Flotation Process Metering of Concentrate, Slurry, Air and Water Flows Using Non-Intrusive Fibre-Optic Sensing

D. Finfer

Silixa Ltd, Elstree, United Kingdom

Corresponding author: daniel.finfer@silixa.com

Closed-loop flow control in flotation processes can enable both mass pull and grade control; however, the implementation of flow control systems in flotation plants has traditionally been challenged by a lack of sensing solutions capable of direct concentrate flow measurement. Notably, cameras have been implemented in many cases to address this sensing gap; though camera-based surface froth velocity estimates remain an indirect and potentially error-prone approach to inferring concentrate production rates. Recently, Anglo American's FutureSmart Mining™ program collaborated with Silixa to pioneer the use of non-intrusive distributed fibre optic sensing for direct concentrate flow metering. In early 2017, a pilot at the Mogalakwena North Concentrator was executed whereby a single, continuous length of optical sensing fibre was used to meter a variety of flotation flows, including water, slurry, air, and concentrate flows. The results indicate that this new technology can meter many process flows simultaneously throughout flotation plants using nonintrusive instrumentation, opening a new era for closed-loop flow control in flotation.

INTRODUCTION

Flotation process control can be used to maintain production set points, achieve robustness against ore grade variability, and minimise the use of process water. Control methods such as mass pull control theoretically rely on the presence of flow sensors throughout the plant; however, practical considerations dictate that the metering of flows in flotation banks is often limited to main feeds, concentrate from sumps, final tailings, and central air measurements. Camera sensing has been developed to enable cell-by-cell production estimation, but camera applications are often restricted to particular production conditions that may be difficult to achieve on a day-to-day basis. In recent years, a new technological candidate, based on distributed acoustic sensing (DAS), has emerged for the metering of flow throughout an entire industrial process. Previous work (Finfer *et al*., 2017) has demonstrated how it is possible to use process metering based on DAS to enable non-intrusive flow metering on many pipes throughout a mining plant using only a single, continuous length of optical fibre. Here, it is considered how this emerging technology can be applied for the purpose of flotation control in a real-world environment.

A pilot was executed to evaluate the potential to use fibre optic DAS for the purpose of identifying whether this technology can be used to obtain high granularity flow measurement on high numbers of flows throughout the entire flotation process. In this initial flotation pilot, a process metering fibre optic circuit was installed at Anglo American's Mogalakwena North Concentrator, including a single flow measurement for each of the following: slurry feed, aeration, concentrate, and sump. All measurements were made simultaneously using a single length of optical fibre. It will be seen that this method is a highly promising sensing method for flotation mass pull control as well as peak air control, and that the retrofit-compatibility of the technology makes this technique applicable to brownfield and greenfield environments alike.

BACKGROUND

Flotation is the primary separation process in use for platinum-group minerals (PGMs) at Mogalakwena Mine. The North Concentrator at that site is controlled using a multi-layer approach incorporating both a stabilising layer and an optimisation layer, and takes advantage of a range of control techniques, including fuzzy logic, rule-based and model predictive control (Muller *et al.*, 2010). The goal of the control system is to stabilise output as the quality and concentration of minerals varies so as to be able to operate at a target recovery rate on an ongoing basis. As with any large plant control scheme, both measurement quality and quantity are essential.

The optimisation layer at Mogalakwena is based on mass pull control, which profiles the solid mass overflow rate, or the rate at which concentrate is pulled from the cells (Maldonado *et al.*, 2012). Recent years have seen many plants adopt this strategy, partly as a result of the fact that froth-velocity estimation can be performed non-invasively on a cell-by-cell basis using arrays of calibrated imaging cameras. In addition to being non-invasive, camera systems are retrofit-capable, and can function over a range of foam conditions; however, the mass pull output provided by camera systems is typically based on images from a minority region of the overall cell upper surface area, making output susceptible to error in cases of spatially non-uniform flow activity. Further, cameras must be cleaned on a regular basis to ensure foam visibility, and often require dedicated, high bandwidth data networks to be installed at the time of installation. Addressing these challenges, while still avoiding reliance on a retention time-based model, would provide site with an opportunity to address better the classical target of mass pull control: long-term, robust, maximised production output despite variable feed characteristics.

