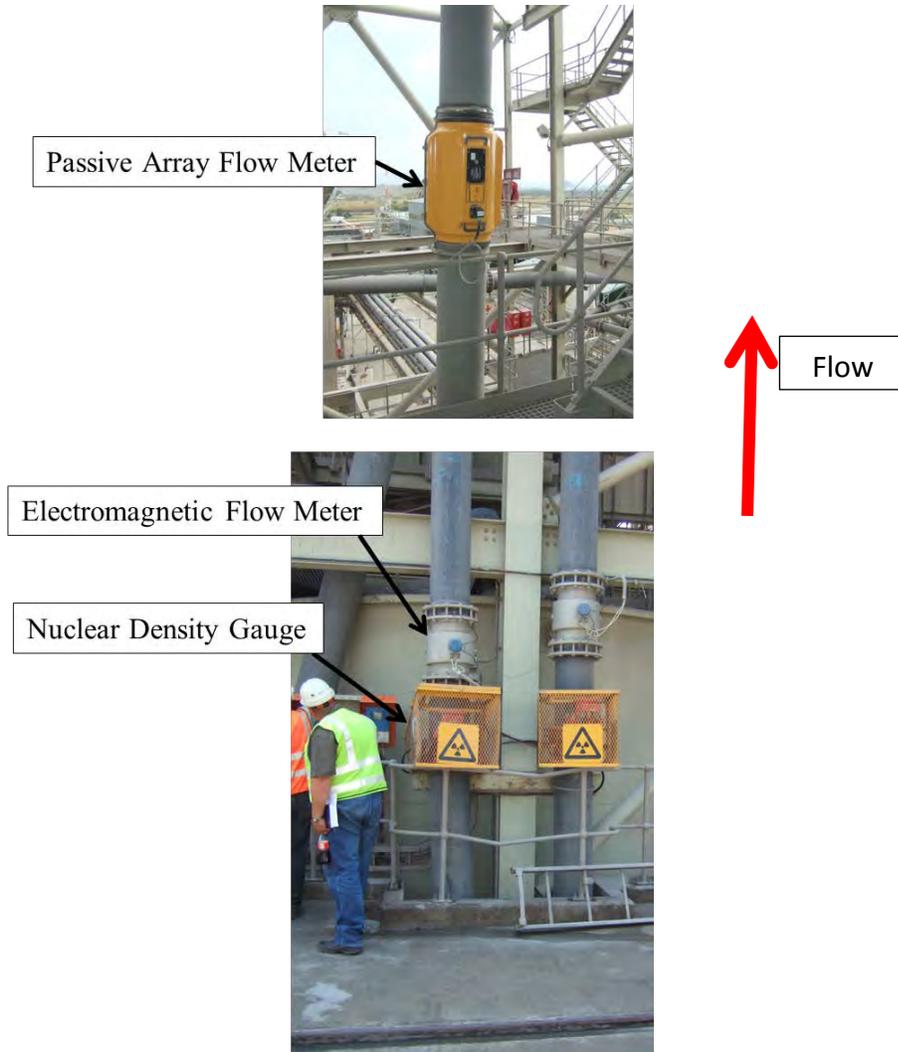


Figure 5. Passive array flow meter, electromagnetic flow meter, and nuclear density gauge on same pipe. Flow is the upwards direction

A comparison of the electromagnetic flow meter reading and the array-based flow meter reading is shown in Figure 6. The filtering is believed to be similar on both flow meters. Flow reading comparisons taken during other time periods exhibited similar behaviour.

