Improved Flow Monitoring for Process Efficiency Improvements through New Technology Utilizing Non-Invasive Passive Arrays

Christian O'Keefe
CiDRA Minerals Processing, Wallingford, CT, USA

Robert Maron
CiDRA Minerals Processing, Wallingford, CT, USA

Paul Rothman
CiDRA Minerals Processing, Wallingford, CT, USA

ABSTRACT: Industrial minerals processing has some demanding flow measurement requirements, which have not been adequately met by traditional flowmeter technologies such as electromagnetic or Doppler flowmeters. A new flow measurement principle that overcomes many of the disadvantages of the traditional approaches has been discovered and been placed into practice in over 152 processing plants. This technology is based on the combination of an axial array of passive sensors wrapped around the outside of the process pipe and powerful array processing algorithms to accurately determine the volumetric flow rate of most fluids including gases, clean liquids, and slurries as well as liquids and slurries with entrained air. The principle of operation will be described, along with examples of its proven ability to provide accurate, reliable flow measurements in hydrocyclone/screen feed lines, pipelines for leak detection, and the presence of slurry containing magnetic ore such as magnetite.

INTRODUCTION

Accurate, robust measurement of true volumetric flow is necessary for many critical areas of minerals preparation. These areas include leak detection in tailings lines or pipelines, control of dense media cyclones and hydrocyclones, proper loading of dense media separation vessels and screens, mass balancing, flotation circuit loading, 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 endeavor for process control engineers because of many process influences. These influences include pipe wall scale buildup, the presence of magnetite, changing process fluid properties, calibration drift, and the presence of entrained air bubbles. In most cases, it is now possible to perform accurate flow measurements in the presence of these influences through the use of the latest generation of flow measurement technology based on arrays of sensors. In addition, new measurements such as the amount of air bubbles entrained within a slurry or liquid are now possible. The latter is used for pump monitoring, true volumetric flow measurement, and correction of nuclear density gauges to ensure operation at a desired specific gravity and for mass flow measurements. It does so accurately and reliably without making contact with the slurry. 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

Overview

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. Thus each disturbance class may be clearly identified and accurately measured.

Passive Array Hardware

In a commercial embodiment of this measurement principle, a flexible band of passive sensors is wrapped around and tightened onto the pipe. This is a dry fit that does not require gels or couplants since no ultrasonic waves are used. The sensor band is always 50 cm long in the axial direction of the pipe and equal to the circumference of the pipe in the orthogonal dimension. The typical installation procedure and hardware embodiment is outlined in Figure 1. First the pipe is wiped down and any high points are sanded or filed away. Second, the flexible sensor band is wrapped around the pipe and a series of captive screws on the sensor band are used to tighten the band onto the pipe. Each screw uses a stack of spring washers to allow for pipe expansion and contraction, as well as to ensure a set clamping force without requiring torque wrenches or screwdrivers. Third, a protective cover with signal conditioning and diagnostics electronics is installed over the sensor band, and the sensor band is connected to the electronics in the cover. Fourth, the cable from the sensor head to the transmitter is installed and wired to the transmitter. Fifth, the easy to use front panel menu on the transmitter is used to configure the transmitter.

