Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

Flotation Control Incorporating Fuzzy Logic and Image Analysis:

P. Dawson*. R. Koorts.**

*FQML, Kansanshi, Solwezi, Zambia
(Tel: +260 (0) 96 584 3924; e-mail: peter.dawson@fqml.com).
**BluESP (Pty) Ltd, Johannesburg, South Africa
(Tel: +27 (0) 82 877 4457; e-mail ryan.koorts@bluesp.co.za)

Abstract: In the metals and mining industry flotation plays a vital role in selectively concentrating and separating valuable minerals from gangue minerals in a process slurry. The control of this has proved difficult in the past with large variations in concentrate grade and the recovery of the valuable minerals as has been experienced at FQML's Kansanshi site. The introduction of image analysis with online grade measurements paired with the advanced process control by means of fuzzy logic has enabled fast, more precise control of the flotation process. This has allowed experienced engineers, metallurgists and operators to build 'best practice control solutions' and deploy this with fuzzy logic, resulting in increased grade and recoveries.

1. INTRODUCTION

Flotation in the mining industry is a process for selectively concentrating and separating valuable minerals from gangue minerals in a process slurry. Along with mechanised mining, flotation is widely considered to have been one of the great breakthroughs in the mining industry. The process involves using a collector to render the valuable mineral surface hydrophobic, thus promoting its attachment to injected air bubbles and subsequent recovery in the froth overflow from an agitated tank. It can also work in the opposite with reverse flotation but that is not looked at here.

The two most important aspects when concentrating the valuable minerals through flotation are the grade produced and the recovery achieved. These two variables are inversely proportional and linked via a grade recovery curve with the aim of striking a balance between achieving maximum recovery at economically viable concentrate grades. The objective function is thus to maximise recovery whilst maintaining high concentrate grades. These variables are controlled via a combination of pulp level manipulation, air injection manipulation and reagent dosage manipulation. This paper looks at a current method of controlling the level and air set points as well as reagent addition to control the grade and recovery of copper in a flotation circuit at First Quantum Minerals' Kansanshi Mine in Zambia.

1.1 Current control and associated issues

Typical methods of controlling recovery and grade relied on lab assay results and a process operator's interpretation of these results. As can be imagined, there is a large time delay between lab analysis results indicating grade/recovery and an operator adjusting a level or air set point. This normally only happens periodically throughout a day giving very rough feedback flotation performance. Even with the addition of a neural network for estimated grade and recovery based on feed characteristics, it is difficult to maintain a solid handle on the grade and recovery. This, often coupled with highly variable feed grades, results in grade and recovery fluctuating over a wide range, with losses resulting from low recoveries worth substantial amounts of money.

1.2 Solution

The answer to this problem is a real time, fast feedback process control solution that consistently manipulates the air and level to optimise recovery while meeting a minimum grade set point. This is achieved by controlling the mass pull of the froth overflow from the flotation cells via air addition, pulp level and reagent addition whilst monitoring the characteristics of the froth. (B. Wright. 1999) mentions Glembotskii proposed factors and descriptions of froths and froth "quality" based on visual parameters/characteristics. Control of flotation circuits are based on monitoring these parameters.

The mass pull can be inferred from the froth velocity over the cell lip. The velocity is monitored by a camera system that performs image analysis on the surface of the froth in a flotation cell. This analysis measures the amount of bubbles present, their size, colour and most importantly their direction and speed of movement. The analysis is computed in an algorithm provided by Halcon Systems that is able to determine the mentioned parameters and have them available in an OPC friendly format.

The parameters are organised in a per cell format. Each flotation cell can be monitored at any time with a current break down of all the mentioned parameters. These parameters along with the image analysis and video stream feed are available for display on the operators' workstation, giving the operators the ability to quickly access the status of any cell at any moment. This negates the need to send an operator to the cell for inspection. These parameters are then used to give an accurate indication of the mass pull of the float cell.

With the addition of a grade analyser, these parameters can be combined to provide advanced control for the flotation circuit. This can allow expert operators to analyse the current state and manipulate changes to the air and level to drive the grade and recovery to its specified set points. This however requires constant monitoring of the system. An easier and more reliable way is to automate this in a control system. A method of implementing this advanced control is with the use of a fuzzy logic based advanced control system.