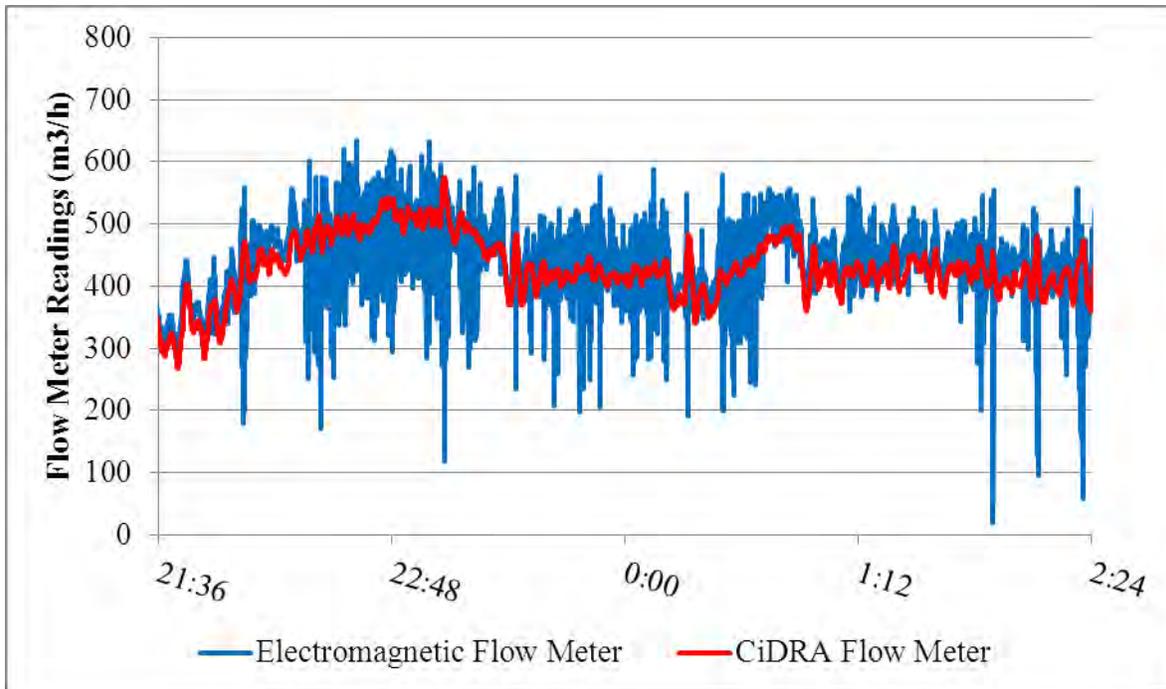


Figure 6. Output readings from the electromagnetic flow meter (blue) and the array based (CiDRA) flow meter (red) as a function of time

Since centrifugal pumps generally adhere to what is known as the pump laws, volumetric flow rate is usually directly proportional to the pump speed. Thus a comparison of the flow reading from each of the two different types of flow meters with the pump speed can be used as an indication of flow meter performance. In Figure 7 a cross plot of the paired electromagnetic flow readings (as the ordinate of each pair) and the corresponding pump speed as a percentage of the maximum speed (the abscissa of each pair) is shown.

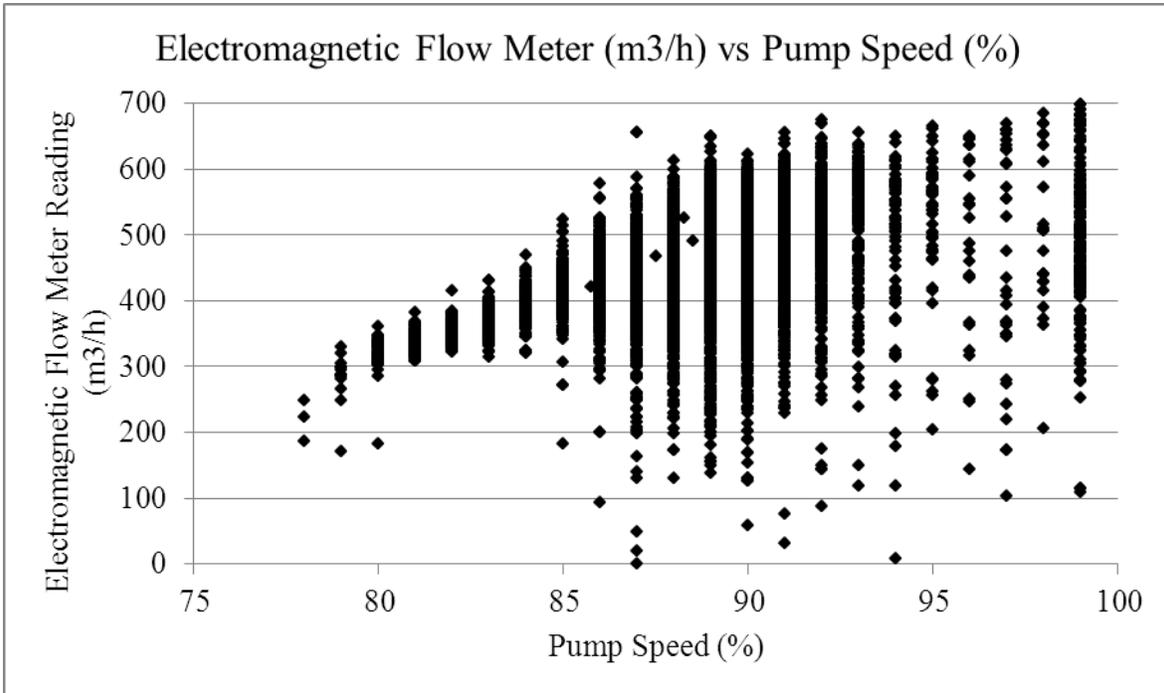


Figure 7. Readings from electromagnetic flow meter (m³/h) compared to pump speed (%)

Likewise, in Figure 8 a cross plot of the paired CiDRA flow readings (as the ordinate of each pair) and the corresponding pump speed as a percentage of the maximum speed (the abscissa of each pair) is shown. A linear regression was performed on each data set and a coefficient of determination (R^2), as a measure of goodness of fit, was determined for each data set. With a possible range of 0 to 1, in which $R^2=1$ indicates a perfect fit and thus a perfect correlation between the flow reading and the pump speed, a higher R^2 value indicates less scatter in the data and a closer match to the ideal proportionality between pump output and pump speed. The two R^2 values are shown in Table I.