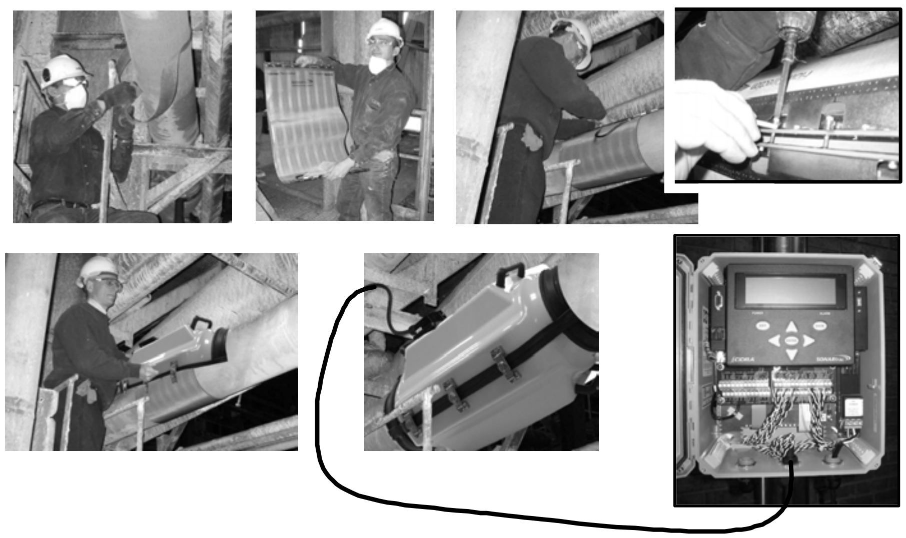

Figure 1. Installation procedure from (top-left) pipe preparation through cleaning and light sanding of pipe to (top-middle and top-right) mounting of the flexible, lightweight sensor band to (bottom-left) installation of the sensor cover and to (bottom-middle and bottom-right) connection of sensor cover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

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 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 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 (exaggerated on the right hand side of Figure 2)
- 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 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 f/s) is required to measure the flow velocity

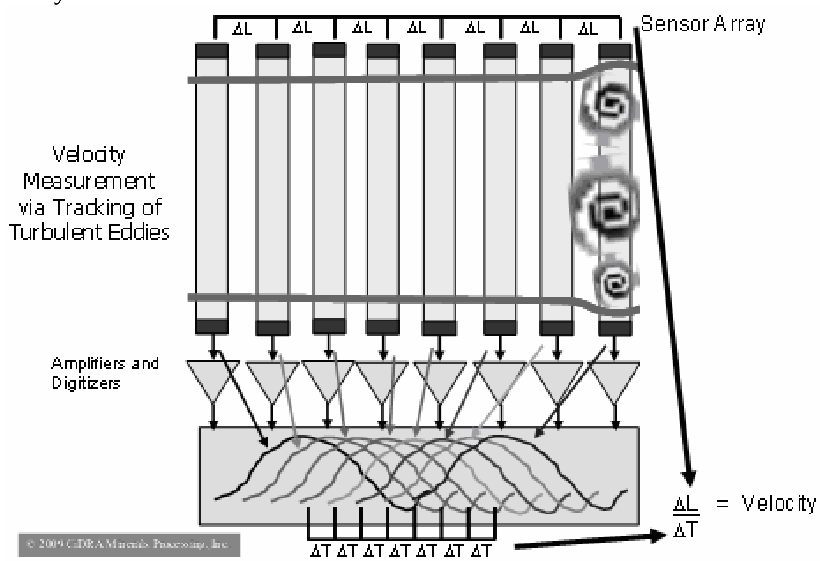

Figure 2. Illustration of strain induced in pipe walls by passing turbulent eddies, resulting in similar signals detected by sensor elements with time or phase differences, leading to velocity measurement

There are many challenges in performing this measurement in an industrial environment. The most difficult of which is resolving the relatively low level vortical disturbances from the relatively high noise levels. This noise includes 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 fiberglass. The pipes can be lined or unlined. When lined, this has been demonstrated on rubber, urethane, cement, basalt, and Teflon lined pipes, as well as 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 traveling in the fluid. In most mineral processing plants there is an abundance of acoustic waves propagating within the process pipes. These acoustic waves are generated naturally from a variety of sources. These sources include 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 slurry. Since the wavelengths of the acoustic waves are much larger than the bubble size, a complex interaction takes place that sets the acoustic velocity to be a strong function of the gas void fraction. The speed of sound is proportional to the square root of the ratio of the compressibility and the density, both of which are heavily influenced by air content. An example of the resulting relationship is shown in Figure 3. The particular values outlined by the curve in this figure are influenced by other factors, particularly pressure. Thus pressure at the location of the array based instrument must be measured or calculated. Once pressure is determined, the array based instrument is used to accurately measure the speed of sound, and the relationship between speed of sound and entrained air content is used to accurately quantify the amount of entrained air.

