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Effect of air profiling and frother concentration on a flotation bank performance

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Abstract: The impact of air distribution on the metallurgical performance of a flotation bank operating with a mineral slurry having a moderate and high frother concentration is assessed. A flotation bank of two and three 5L Denver cells was implemented, and air flow was distributed down the bank as increasing and decreasing profiles. It was observed that when operating the bank configurations with a moderate frother concentration (10 ppm DF 400) the increasing profile provided the highest Cu enrichment ratio at the expense of a slight reduction in Cu recovery. This increase in selectivity was mainly due to a significant reduction in the water recovery and mass-pull in the first cell. When the bank operated with a high frother concentration, i.e., well beyond the CCC, a significant increase in water recovery was observed, producing a significant loss in selectivity that could not be compensated by air profiling.

Keywords: flotation banks, air profiling, frother

1. Introduction

Flotation is a process to continuously produce a concentrate of valuable hydrophobic minerals by selective capture and separation of hydrophobic particles on the surface of bubbles. The process is carried out in cells operated to create two zones: a collection zone to form bubble-particle aggregates by collisions of rising bubbles and suspended particles, and a froth zone to concentrate and separate the aggregates to form a concentrate; an interface separates both zones. The required residence time to achieve a target performance is provided by forming a bank connecting several cells in series; generally, additional flotation stages are necessary to improve the quality of the rougher concentrate produced, and a circuit is formed by adding cleaner stages to refloat a concentrate, and scavenging stages when a tails stream is reprocessed. For example, one of these circuits is illustrated in Fig. 1.

The operation of individual cells is based on controlling the gas flowrate used to generate a population of bubbles, the concentration of a frother in the pulp to reduce or eliminate bubble coalescence, and the distance between the interface and the cell lip (froth depth) to establish the residence time of bubble-particle aggregates in the froth zone. Gas flowrate and froth depth setpoints for individual cells are operator decisions, but in the case of frother concentration, the mineral pulp is dosed to have a stable selected concentration that is circulated along the whole flotation circuit.

Frother in the feed to a bank of cells divides into the concentrate and tailings stream. As the process separates particles with different valuable mineral content, the same frother concentration was expected in these streams. However, measurements have demonstrated that the frother concentrations are significantly different, much higher in the concentrate than in the tailings stream. This phenomenon (frother partitioning), which always occurs to some degree regardless of frother type and flotation machine, is the result of frother adsorption on the surface of bubbles generated in the collection zone, removing some frother from the pulp in the collection zone, and their bursting in the concentrate stream after rising and overflowing the collection and froth zones, releasing the adsorbed frother into the concentrate liquid phase. Although the frother released into the concentrate is always a fraction of that adsorbed on the bubbles in the collection zone, the undetected drop of concentration in the tailings

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stream and the high concentration measured in the concentrate stream reflect the high and small volumetric flowrates of these streams, respectively. Fig. 2 illustrates measurements of frother partitioning in the flotation circuit depicted in Fig. 1.

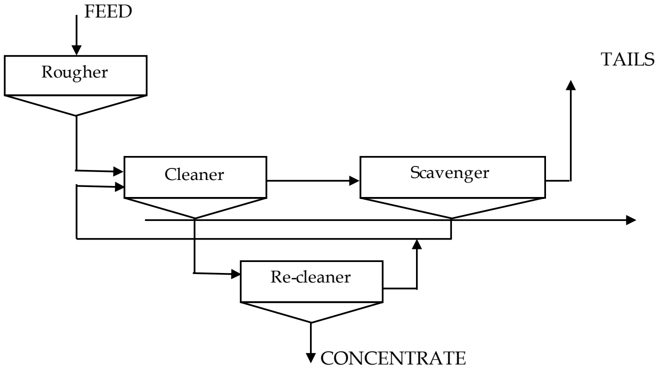

Fig. 1. Typical flotation circuit, including roughing, cleaning, and scavenging stages