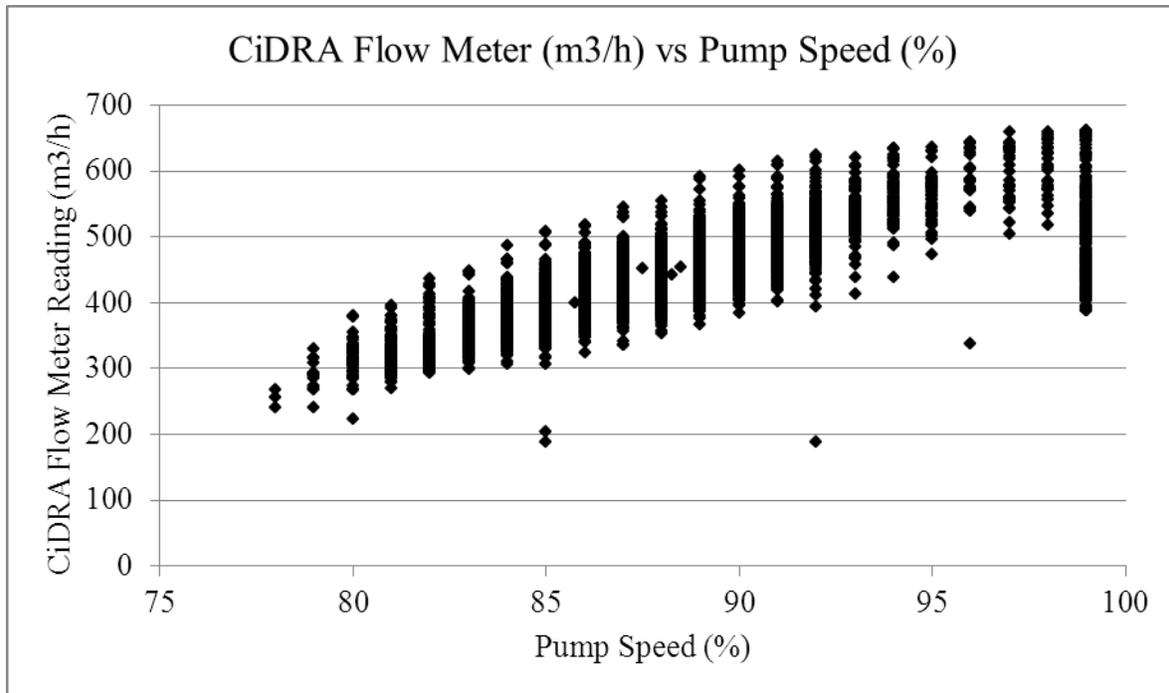


Figure 8. Readings from CiDRA flow meter compared to pump speed

Table I. Coefficient of determination R^2 for the two flow meters

	Electromagnetic flow meter	CiDRA flow meter
R^2	0.19	0.66

Flotation concentrate lines

In most concentrator plants, the rougher, cleaner, or scavenger flotation concentrate travels by gravity to a consolidated pump box or tank. From here, the concentrate is pumped to thickeners or cleaners. The volumetric flow rate of the consolidated concentrate is measured in order to calculate the mass flow rate. Flotation concentrates usually contains high levels of entrained air, which can be very stable due to the frother chemicals typically added in the flotation process. Despite the presence of pump boxes, tanks, or sumps, which allow some of the entrained air to escape, the concentrate exiting often contain high and varying amounts of entrained air. The amount of entrained air in a pipeline varies depending on the residence times, froth stability, presence of water sprays, net downward slurry velocity, the size of the bubbles, and also the means in which the slurry enters the holding tank.

These air bubbles impact the volumetric flow rate measurement of most flow meters and the density measurements produced by nuclear density gauges.

At Xstrata's Alloy's Eland Platinum concentrator, nine flow meters were installed, of which five (on the cleaners) were configured to measure both volumetric flow rate and gas void fraction (amount of entrained air bubbles) and four (on the roughers) were configured to measure only volumetric flow rate. One such flow meter installation is shown in Figure 9. For flow measurements, vertical installations with upwards flow (such as shown in Figure 9) are usually superior to horizontal installations, since the vertical installations ensure a full pipe. In horizontal installations, flow conditions and the slurry characteristics can result in the deposition of solids on the bottom of the pipe. In addition, if there are air bubbles present, a horizontal pipe provides the opportunity for the air to rise to the top of the pipe, consolidate, and form an air pocket. In either situation, the entire internal cross-section of the pipe will not be fully flowing, thus potentially creating an erroneous flow reading. A vertical installation also creates a spread in the distribution of air bubbles across the interior of the pipe, which enhances the ability of the meter to perform a gas void fraction measurement.