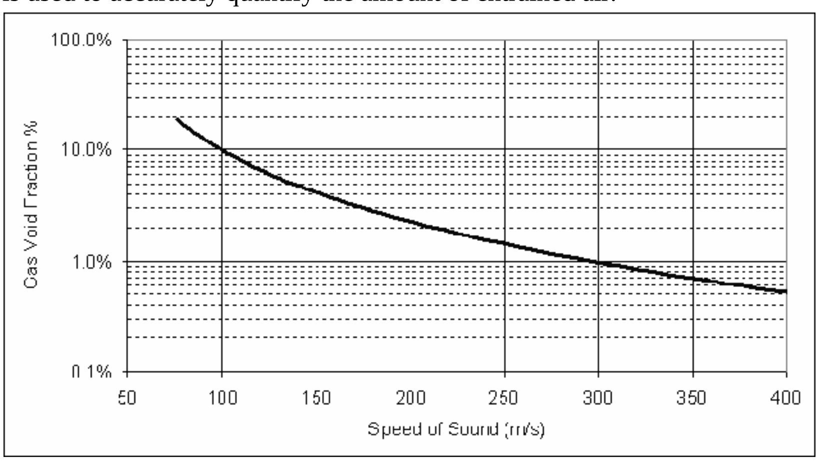

Figure 3. Example of relationship between gas void fraction (entrained air bubbles) and speed of sound

OPERATIONAL CASE STUDIES

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

Feed to Hydrocyclone Battery and Screen: Comparison of Array-Based Flowmeter and Electromagnetic Flowmeter to 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 300mm polyethylene pipe as illustrated in the right side of Figure 4. 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.

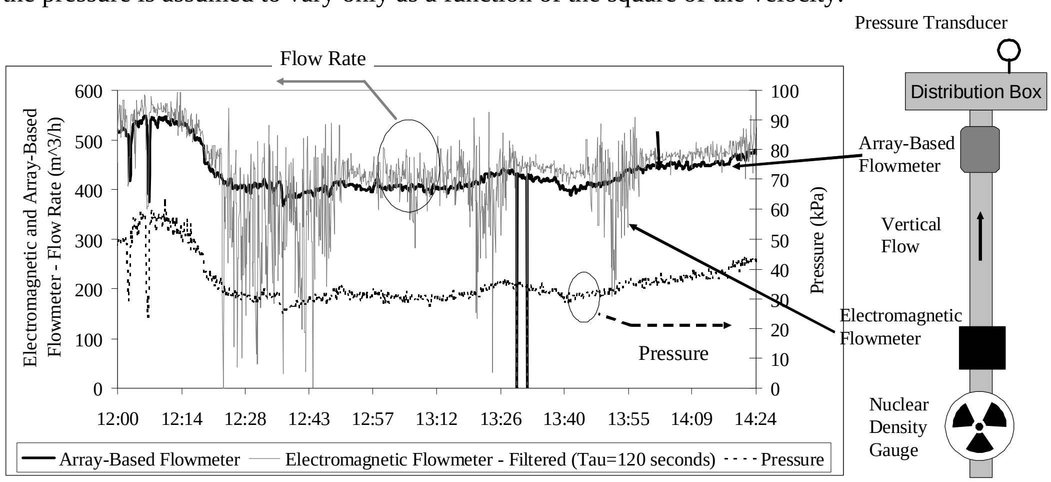

Figure 4: Comparison of readings from array-based flowmeter, electromagnetic flowmeter and pressure transducer

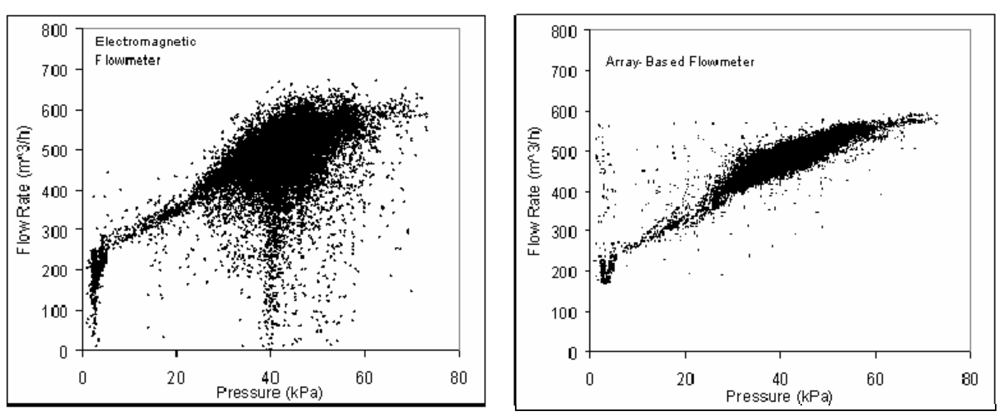

Figure 5. (Left) Crossplot of electromagnetic flowmeter readings versus pressure. (Right) Crossplot of array-based flowmeter readings versus pressure