There are many advantages to using fuzzy logic as the basis for the control application. The first is that it is very easy to use and understand. Very little maths is used so it appeals to a wide range of plant personal and staff. This is one of fuzzy logic's greatest strengths. Fuzzy logic couples easily with descriptive terms that are often used in operating circles, allowing expert knowledge to be harnessed and applied in practice.

(G. C. Smith *et al*. 2004) explore in greater depths the challenges control faces in the flotation and comminution field, such as interaction between process units, large dead times, slow communications between field units and the controllers, non-linear systems, disturbances entering the process, processes with varying dynamics and many more.

(B. Wright. 1999) explores alternative methods for the control of flotation using visual factors, in particular the work of Kordek and Lenczowski in the late 1980s. Their work centred on the analysis of froth images by obtaining Optical Fourier Transforms (using a diffractometer) from images of both laboratory and plant froths. They mention that knowledge of the focal length of the transforming lens and the geometric dimensions of the detector allows the size of structures (in this case bubbles) in the analysed images to be related to light intensity distribution in the diffraction pattern.

2. HARNESSING EXPERT KNOWLEDGE

Fuzzy logic is able to provide programmable logic controllers with the ability to make "reasoned" decisions about a process and consequently allowing them to make independent output calculations resulting from system inputs. Fuzzy logic systems incorporate a three-step process, fuzzification, fuzzy processing, and defuzzification which evaluate system parameters. During fuzzification, the fuzzy system translates inputs into sets of data defined by membership functions and labels. In the second step of fuzzy processing, the system analyses the input sets by comparing them against a set of predetermined expert logic. And lastly during defuzzification, the system translates the fuzzy processing data into a control system output. Thereby, combining this three-step process, a PLC with fuzzy logic capabilities can sensibly determine the proper control response to system inputs based on collective predefined criteria.

Fuzzy logic thereby taps into the process knowledge of the operators and metallurgists to build a 'best practice' control solution. This knowledge takes the form of knowing for example how much level to increase to improve recovery by "a little", how much air to cut back on to reduce the bubble count by "a lot" etc. This knowledge is built into a data base under the form of fuzzy logic.

This is in the form of fuzzy sets for the range of velocities, grades, recoveries etc. The following figure (Fig. 1) is a fuzzy set example for velocity with five membership functions, Very Slow, Slow, OK, Fast and Very Fast.

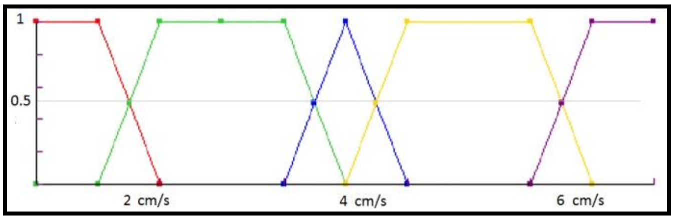

Figure 1: Five membership function for velocity of froth

The velocity reading is fuzzified with a fuzzy set, as in the example above (Fig. 1), according to the velocity reading computed in the image analysis engine. For example a reading of 6 cm/s would be fuzzified as being in-between high and very high. This is then added as an input to logic built by plant engineers and operators, termed earlier as 'Expert Knowledge' where it is used in deciding the next control move, if any.

During defuzzification the logic built around the 'Expert Knowledge' computes an output into a real control action. The following is a defuzzy set example for a velocity on a particular cell. Using the velocity measurement, with additional parameters such as grade and recovery values, the logic computes whether there should be an increase or decrease in froth velocity. In the example below (Fig 2), the severity of this action is defuzzified into a step change in level. Similarly, there are defuzzy sets for air addition and reagent dosage.