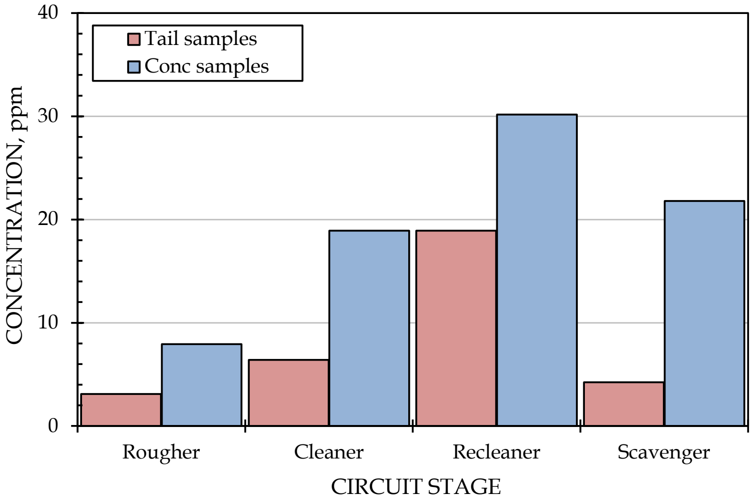

Fig. 2. Frother partitioning in a flotation circuit

Optimizing banks is a complex task as the contribution of local changes in the operating condition of a given cell on the overall bank performance is not directly measured, which limits, for example, the application of the dynamic programming technique developed for optimizing serially structure processes (Bellman, 1957; Aris, 1964; Ray and Szekely, 1973). Several strategies have been proposed to optimize banks, such as air profiling (Cooper et al., 2004; Aslan and Boz, 2010), mass pull profiling (Supomo et al., 2008), and peak air recovery (PAR) strategy (Hadler et al., 2009; 2010; 2012).

Setting an increasing air rate profile down the bank has been found to improve selectivity against sulfide and non-sulfide gangue, usually at the expense of a slight reduction in overall recovery (Cooper et al., 2004; Aslan and Boz, 2010). These results have been mainly obtained for cleaner banks, and the increase in selectivity is attributed to a significant reduction in the mass pull in the first cells.

Using simple fully mixed kinetic flotation models, Maldonado and co-workers found that a balanced cell-by-cell recovery provided the highest separation efficiency, measured as the difference in recovery between two floatable minerals, for a target bank recovery (Maldonado et al., 2011). This theoretical analysis was then extended to the case of separating a floatable from a non-floatable mineral using the JKSimFloat simulator (Singh and Finch, 2014). A balanced mass-pull profiling provided the best results, closely followed by a balanced recovery profiling. In both cases, the rationale is that over-pulling in the first cells cannot be compensated down the bank due to the bank's serial structure. Recently, Finch and Tan, (2022) analyzed some industrial data available in the light of the mass-pull profiling strategy and found that the data supported the theory. Unfortunately, data is scarce and corrupted by process variations.

It is known that different mechanisms govern the recovery of hydrophobic and hydrophilic minerals. The first one, referred to as true flotation, relies on the selective attachment of hydrophobic mineral particles to air bubbles. In contrast, recovery of gangue minerals by entrainment is governed by the action of ascending swarms of bubbles that mechanically and unselectively push pulp into the froth (Smith and Warren, 1989). The entrainment of finely gangue particles strongly correlates to water recovery (Wang et al., 2015).

Recent investigations have found that gas holdup underneath the froth is essential in predicting water transport and mass pull (Moyo et al., 2007; Martinez et al., 2020; Femenias et al., 2022). In practice, gas holdup can be varied by modifying the air rate and the type and concentration of frothers (Yianatos and Finch, 1990). For a given gas rate, the increase in frother concentration results in an exponential decrease in bubble size, translating into an increase in gas holdup (Azgomi et al., 2007). The critical coalescence concentration (CCC) allows us to identify two operating zones: a low-concentration region where bubble size is sensitive to concentration variations and a high-concentration region where bubble size almost no longer varies with frother (Cho and Laskowski, 2002). Excessive frother concentration incurred economic costs and favored water recovery and gangue entrainment, reducing selectivity; Finch and Wills, (2010) suggested operating slightly above the CCC. Unfortunately, frother partitioning, water recirculation containing remanent frother, and the lack of a simple and reliable method to measure frother concentration make industrial frother control very challenging. For example, it has been observed that, due to frother partitioning, frother concentration in cleaner stages can be significantly higher than in the rougher stage, which compromises selectivity (Zangooi et al., 2010; Zangooi et al., 2017). A novel frother chemistry that behaves as a strong frother in the rougher stage and switches to a weak one as pH increases in the cleaner stage may help to mitigate the loss in selectivity due to partitioning (Bhambhani et al., 2023). Although previous results on air profiling have focused on cleaner stages, no information regarding frother concentration has been reported.