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 5. 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 5. After application of heavy filtering to the electromagnetic flowmeter reading, an overall trend relative to the readings from the pressure transducer and array-based flowmeters can be seen in Figure 6. The resulting erroneous dips in the electromagnetic flowmeter readings cannot be explained by magnetic material passing through the flowmeter or material striking the electrodes. In contrast, the array-based flowmeter exhibits excellent agreement with the pressure reading.

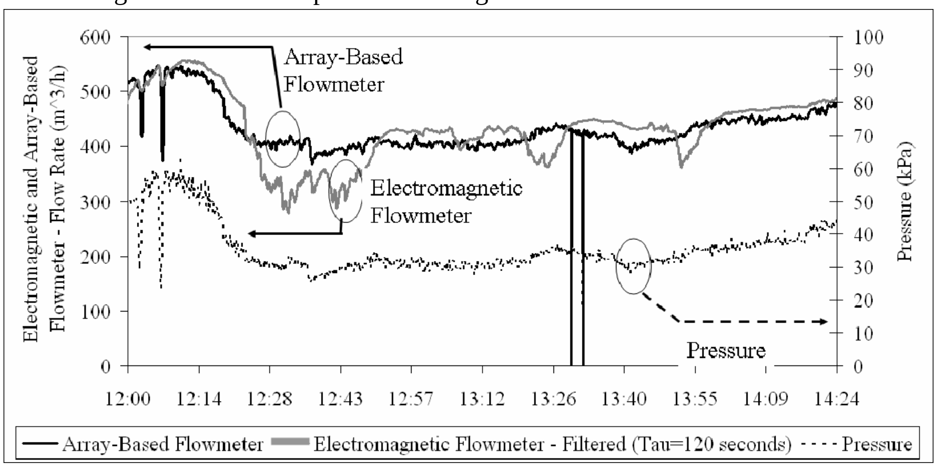

Figure 6. Comparison of readings from array-based flowmeter and pressure readings along with filtered reading from electromagnetic flowmeter (first order filter of 120 seconds applied to electromagnetic flowmeter)

Measuring Flow in the Presence of Magnetite or Other Magnetic Ore

Magnetite is commonly used dense media separation processes but it introduces challenges in measuring flow using electromagnetic flowmeters. The magnetite, even in small quantities, changes the magnetic field within the electromagnetic flowmeter and can cause the flowmeter to register a higher flow rate than the actual flow rate, or introduce a high quantity of noise in the flow rate output. Electromagnetic flowmeter manufacturers have attempted to circumvent the impact of magnetic ore with a third coil, with magnetic field measurements, and with manual offset adjustments based on laboratory samples of the typical slurry. These methods have resulted in mixed results in which many times, the calibration or offset changes depending on the quantity of magnetite present.

A better solution is to use a flowmeter technology that is not impacted by the presence of magnetite. Since the passive array technology used in the array-based flow monitoring system does not rely on the use of any magnetic fields, it is totally impervious to the effects of magnetite. An example of this is illustrated in Figure 7 in which an array-based flowmeter is compared against an electromagnetic flowmeter. In this test, the flow rate was held constant from the beginning of the time period shown in the figure until approximately the time 06:00. In the figure, one can see that as the density of the magnetic ore increases, the electromagnetic flowmeter erroneously reports a higher flow rate, whereas the array-based flowmeter correctly continues reporting no change in the flow rate.