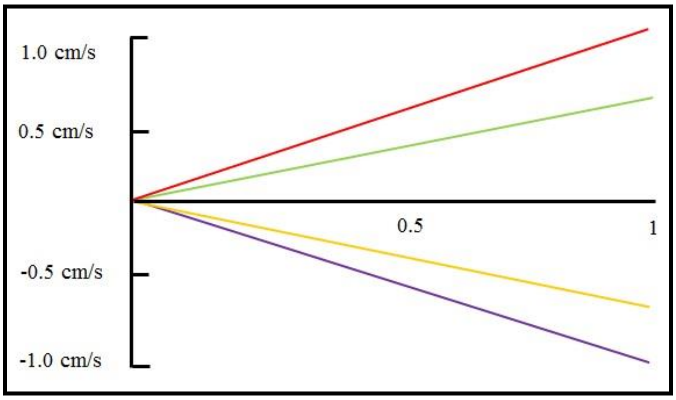

Figure 2: Velocity defuzzy set

3. HARDWARE

The general hardware involved with the image analysis consists of the following:

- Camera for image capturing
- LED / IR light for night / low light operation
- POE injector
- Network switch
- Field panel

3.1 Hardware setup

The power for the camera is supplied via a POE (power over Ethernet) injector and fed via an Ethernet cable. This POE is located in the field in a panel where a power supply powers the injector. Depending on the amount of cameras in a bank of cells, a field panel can have any number of cameras linked to it, feeding the information back to the control room via either a copper or fibre optic cable. Cameras are houses in rugged 'manufactured on site' boxes. These boxes aid to a degree in protecting the cameras from rain, direct sunlight and dust. They are also used to position the cameras over the flotation cell allowing for direct image capture of flotation froth, close to the overflow launder. In addition to the camera mounted in the box, LED or IR lights are used to aid the capturing of images with low light conditions. These lights can either be powered via Ethernet or with a direct power supply. Axis cameras have been utilised due to their weather resistant and rugged outdoor properties.

The following (Fig. 3) is an example of the general hardware set up for one cell.

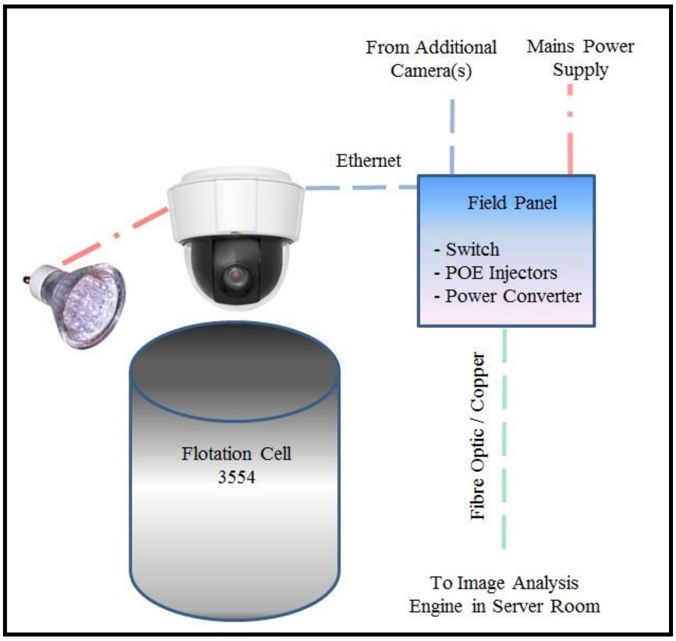

Figure 3: Image analysis hardware setup

4. HOW IT COMES TOGETHER

The advanced control solution ties the hardware with the expert knowledge to provide advanced control of the grade and recovery with minimal supervision. An image is captured with the camera and sent to the image analysis engine. This engine compares the current image with the previous image in an algorithm to determine differences in bubble position, size, count etc. The algorithm translates these differences into the meaningful parameters that we use such as bubble velocity, bubble count, bubble size, stability etc. The parameters are then configured in an OPC manager and read by the APC controller. This is combined with the additional plant data of grade and recovery from an XRF or defuse spectroscopy on-stream-analyser. The APC controller then performs fuzzification and compares these parameters with sets of data mentioned earlier as fuzzy sets (fuzzy processing) as well as rules defined by metallurgists, engineers and operators. The expert system individually looks at which manipulated variables to move and by how much, such as air or level. The outcomes of these rules and fuzzy sets are then defuzzified to provide a control action as an output for the DCS and plant. The following diagram (Fig. 4) illustrates this in the simplest manner.

