OPTIMISING FROTH STABILITY OF COPPER FLOTATION TAILINGS

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ABSTRACT

Linking results from laboratory scale experiments to industrial flotation behaviour is challenging. Typically, such experiments involve batch tests in which the system does not operate at steady-state, making it difficult to infer the effects that operating conditions have on flotation performance. In order to overcome this limitation a 4-litre recirculating tank was previously developed at Imperial College London. This tank is capable of reaching, and operating at, steady-state by recycling overflowing concentrate back into the feed. As well as instruments to control operating conditions, it is fitted with a system of sensors that allow the surface of the froth to be dynamically monitored. From this information, it is possible to measure the air recovery—a proxy for froth stability. Thus, this bench-scale tank can be used to understand the effect of differing operating conditions on flotation performance at steady state. However, so far, this cell has only been used to investigate idealised systems with only one or two species.

Reprocessing of tailings dams is not only environmentally desirable but also increasingly economically feasible due to the declining head grades of primary deposits. There is also the added benefit of no further milling being required prior to flotation. However, the effects of fine and ultrafine particles on froth stability are not yet fully understood. In this work, the bench-scale continuous tank has been used for the first time to determine the flotation response of a complex feed, consisting of samples from a copper tailings dam, to changes in operating conditions. It was shown that the froth stability in the system is comparable to that of previous work and industrial tests, with a peak in air recovery being found at a superficial gas velocity of 1.13 cm/s. There is scope to optimise the froth stability of tailings flotation for enhanced metallurgical performance.

KEYWORDS

Froth flotation, Stability, Air Recovery, Copper Tailings, Continuous Flotation

INTRODUCTION

The global demand for metals, such as copper, is increasing, putting a strain on the mining companies as head grades of deposits are decreasing. At the beginning of the 20th century copper tailings dams had a grade of 0.75% compared to only 0.14% today (Gordon, 2002). This drop is due to an improvement in processing efficiency (Falagán et al., 2017). Reprocessing these historic tailings dams can therefore be attractive to the mining industry, as they are relatively high grade. There are also other benefits, for instance there is no comminution requirement.

Added to this, by reprocessing the waste material mining companies can reduce the significant environmental problems associated with tailings dams (Chen et al., 2014). It is therefore vital to carry out research into understanding the effects of different operating conditions on the flotation performance of tailings material.

Due to the complexities involved with carrying out experiments in an industrial setting, a vast amount of flotation research is done at the laboratory scale. The majority of laboratory scale testing, for mechanically stirred flotation, uses batch tests, e.g. a Denver cell (Wills & Napier-Munn, 2006). These are relatively simple and easy to conduct and are often used due to their suitability for optimising flotation chemistry. However, they are limited by not operating at steady state. A continuous flotation cell has been developed by Norori-McCormac et al. (2017). In this cell the overflowing concentrate is pumped back into the pulp phase allowing steady state to be achieved and maintained for over an hour. This is extremely beneficial to laboratory research as it provides a better comparison to industrial flotation.

In order to relate experiments to industrial processes it is important to be able to quantify the flotation performance. There are various different metrics commonly used to do this, with grade and recovery being the most obvious. Another valuable performance indicator is froth stability. There are several different measures of stability depending on the type of system being investigated. When considering a continuous system, air recovery, or the fraction of air entering the cell that over flows the lip, is a robust measure. It is defined in equation 1:

$$\alpha = \frac{v_f.h.w}{Q_a}, \qquad (1)$$

where α is the air recovery, v_f is the overflowing froth velocity, h is the height of the overflowing froth over the cell lip, w is the overflowing lip length and Q_a is the flow rate of air into the cell. It is important to note that the relationship between air recovery and air rate is not linear, Hadler & Cilliers (2009) established that, when increasing the air rate a peak in air recovery can be seen. This is due to a trade-off between stability and mobility. Hadler et al. (2010) demonstrated that, in an industrial setting, changing the air flowrate to the PAR caused an increased mineral recovery with only a small drop in the grade of the concentrate.