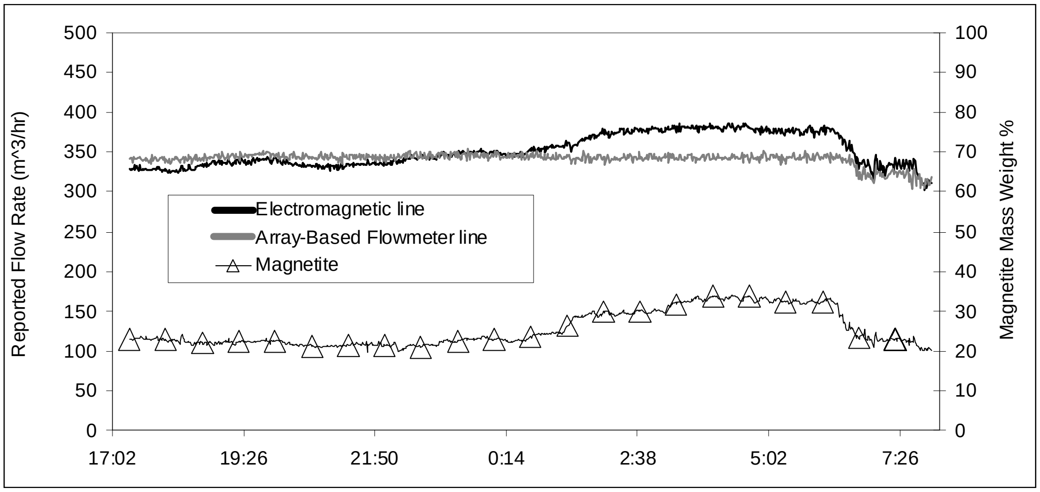

Figure 7 Electromagnetic flowmeter erroneously responds to magnetite while array-based flowmeter reports correct reading

Pipeline Leak Detection

Due to environmental concerns and the desire to detect the loss of concentrate, leak detection in pipelines is an important aspect of pipeline operation. Until now few pipelines were able to use a volumetric accounting method, also known as mass flow leak detection, due to the high noise and drift seen in older flowmeter technologies such as Doppler ultrasonic and electromagnetic flowmeters. The array-based flowmeter technology such as the CiDRA flow monitoring system has enabled the use of volumetric account methods for leak detection as evidenced on several large visibility concentrate and tailings pipelines. One such example, as applied to a coal waste tailings line, is shown in Figure 8. The black line is the signal from the array-based flowmeter installed at the plant end of a 10 inch (250mm) polyethylene pipe and the gray line is the signal from an array based flowmeter installed on discharge end of the same pipe with a distance of approximately 1500 m of pipe separating the two. The dashed line is the percentage difference between the two readings, and it generally stays within +/- 2%. This level is usually achievable if the flowmeters are properly installed, at suitable installation locations, and if the pipeline is operated correctly.

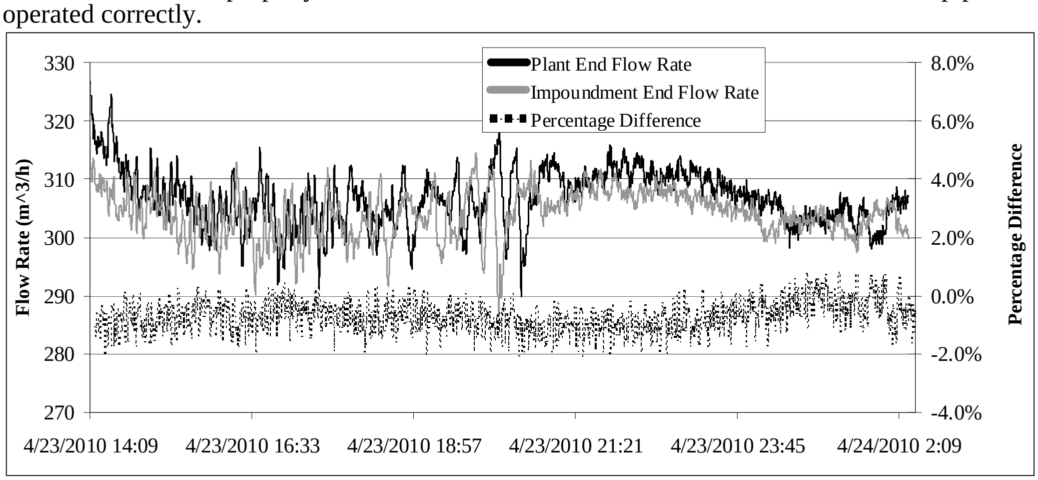

Figure 8. Coal tailings pipeline leak detection with outputs from both array-based flowmeters shown and percentage difference in reading

Control of Classifier Feed Flow using Array-Based Flowmeter

Classifier feed flow is typically used for control with the aim of managing circulating load so as to ensure optimum mill feed rate, while avoiding overload and maximizing throughput. In one particular application, a 400mm feed line has been instrumented with an electromagnetic flowmeter and an array-based flowmeter.