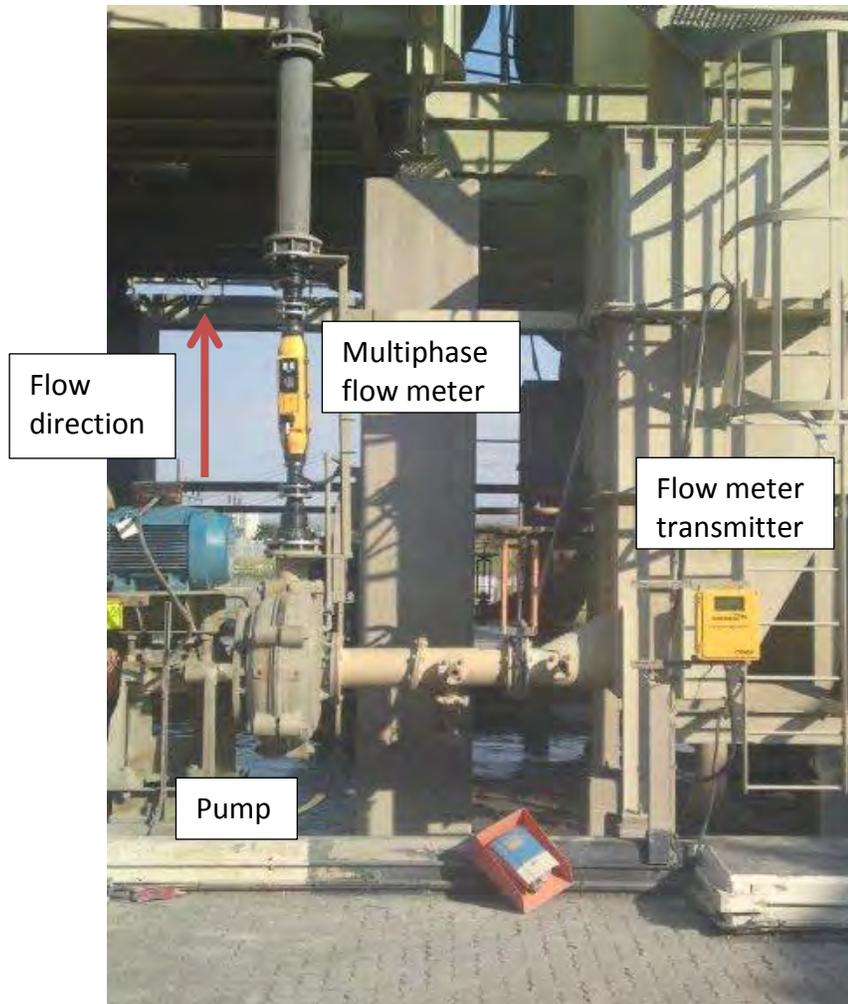


Figure 9. Measurement of multiphase concentrate slurry flow on pump discharge

The measurement of both volumetric flow rate and entrained air provides several key pieces of information. Firstly, changing entrained air content, particularly increasing percentage of entrained air, can be an indication of low sump levels, faulty level gauges, insufficient residence time for air bubbles to leave the slurry, air leakage through gaskets, and even possible damage to pump impellers. Secondly, the entrained air measurement can be used to compensate the volumetric flow rate to provide the volumetric flow rate of only the liquid and solids components. Thirdly, the entrained air measurement can be used to compensate for air bubble-induced errors in the density measurement.

An example of the first piece of information, in which changing entrained air content can provide an indication of faulty equipment or an undesirable operating condition, such as a low sump level, is shown in Figure 10. The graphs illustrate how a low sump level in a secondary re-cleaner concentrate pump box results in an increased air content (gas void fraction) in the slurry discharged from the pump.