Norori-McCormac et al. (2017) used the continuously overflowing flotation cell, as described previously, to investigate the relationship between particle size, superficial gas velocity and air recovery. This system used only a single species, silica, in order to have a better control on particle size and remove oxidation or liberation effects. The results showed that at the highest air rates a finer feed particle size distribution results in higher air recoveries and therefore more stable froths. However at the lowest air rate an intermediate particle size gave the higher air recovery, suggesting that the relationship is complex. It was also shown that the system was comparable to industrial froths, especially when considering the peak in air recovery. Aktas et al. (2008) also studied the effects of particle size on froth stability. This work used a platinum group metal (PGM) ore in an adapted Denver cell as used by Barbian et al. (2003). The results showed a decrease in froth stability with an increase in particle size, again showing that fine particles produced a more stable froth. It is important to note that the measure of froth stability used here is dynamic froth stability and not air recovery. McFadzean et al. (2016) also found the same relationship between particle size and froth stability, again using dynamic froth stability and a PGM ore.

This work expands on that done by Norori-McCormac et al. (2017), by using the same continuously overflowing flotation cell, however instead of a single species system a copper tailings ore is used. This allows a closer comparison of the cell to industrial systems. It also makes it possible to better understand the relationships between different operating conditions, particularly particle size and superficial gas velocity, and froth stability for a copper tailings ore.

MATERIALS AND METHODS

Materials

The samples used in this study were obtained from a processing plant that reprocesses both historic and fresh copper tailings. These have grades of 0.27% Cu and 0.12% Cu respectively. Due to the nature of tailings, approximately 50% of the material entering the plant is less than 10µm. The plant uses a primary hydrocyclone to split the material, the overflow has a d90 of 63.7µm and the underflow 279µm (figure 1). Samples were obtained, from both the overflow and underflow streams, as a slurry which was then dried. This allowed the two sizes to be combined in different ratios to produce three different particle size distributions investigated in this work (table 1).

Table 1 – Particle size distributions for three different feeds when combining overflow and underflow material in different ratios

Overflow	Underflow	d10, µm	d50, µm	d90, µm
0.75	0.25	3.4	36	117
0.25	0.75	5.0	82	225
0	1	5.8	105	279