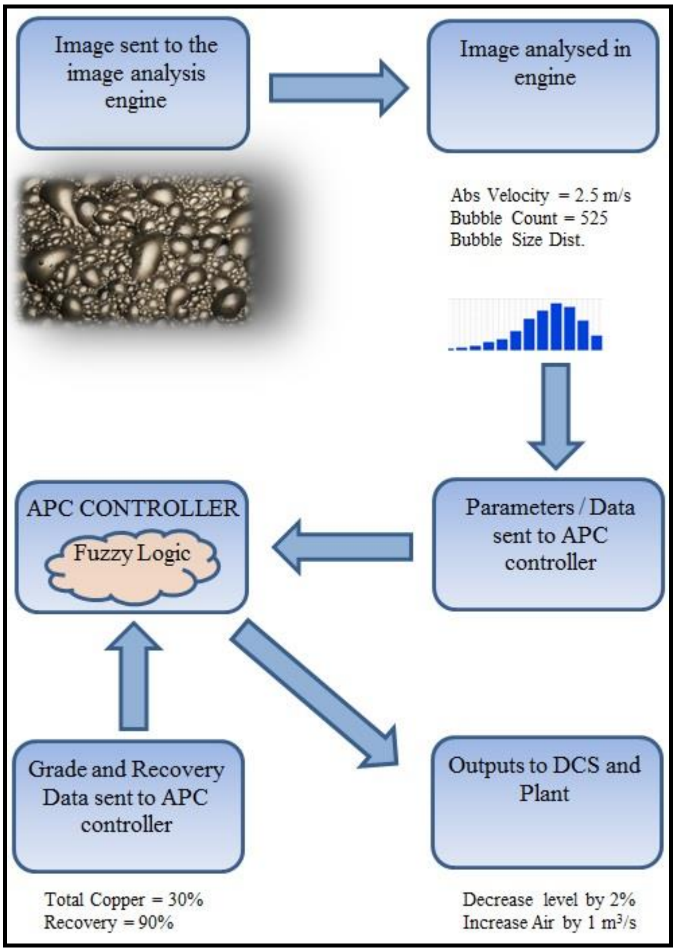

Figure 4: Image analysis execution process

The mentioned fuzzy processing and rule evaluation is represented in the following two figures. Figure 5 examines the rules and actions associated with the concentrate grade and recovery relationship. The amount of action required is dependent on the fuzzy grade associated with the three membership functions of the fuzzy processed data, Low, Ok and High. Figure 6 compares the current velocity value to the rate of change and looks at controlling the velocity to a set point by manipulating the air and / or froth depth.

Feed grade Ok logic table				
		Conc Grade low	Conc Grade OK	Conc Grade high
Rec low	FT3304	dec vel	inc vel	inc vel
	FT3305	inc vel	inc vel	inc vel
	FT3301	inc vel	inc vel	inc vel
	FT3302	inc vel	inc vel	inc vel
	FT3303	inc vel	inc vel	inc vel
	FT3306	inc vel	inc vel	inc vel
Rec OK	FT3304	dec vel	dec vel	inc vel
	FT3305	dec vel	inc vel	inc vel
	FT3301	inc vel	inc vel	inc vel
	FT3302	inc vel	inc vel	inc vel
	FT3303	inc vel	inc vel	inc vel
	FT3306	inc vel	inc vel	inc vel
Rec high	FT3304	dec vel	dec vel	no action
	FT3305	dec vel	dec vel	no action
	FT3301	dec vel	dec vel	no action
	FT3302	dec vel	dec vel	no action
	FT3303	no action	no action	no action
	FT3306	no action	no action	no action

Figure 5: Fuzzy Logic Sets and Rules

FT3304			
	Speed low	Speed Ok	Speed high
Speed dec fast	air inc fast, FD dec fast	air inc fast, FD dec fast	air inc, FD dec
Speed dec	air inc fast, FD dec fast	no action	air inc, FD dec
Speed stable	air inc, FD dec	no action	air dec, FD inc
Speed inc	air inc, FD dec	no action	air dec fast, FD inc fast
Speed inc fast	air dec, FD inc	air dec fast, FD inc fast	air dec fast, FD inc fast