Therefore, it is anticipated that site would benefit economically from the use of a sensing technology capable of directly providing mass pull from all cells. It is desired to have a solution that can be installed non-intrusively, requires minimal calibration effort, is highly rugged against the challenging conditions encountered in flotation plants, and is straightforward to apply throughout a plant to achieve granular flow data over a range of flow types and flow conditions.

TECHNOLOGY

In this section, distributed fibre optic sensing technology is introduced, and the way in which flow can be measured non-intrusively using distributed acoustics is described.

Distributed Acoustic Sensing

DAS technology makes it possible to measure the acoustic signal at every point along standard telecommunications-grade optical fibre with a spatial resolution on the order of metres. In effect, DAS makes it possible to use unmodified optical fibre as a wide aperture acoustic array with many thousands of sensing elements.

Figure 1 is useful for illustrating the operation principle for this technology. Consider the case where an acoustic field interacts with an optical cable. The acoustic perturbations will create dynamic strain variations along the cable, which will in turn mechanically impart these disturbances on to the optical fibre within the cable. Variations in dynamic strain within the fibre will tend to create small but observable changes in the way the optical fibre transmits and reflects light.

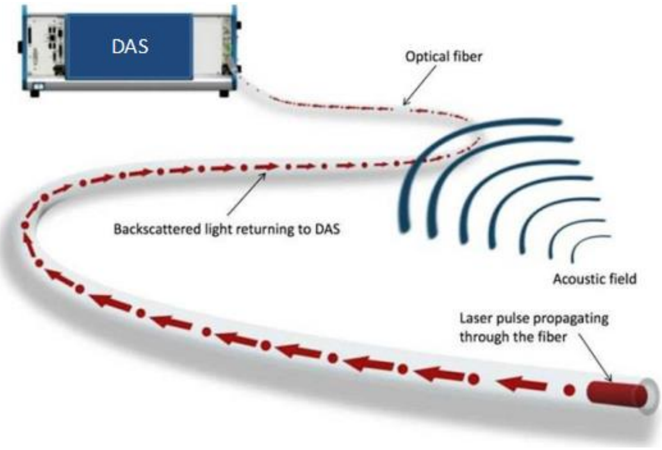

Figure 1: By observing temporal variations in optical backscatter properties, distributed acoustic sensing (DAS) makes it possible to measure the acoustic signal at all points along a telecommunications-grade optical fibre.

By pulsing the fibre and capturing the backscattered signal, it is possible to measure distortions throughout the optical pathway and hence determine the vibroacoustic signals responsible for the distortions. Acoustic signals measured in this fashion are inherently time-synchronised along the entire optical fibre, and exhibit phase and amplitude characteristics that are equivalent to the output thta would be obtained from calibrated point sensors of dynamic strain. The spatial resolution obtained with such a distributed fibre sensor is about one metre, as shown previously (Farhadiroushan *et al.*, 2009) and as demonstrated in industrial applications (Parker *et al.*, 2014).

DAS is already used in the Oil & Gas industry for a wide range of applications including seismic acquisition (Daley *et al.*, 2013) and in-well flow measurement (Xiao *et al.*, 2013). In contrast, the mining industry is only beginning to make use of this technology, with applications currently identified in the areas of seismic sensing, conveyor belt monitoring and, as discussed here, flow metering.

Process metering using distributed acoustic sensing

Certain implementations of DAS make it possible to meter flow within pipes. This application is attractive because sensing fibre is both low-cost and non-intrusive, and the sensing architecture makes it possible to measure several flows simultaneously. Previous publications have described the theory (Finfer *et al.*, 2014) (Finfer *et al.*, 2015) for this application, as summarised below. Following this theoretical summary, this paper will focus on the potential use of this technology in the particular area of flotation control.