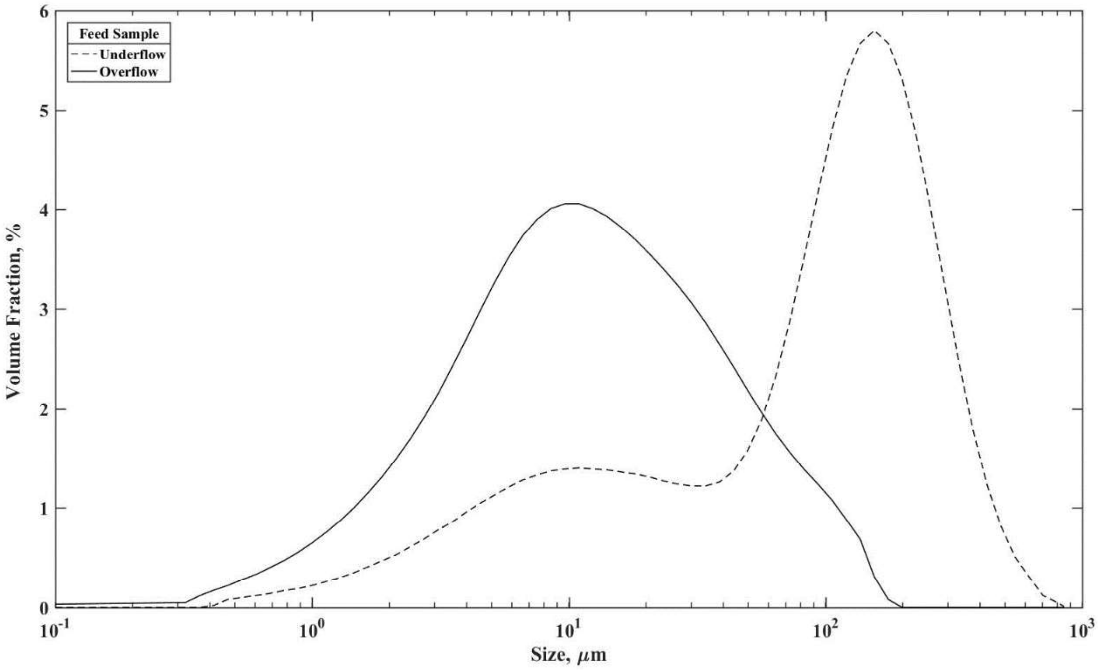


Figure 1 – Particle size distributions of the overflow (solid line) and underflow (dashed line) streams

The reagent environment used here was developed by Molina et al. (2016). The collector used was Sodium Isopropyl Xanthate at 50 g/t and the frother was DowFroth 400 (supplied by Nasaco Ltd.) at 20 g/t. Lime, *CaO* (supplied by Arcos Organics), was used to ensure a constant pH of 9 across all experiments.

Experimental System

The experimental system used in this work is a four litre recirculating cell developed by and described in Norori-McCormac et al. (2017). The overflowing concentrate is pumped back into the cell allowing for continuous operation and for steady state conditions to be achieved. A schematic of the cell can be seen in figure 2.

For each experiment 900*g* of copper tailings, with the three different size distributions in table 1, were combined with 2.9*L* of deionised water to form the slurry. This was then added to the cell with the frother and collector and agitated, at 950 rpm, to condition for 15 minutes. Three different air rates were used across the experiments, 0.65, 0.92 and 1.18 cm/s, and combined with three different impeller speeds, 800, 950 and 1100 rpm. As a full factorial of the three variables at three levels would be time consuming and so a Box-Behnken fractional factorial design was chosen instead. This is a standard fractional design which is considered sufficient, balanced, orthogonal and rotatable, which reduces the required number of experiments from 27 to 15. Seven different conditions were run, including repeated conditions, in each experiment giving a total run time of 1 hour and 45 minutes.

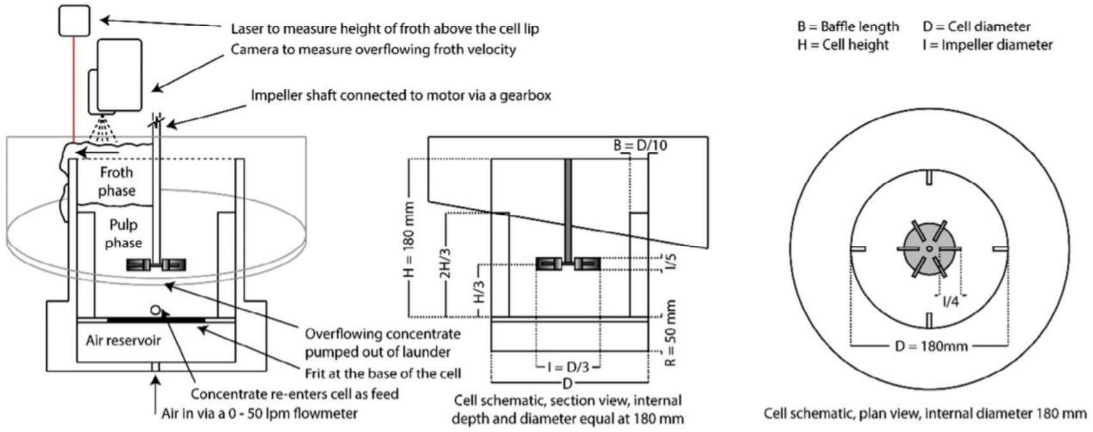


Figure 2 – A Schematic of the four litre recirculating cell (Norori-McCormac et al., 2017)

At each of the operating condition combinations, the system was conditioned for 5 minutes before measuring the overflowing froth height and velocity for a period of 10 minutes. An on-line laser (ifm electronics, 01D300) was used to measure the height via LabVIEW. A web camera (Logitech, C525) was combined with FrothTracker, an in house image analysis program, and used to measure the froth velocity. These values allowed air recovery to be calculated using equation 1.