Figure 6: Velocity control looking at velocity and ROC

5. PERFORMANCE ANALYSIS

Flotation performance, especially in large scale production environments, has long been considered to be part science and part the experience of the operators. The science part relates largely to which reagents are used and how they are dosed. This can be tested in laboratories and accurately measured in the field. The operators experience deals with the subjective decision making around mass pull management using pulp level and air addition. Even with the most experienced operators, consistent grade and recovery performance is rare.

With the development of imagining analysis techniques over the last few years, the ability to measure the froth velocity over the cell lip, and thus infer mass pull has become a possibility. This ability to measure and thus control mass pull has greatly improved flotation performance for operations with fairly consistent feed ore characteristics.

5.1 Velocity control

Left up to the operator to control, the velocity of the cell varies dramatically over a 24 hour period. This instability may be as a result of changes in ore characteristics, cell hydrodynamic changes such as pulp density, recycle stream disturbance or even changes in blower air pressure. The APC system can compensate for all of these disturbances by constantly manipulating the air and froth levels. This dramatically stabilises the cell mass pull, and thus improves performance. Figures 7 and 8 showcase the fluctuation in velocity of a particular cell with manual control (Fig. 7) and with APC control (Fig. 8).

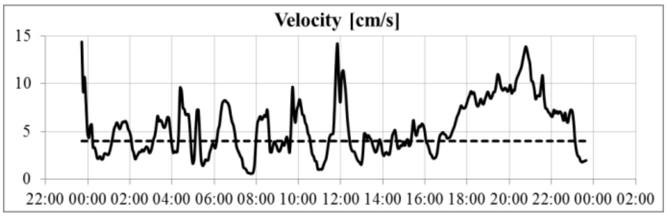

Figure 7: Velocity without APC control

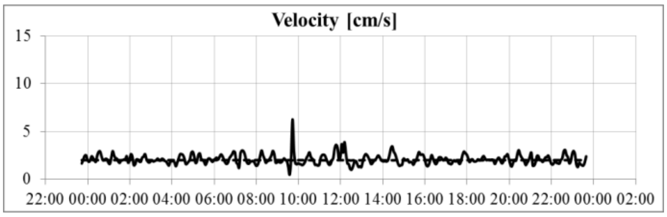

Figure 8: Velocity with APC control

5.2 Velocity control with inconsistent feed characteristics

For operations with highly variable feed mineralogy and grade, the real benefit of this technology comes in manipulating the mass pull based on real time grade measurements from on-stream grade analysers such as XRF instruments. As can be seen in the following three figures, the variation in feed characteristics is dealt with by constantly manipulating the velocity (Fig. 9) by level and air handles. This in turn enables the final recovery (Fig. 10) and grade (Fig. 11) of the concentrate to be controlled to a tighter band.