Eddy tracking

As turbulent flow passes through a pipe, eddies of varying size are generated and dissipated continuously. The amount of time over which this generation and dissipation occurs is known as the eddy lifetime, and its spatial equivalent varies with the inverse square root of the Reynold's number (Mathieu & Scott, 2000). For the purpose of illustration, consider a single eddy passing through a fixed cross-section of a pipe. This single eddy, which will travel at nearly the speed of the fluid, will tend to create a localized disturbance in the cross-section of the pipe. This localized disturbance will induce a small perturbation on the pipe exterior for that fixed region. By using a synchronized array of radial strain sensors to observe the eddy as it moves through a successive series of cross-sections, it can be possible to track this single eddy as it passes within the fluid. In practice, a multitude of eddies are present throughout the cross-section of a turbulent constrained flow, all of which can be used to monitor flow speed. Previous work has shown that, if an array of synchronized hoop-strain sensors is spaced with intervals less than the coherence distance for the flow, then the local convection of these vortex entities can be used to monitor the flow speed (Gysling & Myers, 2000).

DAS technology also makes it possible to observe this physical flow phenomenon. By wrapping a continuous length of fibre helically around the exterior pipe, the DAS system can measure the dynamic radial strain (hoop strain) field within a section of a pipe and thereby measure the convection speeds of eddies. The calculation of flow speeds using this approach can be done automatically on a continuous basis at several flow measurement zones simultaneously.

Sensitivity and accuracy

The eddy tracking mechanism described above is robust for a wide range of flow types, provided that the flow presents eddy energy that is perceptible to the system in a given orientation. In general terms, the minimum perceptible flow rate is driven by several factors, including: Reynold's number, pipe wall properties, fullness of pipe, geometry of pipe, and the overall length of pipe that is instrumented with fibre. Field experience (Finfer *et al*., 2017) has shown that this measurement mechanism is reliable for the metering of industrial liquid flows, and can be calibrated to an accuracy of better than 1%. Notably, in the case of low speed gas flows, the naturally occurring eddy power may be insufficient for detection using this technique. In such cases, it may be more appropriate to rely on other physics, as described below.

Doppler flow speed

The propagation of sound through a flow can be used to measure the flow speed via the Doppler shift effect. Flow speed monitoring via DAS is performed using the following steps. A fibre optic cable is first mechanically coupled to a pipe. For industrial metering, this coupling usually involves wrapping a fibre densely around the outside of a pipe. The signal is then recorded and analysed for sound speed using in the frequency–wavenumber (*f*–k) domain (Gray, 1980). By analysing the *f*–*k* output, the sound speed in the upstream- and downstream-travelling directions can be determined. The two fluid-borne sound speeds can then be compared with each other, and the Doppler principle can be applied to extract the flow speed. The ability for DAS to meter flow using naturally occurring sound has been previously reported in a variety of environments, including subsurface wells in the Oil & Gas industry (Johannessen *et al*., 2012), and can be used in surface metering for flows where eddy flow data may not be available.

This paper now describes how the technical metering capabilities described above were demonstrated in an operational flotation plant.

PILOT

In May 2017, Silixa was commissioned by Anglo American's Technology & Sustainability team, in coordination with Anglo American Platinum, to execute the world's first pervasive process metering installation within a mining processing plant using non-intrusive DAS technology. This pilot was executed on a PGM rougher flotation bank (RB2) at Mogalakwena North Concentrator. Several flotation process flows were monitored using a single, continuous length of optical sensing fibre: 1) water feed, 2) flotation concentrate outflow, 3) slurry sump flow and 4) air flow. The purpose of the May 2017 pilot was to establish the potential scope for non-invasive process metering technology to be used within flotation, particularly with respect to the measurement of concentrate flow.

Setup

Silixa shipped equipment and materials to site, and dispatched installation personnel to site. Mine site personnel installed scaffolding and identified unused optical fibre between the server room and sensing zones that could be used as sensing conduit for the system. Following site induction, Silixa personnel attended each measurement zone to install sensing fibre in a non-intrusive fashion. An overview of the site installation is given in Figure 2, with images of the metering zones shown in Figure 3.