This paper assesses the impact of air distribution on the performance of a bank of two and three laboratory flotation cells when operating at a frother concentration slightly beyond and well beyond the critical coalescence concentration.

2. Materials and methods

2.1. Setup

Flotation banks made of two and three laboratory flotation cells were implemented. **Fig. 3** illustrates this setup for the case of a bank of three cells. Denver 5L flotation cells were used, such as those typically used for batch flotation testing. Flotation vessels fabricated on transparent plastic were modified to allow continuous feed and discharge of mineral slurry. The feed, tails, and intermediate flows between cells were manipulated using variable-speed peristaltic pumps (MasterFlex model 77601-00). Superficial gas velocity in each cell was continuously regulated using mass flow controllers (MKS model GE50A for the first two cells and Aalborg model GFC37 for the third cell). Sensors/Actuator signals were centralized in an I/O system (Schneider Electric, model Advantys) connected to a computer running iFIX 5.0 (General Electric) as HMI software.

An arrangement of 150L and 60L conditioning tanks, equipped with internal circulation inlets, double impeller, and baffles, as shown in Fig. 4, proved to maintain feed properties invariant during the test duration. The pulp level in the 60L tank was kept regulated during the test to provide constant inlet pressure to the pump feeding bank.

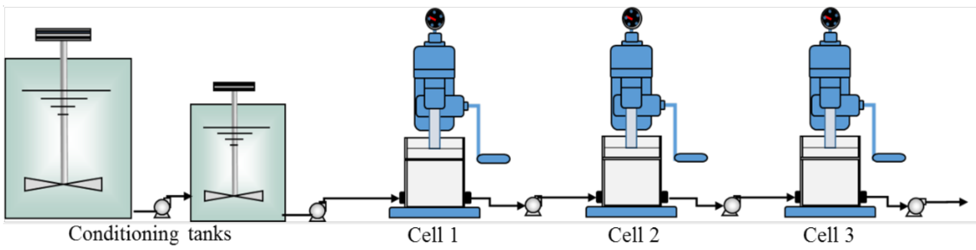

Fig. 3. Illustration of the experimental setup for a bank of three cells

Fig. 4. (a) Conditioning tanks: 150L (blue) and 60L (black); (b) Interior view of the larger tank

2.2. Methodology

The flotation testing used ore from the Candelaria Mine in northern Chile. The primary sulfide minerals present in the ore are chalcopyrite, magnetite, pyrite, pyrrhotite, and sphalerite. Biotite, calc-silicate minerals, potassium feldspar, and magnetite constitute the gangue minerals. The ore was primarily reduced in size in a jaw crusher, followed by a dry ball mill grinding to produce cumulative size distributions with an F80 around 155 µm. After that, a sample was sent for wet Cu chemical analysis. For each bank flotation test, 85 kg of mineral finely ground was combined with 200 kg of Santiago's tap water (0.7-0.8 mS/cm), forming a suspension containing 30% solids by weight. The natural pH of the slurry, 7.5, was modified by adding lime to reach a target value of 10.5. Sodium isopropyl xanthate (ISPX) was used as a collector and dosed at a 5 g/t concentration. A polyglycol DF400 was used as frother with one of the two concentrations tested, namely 10 and 30 ppm. The slurry was conditioned with reagents for 10 minutes in the conditioning tanks, and then a constant flow rate was fed to the first cell of the bank. Each cell was operated at a fixed impeller speed of 1000 rev/min, and gas rate was provided and regulated using air mass flow controllers. A froth depth of 1 cm was regulated in each cell by visual inspection of the pulp-froth interface through the transparent flotation vessel and by manipulating the respective tailing pump speed. Froth overflowing was not disturbed during the tests, for example, by using mechanical scrapping. The steady-state condition was detected by monitoring froth depths and mass-pulls invariance to time after reaching three times the bank residence time. Once the steady-state condition was reached, samples were taken for metallurgical performance assessment. After filtering and drying, samples were sent for Cu and Fe wet chemical assays. In addition, solid content was also measured. A constrained optimization problem was formulated and solved using the Excel Solver tool for mass balance and data reconciliation (Wills and Finch, 2014).