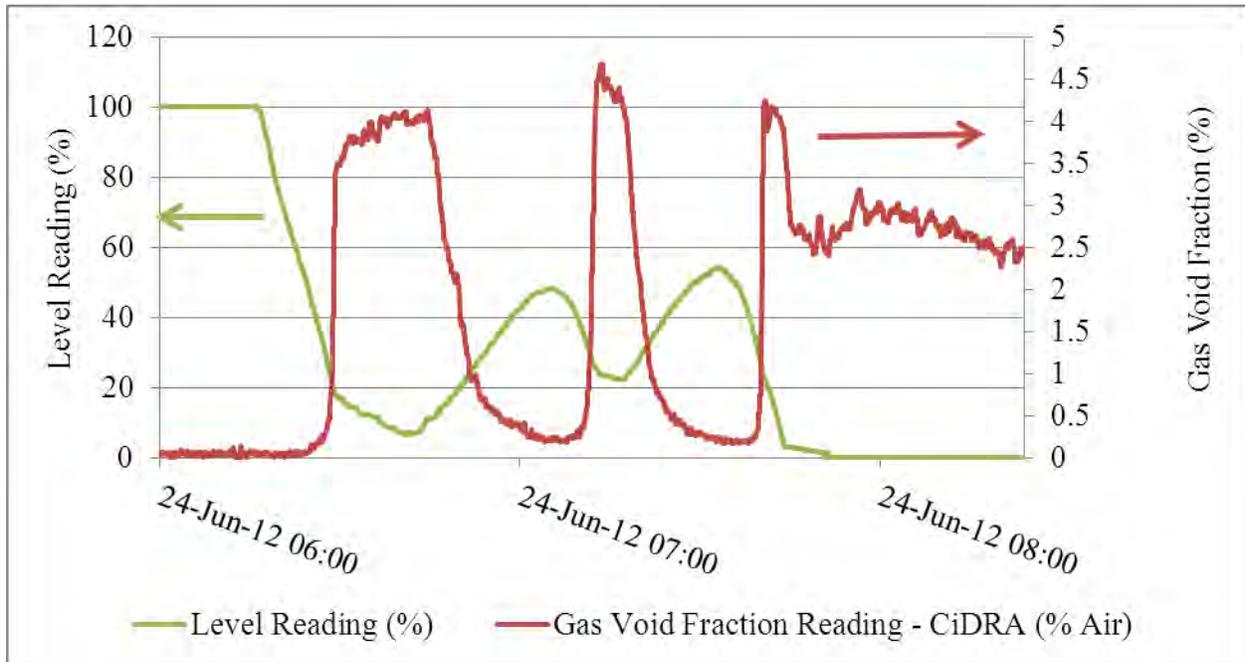


Figure 10. Change in entrained air content (gas void fraction) with changes in sump level

The impact of increased air content on the pumping efficiency can be seen in Figure 11, in which the pump speed is seen to remain constant, but the flow rate is inversely proportional to the entrained air content. This is typical for centrifugal pumps due to the decrease in pumping efficiency that occurs with increased air content in the slurry.

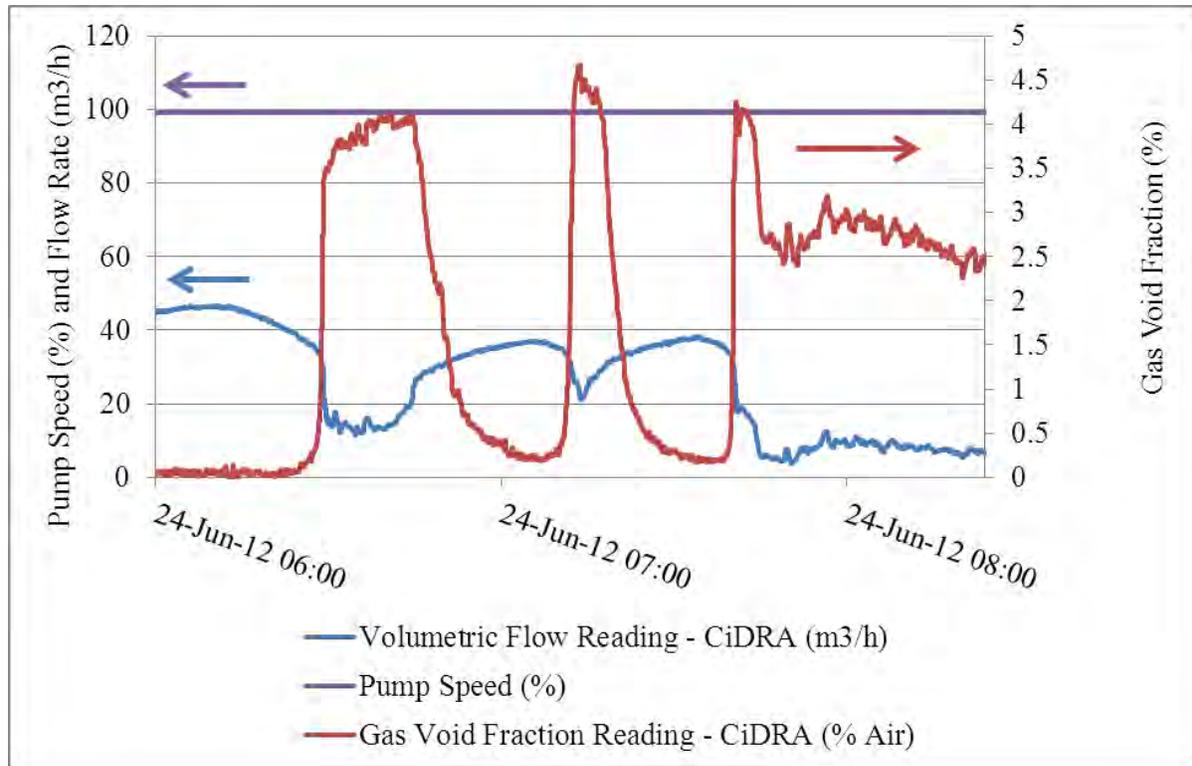


Figure 11. Changes in flow rate due to presence of entrained air in centrifugal pump