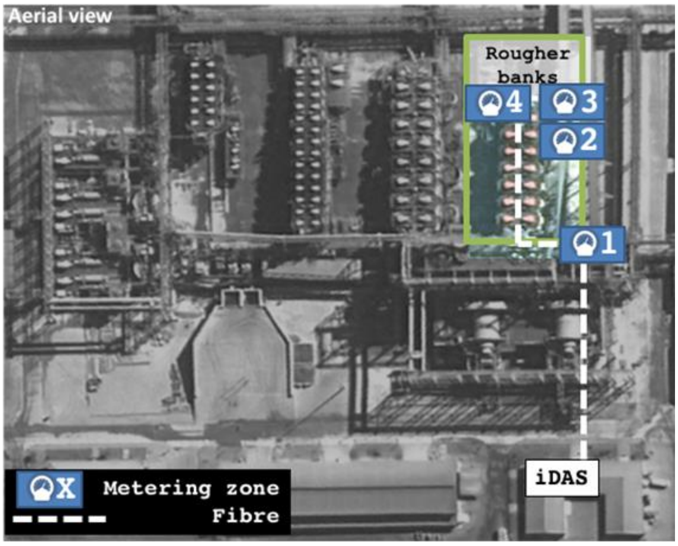

Figure 2: Aerial photograph of Mogalakwena North Concentrator (MNC). The DAS unit and processing server were installed in a temperature-controlled network server room. Single mode optical fibre led from the DAS to each flow measurement zone (1-4) in succession in a single, continuous optical circuit.

Zone	Label
1	Water feed
2	Flotation Cell Concentrate
3	Slurry Sump
4	Air Feed

Figure 3: Elevation views of rougher bank (RB2) installation at Mogalakwena North Concentrator. Each metering zone is identified as per the numbering applied in Figure 2.

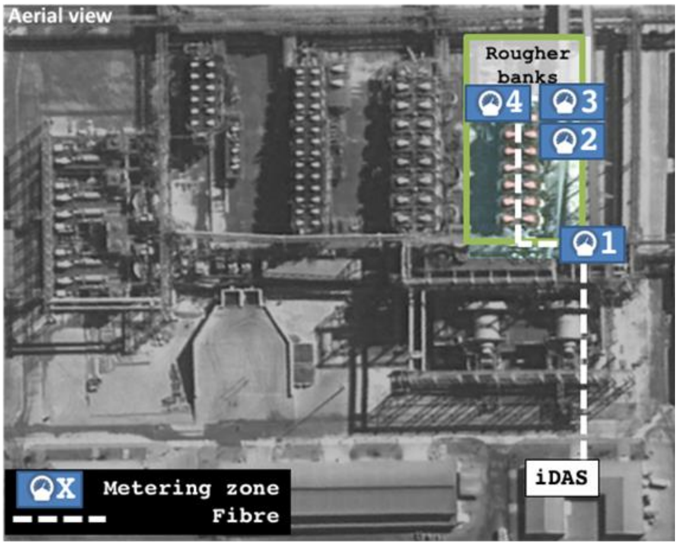

Figure 2

Figure 4: Detailed view of zone 2, the flotation cell concentrate flow metering zone, following installation. Platinum sluff can be seen flowing over the flow meter.