The operation of a single cell was first characterized to determine the frother concentrations dosages to be used in the study. The Sauter mean bubble diameter was measured for different frother concentrations, slightly above CCC and well beyond CCC, and at different gas rates. For the continuous tests, the peristaltic cell was calibrated to deliver a slurry flow at a rate of 2.4 L/min. Two configurations were tested, i.e., a bank comprising two and three cells. Two superficial gas velocity profiles were implemented, i.e., decreasing and increasing profiles, as detailed in Table 1 for a bank of two cells and Table 2 for a bank of three cells.

Fig. 5 shows a photograph of the bank of three cells operating under a decreasing air profiling strategy and 10 ppm frother concentration.

2.3. Bubble size measurement

For a single-cell continuous flotation, bubble size was measured in an air-water system, using the McGill bubble viewer. Images were processed using the Image J software, which provides the major (d_M) and minor (d_m)diameters of an ellipse fitted to the contour of a bubble. The volume diameter (d_v) of each bubble was calculated from the major and minor diameter by using the following equation:

$$d_v = \sqrt[3]{d_M \cdot d_m^2} \tag{1}$$

The Sauter mean bubble diameter was then calculated from a set of N bubbles as follows:

$$d_{32} = \frac{\sum_{i=1}^{N} d_{vi}^3}{\sum_{i=1}^{N} d_{vi}^2} \qquad (3)$$

Table 1. Air distribution for a bank of two cells

	Jg (cm/s)		
Air profile	**Cell 1**	**Cell2**	**Total**
Increasing	0.5	1.0	1.5
Decreasing	1.0	0.5	1.5

Table 2. Air distribution for a bank of three cells

	Jg (cm/s)			
Air profile	**Cell 1**	**Cell 2**	**Cell 3**	**Total**
Increasing	0.5	0.75	1.0	2.25
Decreasing	1.0	0.75	0.5	2.25

Fig. 5. Bank of three cells operating under a decreasing Jg profile

3. Results and discussion

3.1. Feed characterization

The ore's specific gravity was measured to be 3.2 using the pycnometer technique. Fig. 6 shows the cumulative passing particle size distribution for six batches of 85 kg each; the average particle size, F80, was measured around 155 µm.

To verify that the solids concentration of the pulp fed to the bank remained invariant during a whole test, the slurry in the conditioning tanks 1 and 2 and the discharge of the first flotation cell (pulp agitated but not aerated) were sampled, and their solid content measured at regular intervals for almost 50 min. Fig. 7 shows that the proposed serial arrangement of two conditioning tanks ensures a constant pulp content fed to the bank during the test.