A second use of entrained air information is to compensate the total volumetric flow rate measurement to obtain the true slurry flow rate, which contains only the solids and liquid portion of the flow, and excludes the flow contribution from air. A graph showing the volumetric flow rate measurement together with the entrained air measurement is shown in Figure 12. In addition, the pump speed data also shown. The relatively constant pump speed would normally result in a relatively constant flow rate. In the presence of high entrained air levels, the flow has a tendency to surge, as it appears to do so in Figure 12. The relatively high entrained air levels, approaching 20 per cent, will directly cause most flow meters to over-report the slurry flow rate, according to the amount of entrained air. If the total multiphase flow rate is measured, together with the amount of entrained air (gas void fraction), then the volumetric flow rate can be corrected by applying Equation [1]:

in which:

TVF = True or compensated volumetric flow rate (solids and liquid portion only)

VF = Volumetric flow rate (uncompensated with solids, liquid and air fraction included)

GVF = Gas void fraction (percentage of volume occupied by entrained air bubbles).

This correction to the volumetric flow rate was applied, and both the uncompensated and compensated volumetric flow rates are shown in Figure 13.

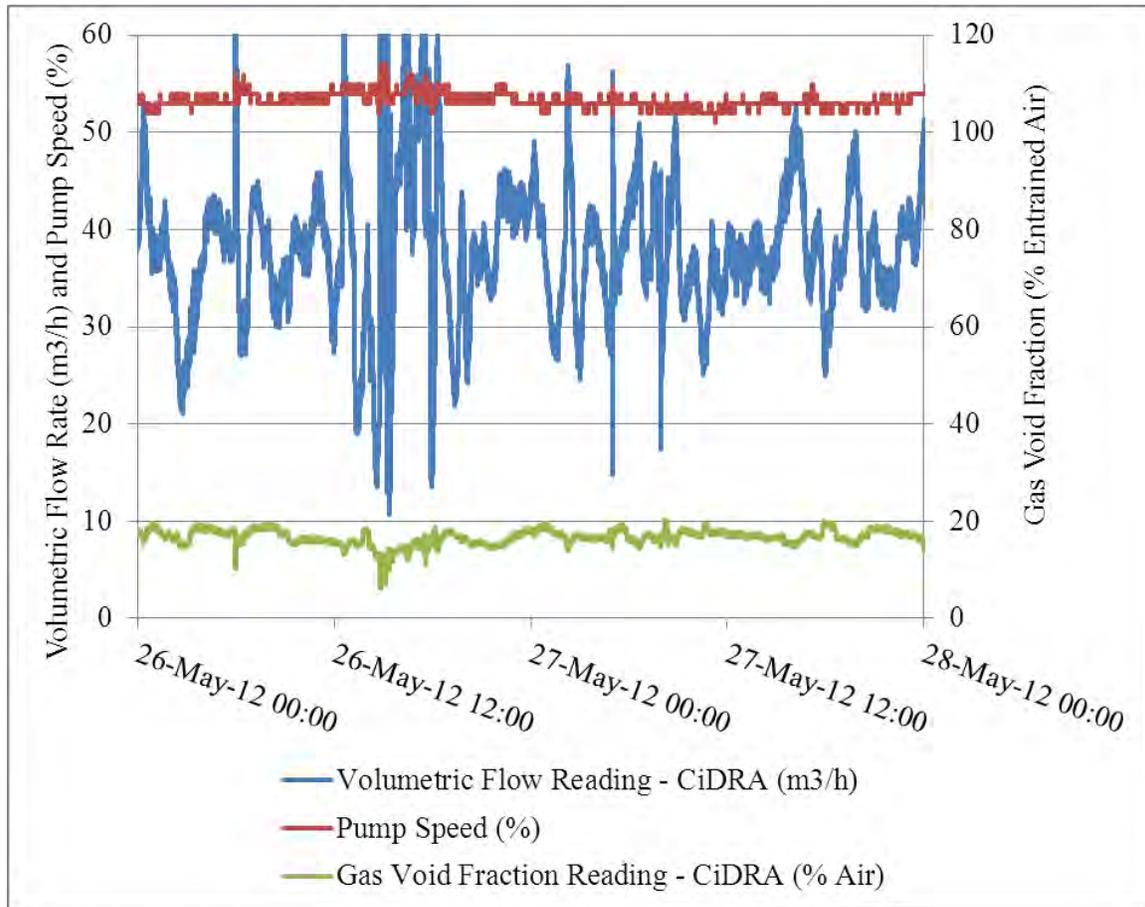


Figure 12. Simultaneous measurement of volumetric flow rate and entrained air content with flow meter. Pump speed is shown for reference purposes