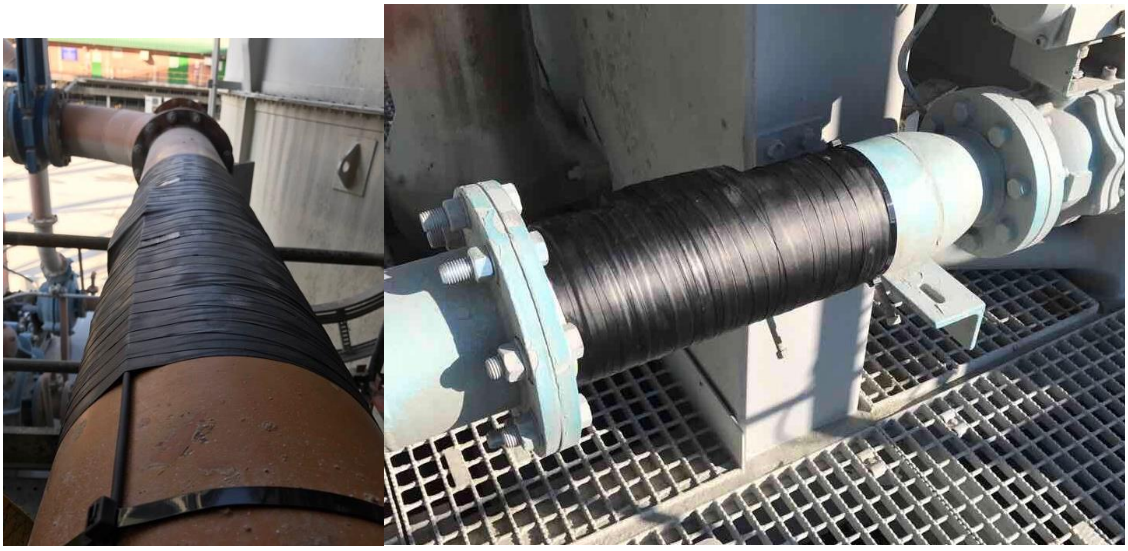

Figure 5: Detailed views of zone 3 and zone 4 following installation. (Left) Slurry slump flow and (right) air feed.

Acquisition
Installation was executed, and the DAS system was initialised. Although a single fibre is used throughout metering installations of this type, it is straightforward for trained operators to identify the positions on the fibre thta correspond to the metering zones. Real-time data metering capability was enabled through the use-custom software installed on a processing server that was also installed at site. Data acquisition and real-time processing was executed for a week-long initial trial during which time reference data were occasionally made available for comparison.

Results
Data from each of the zones monitored is presented below. Where possible, reference data are provided along with data acquired using the optical process metering system. In Figure 6, the flow rate from the water feed pipe is presented. Good correlation throughout the time period is seen between the DAS process metering output, apart from a time window near 22h00m on Sunday, during which high background vibration levels affected system performance.

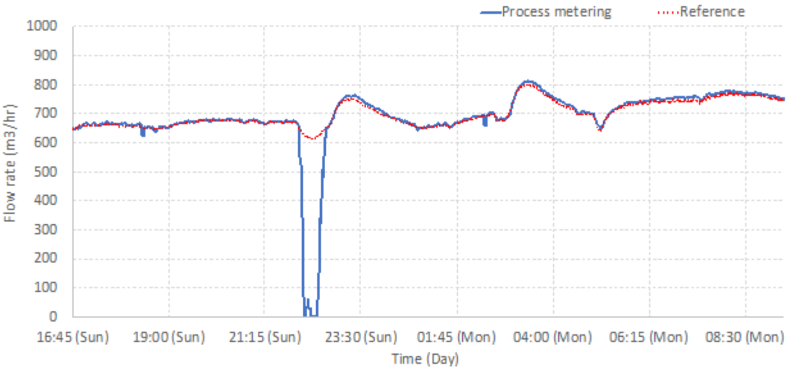

Figure 6: Data from water feed pipe. Good correlation is seen throughout, apart from a time window on Sunday near 22h00m, where the presence of high background vibration levels disrupted the system.

One of the main purposes of this trial was to determine whether this new technology could make it possible to enable direct measurement of concentrate flows within flotation environments. The concentrate flow data set presented here (shown in Figure 7) was obtained from the fibre instrumented on the concentrate launder pipe. Reference data such as that which might be obtained from calibrated cameras was not available in this case.