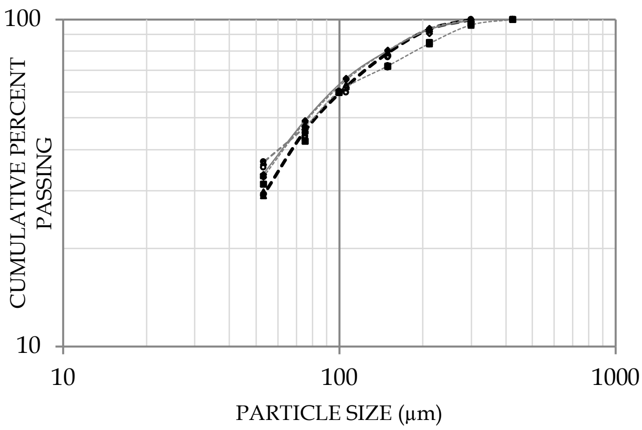

Fig. 6. Feed particle size cumulative distribution

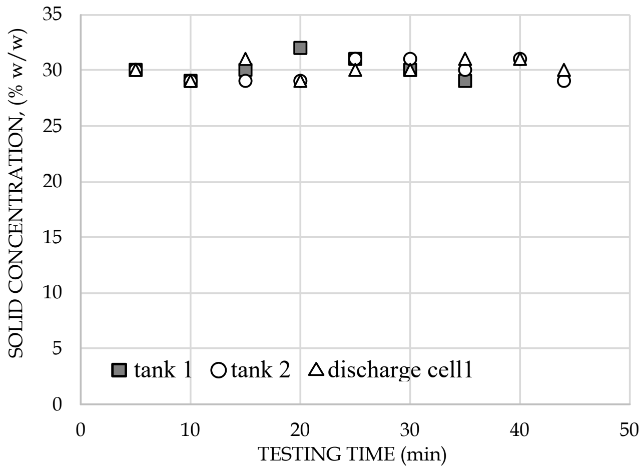

Fig. 7. Solid concentration variation in time

3.2. Bubble size vs frother concentration

Fig. 8 shows the bubble Sauter mean diameter (d32) as a function of the frother concentration for different gas velocities. Critical coalescence concentration, CCC, varied around 6 to 8 ppm. This study selected two frother concentrations for bank testing, 10 and 30 ppm, corresponding to a moderate and excessive frother concentration, i.e., well beyond CCC, respectively.

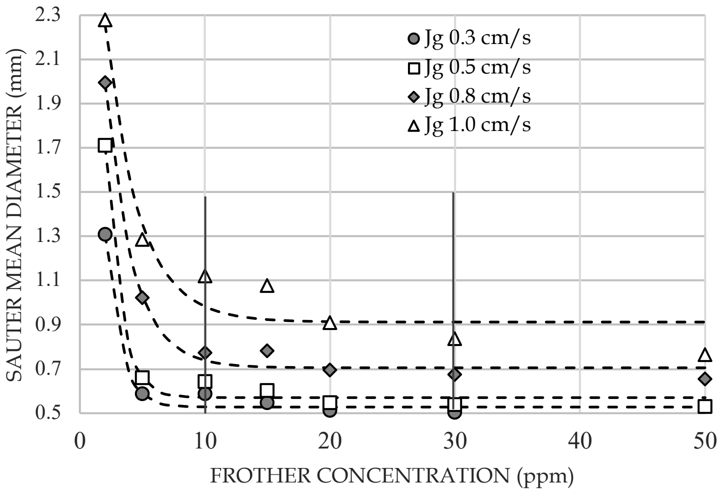

Fig. 8. Bubble size as a function of frother concentration for different gas rates

3.3. Bank performance

Fig. 9 shows the overall Cu enrichment ratio versus recovery for a bank of two and three cells operated under an increasing (Δ symbol) and decreasing (∇ symbol) air profiling and at moderate (10 ppm) and high (30 ppm) DF 400 frother concentration. It can be observed that for 10 ppm frother concentration, the bank metallurgical performance was sensitive to the adopted air distribution. Specifically, the increasing air distribution profile significantly increased selectivity, measured in terms of the copper enrichment ratio; it more than doubled that produced by the decreasing air profiling for a bank of three cells, however, at the expense of a reduction in bank recovery, i.e., one percentage point reduction for a bank of two cells and two points for a bank of three cells. This confirms previous reports of an increase in selectivity when implementing an increasing air distribution profile in cleaner banks (Cooper et al., 2004; Aslan and Boz, 2010). It can also be observed that as the number of cells increased, higher recovery and grades were achieved, but only when a moderate frother concentration was used.

As frother concentration increased from 10 to 30 ppm, a drastic reduction in copper enrichment ratio was observed for the bank of two and three cells, reaching a low value of around three points regardless of the adopted air distribution profile, as shown in Fig. 9. An increase in copper recovery accompanies this reduction in enrichment ratio.