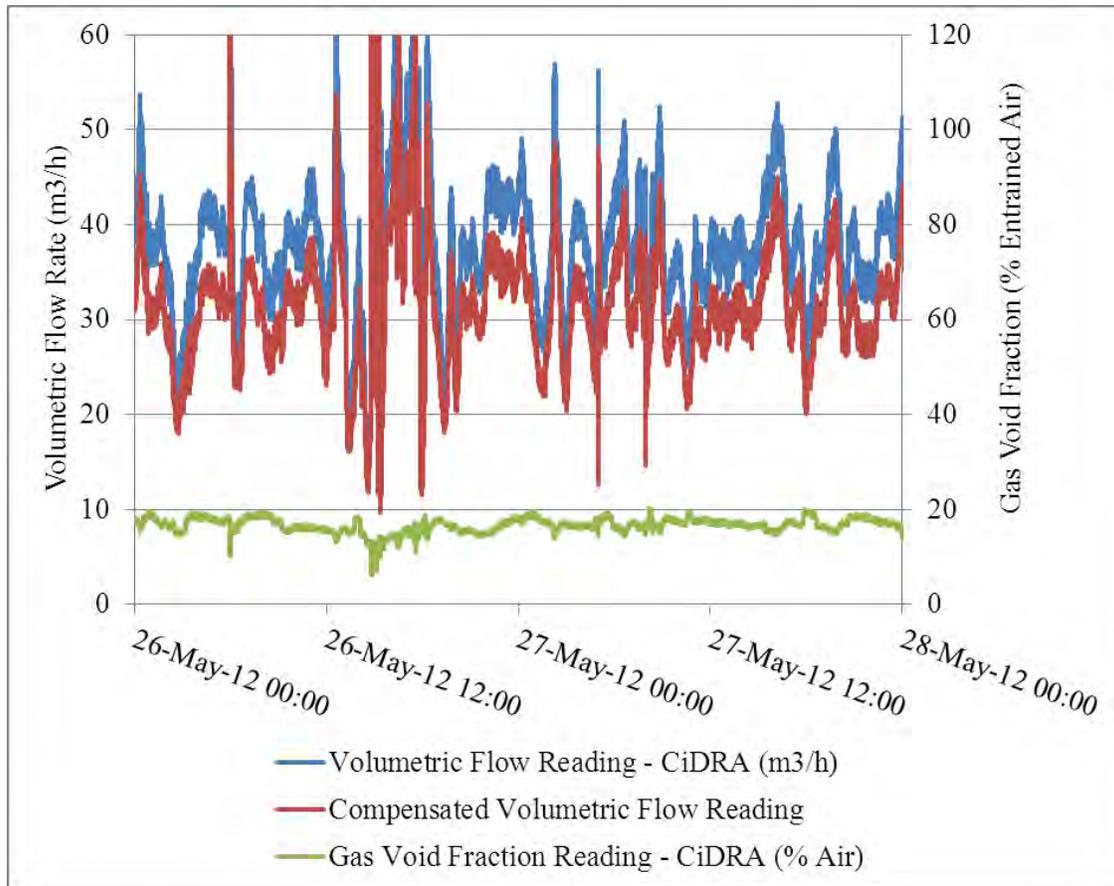


Figure 13. Uncompensated flow rate and flow rate compensated for gas void fraction

Within a flotation circuit, air is introduced into each cell and chemicals are used to create small, stable bubbles and froth, as well as to activate and collect the desired minerals into a stable froth layer. The small, stable air bubbles and froth are necessary for efficient flotation separation of the minerals, but they create measurement problems with most flow instruments and with nuclear 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. When these three values are used to calculate mass flow rate, the errors from the entrained air partially cancel, leaving a large residual error. This residual error is not constant, nor linear, and results in an under-reported mass flow rate. The resulting error in the calculated mass flow rate increases with decreasing specific gravity of the slurry mixture.²

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 these cases the relative specific gravity is the same as the slurry specific gravity. As the relative

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

$$\text{Error} = \frac{-\phi_G}{\frac{\rho_m}{\rho_L} - 1 + \phi_G} = \frac{-\phi_G}{SG_m - 1 + \phi_G} \quad [2]$$

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 $\rho_L \approx 1000 \text{ kg/m}^3$ but can be higher for brines and dense media)

SG_m = relative specific gravity (ρ_m / ρ_L)

ϕ_G = percentage of volume occupied by air (gas void fraction).

At Eland 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 tank 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 per cent to 1.8 per cent (excluding any spurious spikes in the data) with an average value of 0.76 per cent. 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. 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 is shown in Figure 14, in which, excluding the spike in both density and gas void fraction, the density varied typically from 1.085 to 1.090 and the gas void fraction from 0.08 per cent to 1.00 per cent.