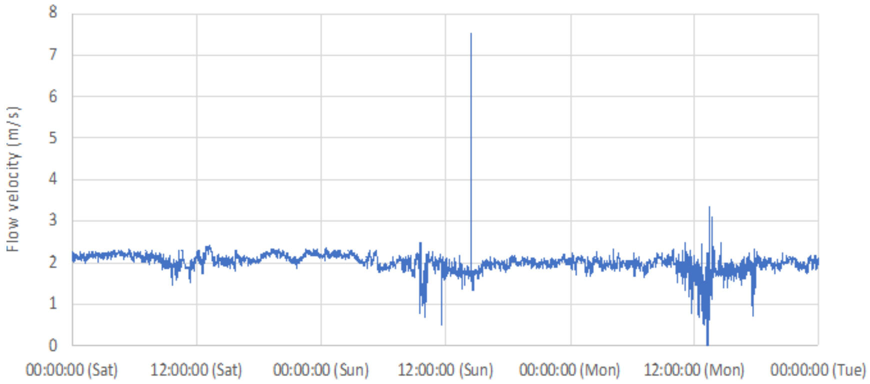

Figure 7: Flow concentrate data obtained from a flotation cell. This output represents the first time that this technology has been applied to concentrate measurement in a flotation application.

Figure 8 presents data from the slurry pump pipe. In this case, the relative large size of the flow line dictated that that flow rate was within 5% of the lower threshold for vortex energy detection nearly throughout the entire duration. As a result, deviations between the reference data and optical output are seen for nearly the entire interval under observation.

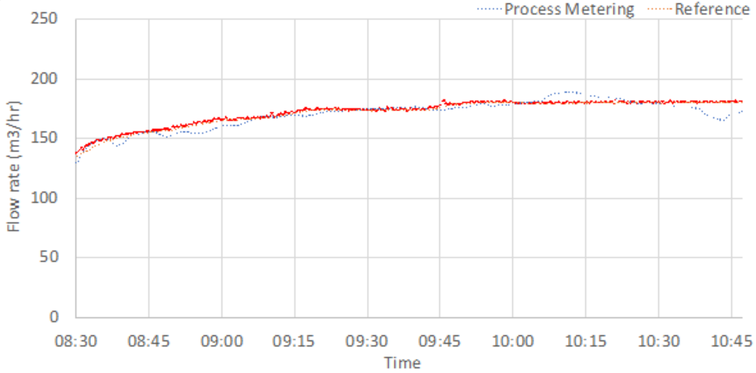

Figure 8: Data from the slurry sump pipe. Deviations between the process metering output and the reference data, in this case, are a result of the fact that the flow condition is close to the minimum system detection threshold for this particular installation.

Air flow data are presented in Figure 9. For this application, data were captured using the speed of sound, as the vortex energy presented by the fluid was insufficient for detection by the optical system. At the time of the pilot, although the system provided real-time output concerning the speed of sound-based flow rate, this output had not yet been incorporated within the data storage routine. Hence, the data comparison was enabled manually by an on-site operator. This approach limited the degree to which sound speed identification routines could be customised for the conditions encountered on site, as indicated by the output variance seen within these data.

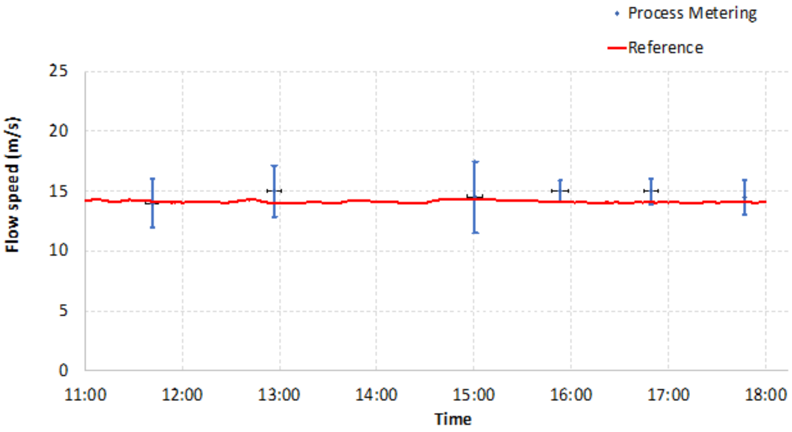

Figure 9: Comparison between air flow data obtained using the process metering system and a reference vent cap. Processing for this application relied on the Doppler method, for which automatic output was not enabled at the time of the trial. As a result, short data segments were sampled manually by the process metering system operator and later overlaid against the reference data. The time period over which sampling was executed is indicated with horizontal error bars, whilst the standard deviation for the data is indicated with the vertical error bars.