Fig. 10 shows the resulting mass-pull profiles for a bank of two and three cells operated with increasing and decreasing air distribution profiles and at 10 and 30 ppm DF 400 frother concentrations. At a moderate frother concentration, i.e., 10 ppm, the increasing air profile produced a significant mass pull reduction in the first cell, resulting in a higher copper concentrate grade than the decreasing profiling. When operating the bank with a high frother concentration, mass-pull is reduced in the first cell but increases in the remaining cells, significantly reducing the enrichment ratio.

Fig. 11 shows the cumulative water recovery for the case of a bank made of three cells operating with a decreasing and increasing air profiling and moderate to high frother concentration. It can be observed that implementing a low gas rate in the first cell significantly reduces water recovery compared to that produced with a high gas rate, and this reduction is even more critical for a high frother concentration. Then, the increasing air profile preserves this reduction in water recovery down the bank, contrary to the high frother concentration case where the initial reduction in water recovery fades away.

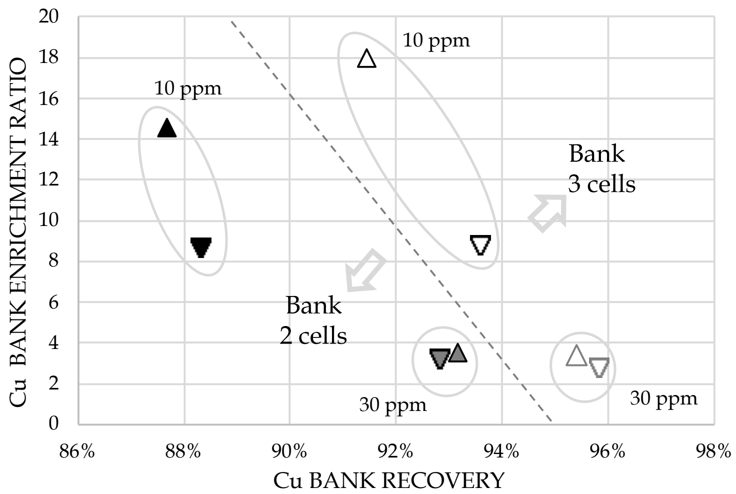

Fig. 9. Overall Cu enrichment ratio versus Cu recovery for a bank of two and three cells