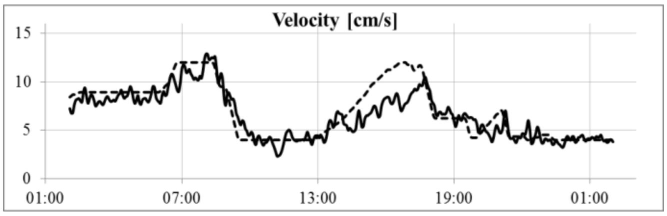

Figure 9: Manipulation of froth velocity

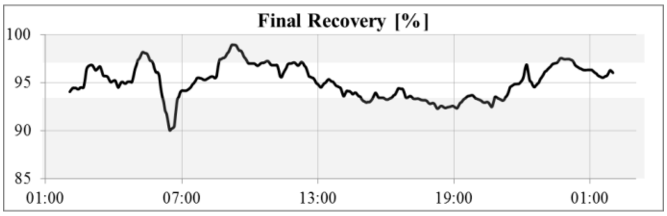

Figure 10: Final recovery

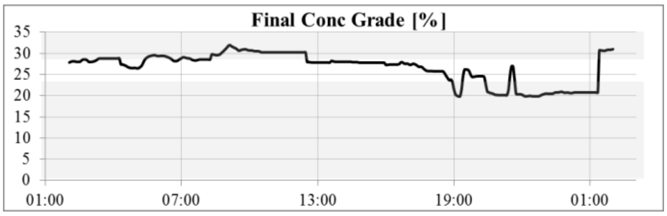

Figure 11: Final concentrate grade

This ability of a control system to respond to changes in feed ore characteristics is far superior to even the most experienced operators, not only reducing losses but improving end product quality and thus the performance of downstream processes.

5.3 Reagent control

Further to using advanced controllers to manage cell mass pull, it was decided to also incorporate the dosage of reagents to the APC system. Laboratory bench floats were used to determine the optimal collector dosage. Using the APC it is possible to increase or decrease the dosage rates within a set range of the base dosage rate in response to real time feed grade and recovery performance values.

The optimal reagent 'recipe' as mentioned holds a firm relationship to the copper in the float feed. As the copper in the float feed varies it is necessary to follow this with the reagent dosage. If the reagent dosage is set to a constant value then there will be times of over dosing as well as under dosing. This in turn results either in a costly waste of reagents and or decreased flotation performance.

The following two figures highlight this situation. The reagent addition to varying amounts of copper in the float feed without reagent APC control is represented in Figure 12. This shows a constant reagent addition. Figure 13 represents reagent addition with APC control. This shows optimal dosage of reagent addition in relation to the amount of copper measured in the float feed.

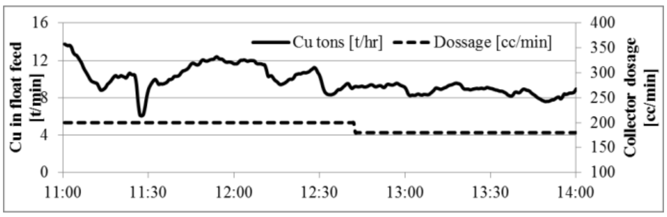

Figure 12: Constant reagent addition

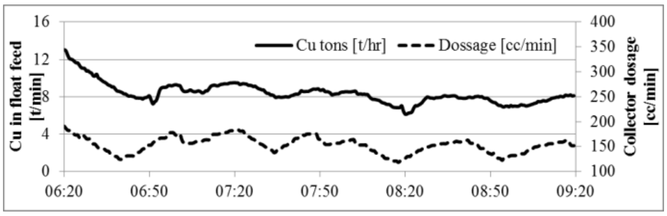

Figure 13: APC control on reagent addition

5.4 Results

Following the implementation of image analysis with fuzzy logic advanced control on the float cells, the recovery performance has increased by 1.0%, the final concentrate grade by 1.3% while the feed grade reduced from 0.81% TCu to 0.76% TCu. This is displayed in Table 1 and the grade and recovery performance curve in Figure 14.

Table 1: Grade and recovery results

	Feed TCu [%]	Final conc [%]	Recovery [%]
Before APC	0.81	23.5	92.4
After APC	0.76	24.8	93.4
Improvement	- 0.5	+ 1.3	+ 1.0