DISCUSSION

Flow metering output has been presented for several zones. The implications of the results for each metering zone are considered further here. In the case of the water feed, the high correlation between the reference data and the output from the process metering system corroborates the main findings from the previous Silixa–Anglo American pilot (Finfer *et al.*, 2017) that this non-intrusive, optical system can be used to obtain accurate flow metering results. It is noted that a sensitivity to high levels of background vibrations is seen, and methods for overcoming this potential limitation are the subject of further R&D.

As mentioned, the primary purpose of this trial was to evaluate whether concentrate flows velocities could be measured using this new sensing technology. Figure 7 shows that this application was successful for the purpose of obtaining an estimate of the flow velocity; however, in this application, practitioner experience indicates that launder tubes generally operate in a partially full condition. In a full-pipe condition, the relationship between flow speed and flow rate is an obvious function of the pipe internal cross-section; however, in cases where the pipe is not full, it is non-trivial to relate flow speed and flow rate. Since, for the mass pull application, it is critical to have an understanding of concentrate production rates on a cell-by-cell basis, additional technology development work is now underway to address this linkage.

Data from the slurry sump are presented. Variance between the reference data and that obtained from the system under test are a result of the fact that the flow speeds achieved on this line are relatively low, and within approximately 5% of the detection threshold for the system. A variety of methods for improving the data quality for this zone are available, including moving the meter further along the pipe to a location more suitable for the application.

It was seen that air flow data could be obtained using the Doppler method, but that the data variance resulting from this approach was as significant as 10% of full scale. However, the primary challenge in data processing for this particular application resulted from the facts that (1) data were recorded manually and (2) limited opportunities for tailoring of the sound speed function were available. It is anticipated that future work will be done to enable rapid optimisation of the flow measurement routine for air flow applications, thereby creating the opportunity to extract accurate flow rates based on ambient noise.

Ultimately, the most important question for this technology relates to the potential application to mass pull control. This pilot has highlighted several features of the sensing architecture that make the optical system well-suited to the flotation sensing application: (1) the system can be installed non-intrusively, making it possible to execute large-scale installation operations without impacting plant production; (2) the metering system is multiplex-capable, so multi-zone installations incorporating as many as 20 independent metering zones can be incorporated along a single optical path; (3) the layout can be adapted to changes in the plant layout over time, for instance in cases where pipe sizes are changed by plant management; (4) data integration and advanced modelling can be accelerated as a result of the fact that multiple fluids, such as water, slurry, concentrate foam and air, can all be measured using a single optical network.

In cases where concentrate flows are a focus, it is envisaged that the system can reduce variability in mass pull-controlled operations, enabling production improvements. Alternatively, in the case of peak air schemes, where "the manipulation of the air addition rate offers the finest level of control of flotation cells", the application of this air metering technology on a cell-by-cell basis can enable the acquisition of key process control measurements (Shean *et al*., 2017)

It is anticipated that the next stage in this development collaboration will involve a pilot implementation of this new metering technology on several concentrate flows throughout a flotation bank. This will allow direct observation of the cell-by-cell mass pull and enable streamlining of the overall installation process.

CONCLUSIONS

An initial pilot for a new, non-intrusive fibre optic flow sensing method was executed at Mogalakwena North Concentrator. It was demonstrated that the system has the ability to measure gas, liquid, slurry, and, critically, concentrate flows. Because the sensing system is straightforward to retrofit in brownfield environments, and requires only low-cost, non-intrusive optical fibre to enable sensing, metering solutions can be envisaged whereby this technology will measure the concentrate and tailings flow from all flotation cells even within a large plant. Further, it was demonstrated that the metering system can be applied to air addition flows with an accuracy that is adequate for trending and control. As a result, the implementation of this technology could have positive implications for both mass pull and peak air control strategies in flotation metallurgy. This pilot installation provided the opportunity for the collaboration team to identify ways in which both the installation methodology and system control software can be improved in order to enable large-scale, permanent installations. It is anticipated that future work will capitalise on the lessons learned, and demonstrate large-scale flotation control using process metering technology.

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