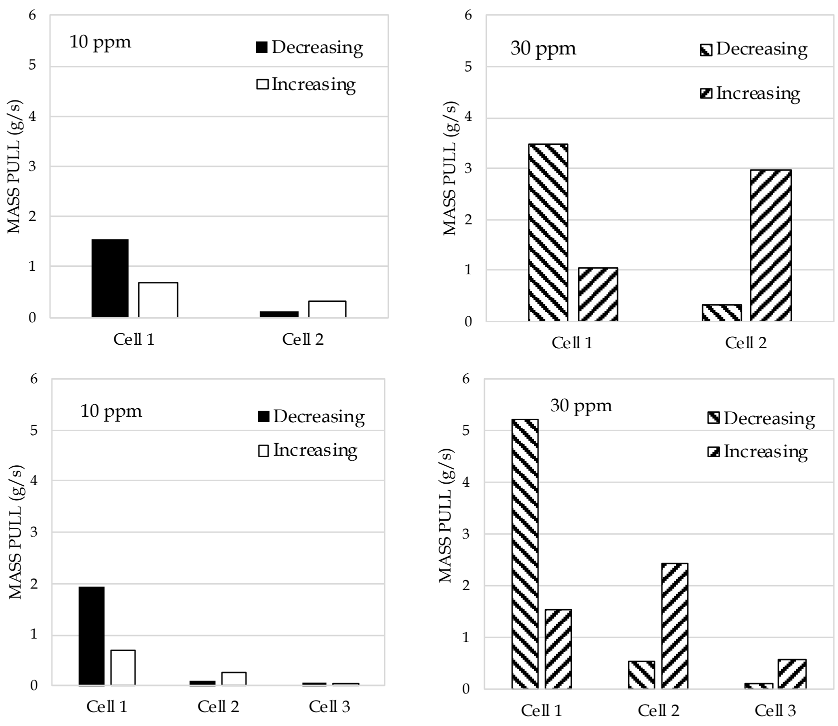

Fig. 10. Mass-pull distribution down the bank

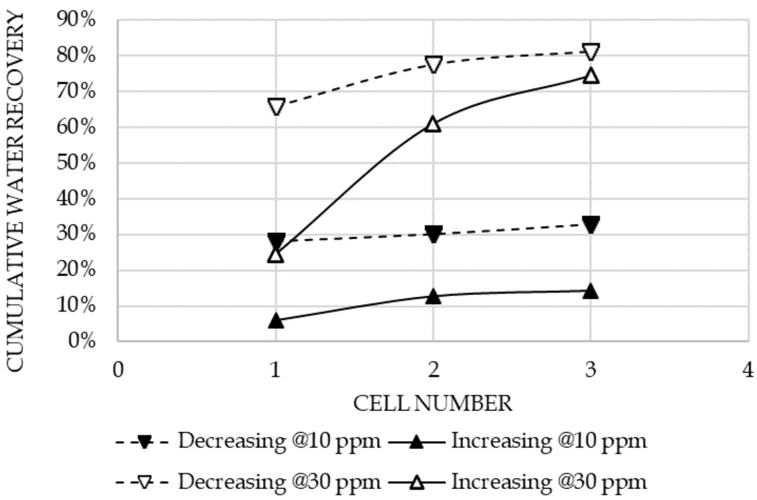

Fig. 11. Cumulative water recovery for decreasing and increasing air profiles and low and high frother concentrations

Despite the large variations in performance obtained when operating with different air profiling and frother concentrations, the overall weight recovery strongly correlated to the enrichment ratio, as shown in Fig. 12. This correlation had also been observed for industrial rougher banks operating with variations in pulp flowrate, pulp density, air flow, and pulp level (Yianatos et al., 2001). At moderate frother concentration (10 ppm), the Cu enrichment ratio varied between 8 and 18 points and was sensitive to air profiling changes; weight recovery kept lower than 10%. At 30 ppm, the Cu enrichment ratio became largely insensitive to air profiling, and weight recovery increased significantly.

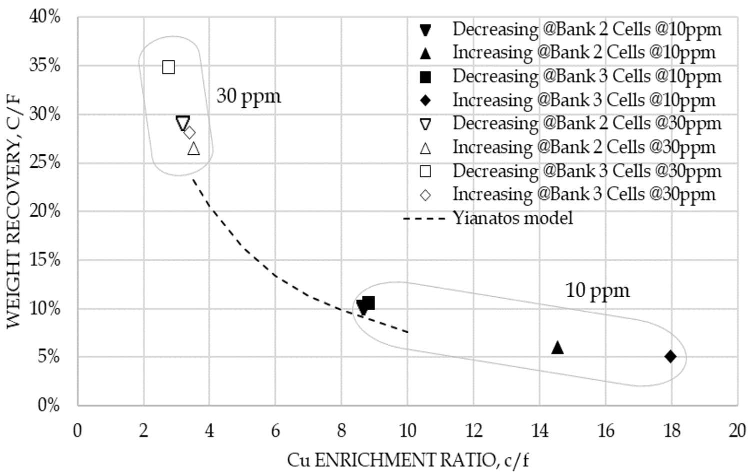

Fig. 12. Overall bank mass-pull versus copper enrichment ratio

4. Conclusions

The impact of air profiling on the performance of a bank of two and three laboratory Denver flotation cells was assessed when processing copper ore at a moderate (10 ppm) and high (30 ppm) DF 400 frother concentration. It was observed that at a moderate frother concentration, performance was sensitive to air distribution, with the increasing air profile resulting in a significantly higher selectivity, though at the expense of a slight reduction in recovery. When frother concentration increased well beyond the CCC, a large increase in water recovery was observed, producing a significant loss in selectivity that could not be compensated by air profiling. These results suggest that a frother concentration slightly to moderately beyond the CCC provides the balance in achieving high recovery in the rougher banks while not compromising selectivity in cleaners. Depending on cleaner stage capacity, gas rate profiling can be modulated in the roughing stage, while an increasing air profile would be preferred for cleaner banks.

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