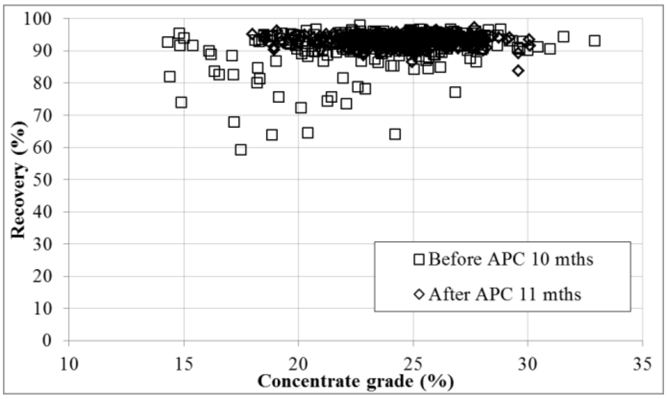

Figure 14: Grade and recovery performance curve

6. DISADVANTAGES AND POSSIBLE IMPROVEMENTS

(S. H. Morar1, M. C. Harris1, D. J. Bradshaw, 2011) showed that although in narrow operating conditions there are links between froth surface descriptors and flotation performance, no universal link exists to directly relate froth surface descriptors to froth performance behaviour. These findings have been mirrored in practice, most notably in circuits with highly variable ore feed grades and mineralogy's. Here the range of bubble sizes, stabilities, surface textures count etc. is so great that no consistent correlation can be achieved to be functionally added to the control system. As such, the froth velocity and direction are the most reliable characteristics for use with advanced control systems.

The calibration of the cameras and images is very important for providing an accurate basis for froth performance and judgement. Accurate size calibration is required for the deduction of bubble sizes. This is done manually by measuring a known length with a captured image and setting its length within the analysis engine. This however opens up the likelihood of error where the level of the froth falls or rises over time with control. This change in level throws out the calibration leading to a difference in actual bubble size and computed bubble size. A possible way to improve this is with the addition of a laser level sensor with interpolated calibrations with differing levels.

The positioning of cameras is also important in determining the froth bubble speed and direction. If the cameras are incorrectly positioned the calculation of the velocity can be skewed. The positioning of the camera determines the direction of froth flow and thus allows for the calculation of absolute velocity. It is also important that there is no interference by sunlight. This type of interference causes 'white' areas which cannot be analysed.

The size of the bubbles and stability of the froth can also lead to problems with measurement. A known issue is that when bubble sizes become very small the image analysis engine struggles to identify them. This is similar with an unstable froth where breakage of the bubbles occurs rapidly. The engine therefor struggles to compare images as it cannot track the actual bubbles and subsequently gives poor readings. This affects the computation of size, count, size distribution and speed.

Cameras have been known to be effected by vibration caused by flotation cell agitators, along with other plant interference. This effects the images been analysed. The 'blurring' of the images due to plant vibrations results in inaccurate readings deduced by the image analysis algorithm. This can have ramifications involving the control of that specific cell. For example the bubble size reading may read too small where in fact it is in a suitable range. This can cause a control action such as reagent set point change which is not required, that moves the cell into a lower performing region. A possible solution is to add dampeners to each camera box to absorb the vibrations. This has been trialled on one camera where excessive vibrations were being experienced. The addition of rubber hosing between the camera and it's attachment to the camera housing has notably improved image quality to the point where control is possible. This should be rolled out in future camera enclosures to insure minimal vibrational interference.

7. CONCLUSION

The introduction of image analysis with online grade analysers has significantly improved the performance of flotation circuits at FQML's Kansanshi site. This has been proven for both sulphide and mixed oxide circuits where copper ores have been floated to form a concentrated slurry. Image analysis coupled with fuzzy logic as well as reagent addition control, has provided a foundation for expert knowledge to be utilised in 'best practice' situations to constantly monitor and control both grade and recoveries to a tighter and higher level. Performance analysis has been conducted in the form of before / after tests to showcase the positive effect of the advanced system. The recovery performance increased by 1.0% and final concentrate grade by 1.3%, while feed grade reduced from 0.81% TCu to 0.76% TCu. There is still room for improvement within control of flotation using image analysis. Vibrational interference along with calibration of the cameras, froth stability, size and positioning can significantly affect the image analysis and consequently the control of variables such as bubble count and velocity. Alternative methods exist for the control of flotation using visual factors. Kordek and Lenczowski presented work on analysis of froth images by obtaining Optical Fourier Transforms (using a diffractometer) from images of both laboratory and plant froths. Other non-machine vision control techniques rely on the measurement of the density and flow rate of the concentrate that is produced from groups of float cells. This method may provide a more accurate indication of actual mass pull, but relies on the inference that the ratio of each cells' contribution to the total is roughly consistent.

Looking to the future of flotation control, machine vision technology would seem to offer the greatest potential for control improvements based on the number of measurable variables it could potentially offer.

8. REFERENCES

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