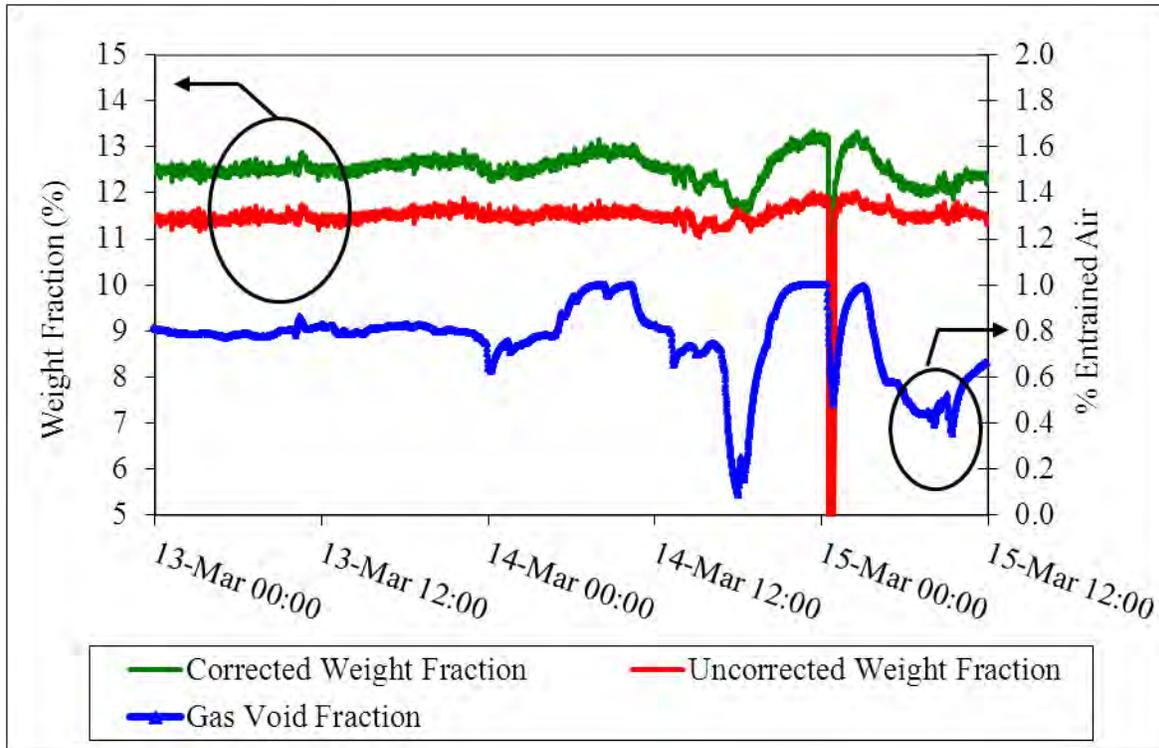


Figure 14. Solids weight fraction corrected for entrained air impact (top trace) and uncorrected for entrained air (middle trace). Gas void fraction is given by the bottom trace

Further development

'Our next phase is utilising the FloatStar Level controller, FloatStar Flow Optimiser, Blue Cube Analyser, and CiDRA flow meters to implement our advanced flotation control. We have already automated mass pull control across the cleaner section. So, your accurate flow measurements are indeed helping us with our broader flotation control strategy'. Moloto, Buang (Xstrata Alloys – Group Manager, Concentrators).

Summary

Array-based instrumentation can be used to measure both volumetric flow and gas void fraction. For volumetric flow rate measurements, it was demonstrated that array-based instrumentation reliably measures flow in the presence of entrained air bubbles or ferromagnetic material. Either condition can pose flow measurement problems with traditional flow meters such as electromagnetic flow meters. Gas void fraction measurement was demonstrated on cleaner lines, which have gas void fractions or entrained air levels ranging from zero to 20 per cent. This gas void fraction measurement was used to determine the true, or compensated volumetric flow rate, by applying a simple formula to eliminate the flow contribution due to the air bubbles.

Conclusion

In circuit flow measurements, improved precision and accuracy are of benefit to plant process control, metallurgical balancing, and accountability.

The CiDRA and Xstrata Alloys Eland Platinum team would like to thank Buang Moloto and the Xstrata Alloys Eland Platinum mine staff for their assistance during the trial, installation, and commissioning of the SONARtrac flowmeters, and especially for their kind comments. ' Those CIDRA flow meters, for instance, are doing wonders for us. Their accuracy and reliability help us with our mass pull strategy.' B. Moloto (Xstrata Alloys – Group Manager, Concentrators).

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Dr. O'Keefe has worked in aerospace R&D including working on the Space Shuttle Boosters, and in the development of instrumentation for DNA based detection of infectious diseases. While at CiDRA Corporation, Dr. O'Keefe worked on the development of fiber optic based temperature and pressure sensors. He also worked on the development, testing and fielding of noninvasive flow meters, gas void fraction meters, gas holdup meters, and other unique instrumentation. For the last seven years, he has focused on developing and applying new sensors and systems to the minerals processing industry.



João Manuel Rodrigues Vilela Felix, *Director*, Felix Project Management & Consulting Services cc.

Joe has worked in the mining R&D environment with De Beers Diamond Research Laboratory developing and implementing instrumentation for the recovery of diamonds within a feed stream. During his 18 years tenure at De Beers he also developed and commercialised a non-nuclear density meter applicable in Dense Media Separation plants. For the past three years as the CiDRA Sales and Engineering representative for Africa he has successfully applied the CiDRA SONARtrac© flow meter system into a number of Platinum, Gold, Copper, Iron Ore, Magnetite and other base metals mining operations to name a few.