At high mill feed rates the electromagnetic flowmeter is prone to spiking and noise due to entrained air and solids impact on the electrodes. The noisy flow measurement causes the control system to react, reducing the linearity between mill feed and circulating load. The result is that circulating load can not be used as the mill limiter and throughput is subsequently reduced.

By applying the array-based technology to the mill classifier feed line to measure volumetric flow and entrained air, an effective control strategy has been implemented to maintain linearity between circulating load and mill feed. On the left hand side of Figure 9 is a plot of the circulating load versus mill feed rate as measured by the electromagnetic flow meter. A linear fit of this data yields an R^2 of 0.53. On the right hand side of Figure 9 is a plot of the circulating load versus mill feed rate as measured by the array-based flowmeter. A linear fit of this data yields an R^2 of 0.72.

The array-based technology and fundamental measurement principal makes it insensitive to high solids content and entrained air within the process stream. This enables the operator to maximize grind circuit throughput. In addition to milling circuit throughput control, the classifier performance may also be optimized. This is accomplished by using the entrained air reading to correct the density measurement on the feed to the classifier.

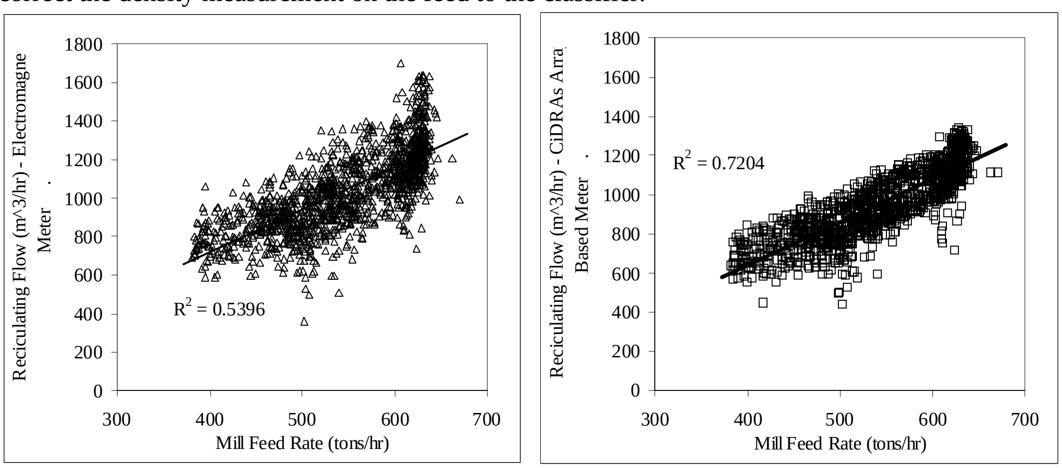

Figure 9. (Left) Circulating flow rate versus mill feed rate as measured by the electromagnetic flowmeter. (Right) Circulating flow rate versus mill feed rate as measured by CiDRA's array-based flowmeter

SUMMARY

The array-based flowmeter technology is field proven and has years of maintenance free operational experience in concentrators and pipelines around the world. The use of this technology solves long standing performance and maintenance flow measurement problems. Such problems include reliable and repeatable flow measurement in the presence of abrasive slurries, slurries with continuously changing solids content, pipes with scale buildup, magnetic ores, and highly aerated concentrate streams. This enhanced flow measurement capability enables operators to more accurately control critical processes. Such processes include grinding mill throughput by controlling circulating load, flotation circuit mass balance and final concentrate accounting by measuring flow and correcting density measurement, and tailings and pipeline management through robust flow measurement. This technology with built-in remote monitoring capability for the mine of the future is currently being used in over 700 minerals processing flow monitoring applications within 22 countries.