RESULTS AND DISCUSSION

A stepwise linear regression was performed to obtain a model for how the particle size, *d90*, impeller speed, ω_i, and superficial gas velocities, J_g, affected the froth stability of the system. Four predictors were used in the initial model, the three key factors in the experiment as well as the time that condition was run from the start of the experiment. Each of the predictors were normalized between -1 and 1 in order to negate the effects of the different orders of magnitude of each predictor. The resulting model would take the form of equation 2, where *y* is the response, *a* is the coefficient and *P* is the predictor.

$$y = a_0 + a_1.P_1 + a_2.P_2 + \dots + a_{1,2}.P_1.P_2 + \dots + a_{1,1}.P_1^2 + \dots \qquad (2)$$

Using a 95% level of significance, or a p-value of less than 0.05, the only terms that were left in the final regression model were particle size, impeller speed, superficial gas velocity and the superficial gas velocity self-interaction. This model has an adjusted R^2 value of 0.887 and a p-value of 1.04×10^{-7} with 15 degrees of freedom. The coefficients, standard error and p-values for each of the variables in the model are seen in table 2 (all values given to 3.s.f). This resulted in equation 2 becoming the final model given in equation 3. When a model has multiple key predictors it can be challenging to uncouple the effects of each. One of the ways to do this is to use an adjusted response. In this case this is the response of air recovery to changes in one of the predictors whilst controlling for all other predictors.

Table 2 – Stepwise Linear regression model coefficients, standard errors and p-values.

Predictor	Coefficient	Standard Error	p-Value

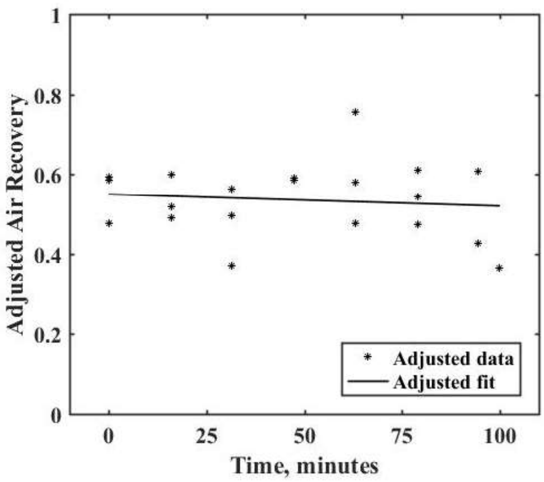
(Intercept)	0.561	0.024	4.25×10^{-13}
d90	-0.155	0.023	7.10×10^{-6}
ω_i	0.252	0.025	6.03×10^{-8}
J_g	0.243	0.035	4.75×10^{-6}
J_g^2	-0.146	0.041	2.69×10^{-3}

$$\alpha = 0.561 - 0.155*d90 + 0.252*\omega_i + 0.243*J_g - 0.146*J_g^2 \quad (3)$$

One of the key requirements of this continuous system is that it performs at a steady state over a long period of time. Figure 3 shows the adjusted response of time on the air recovery with a near flat adjusted fit. The p-value of the time is 0.699, far higher than the 0.05 needed for a 95% level of significance. This indicates that the system is performing at steady state over the 1 hour and 45 minutes of each experiment.

Figure 3 – Adjusted response of time on air recovery

Figure 4 shows the adjust response of varying the d90, impeller speed and superficial gas velocity on the air recovery. The relationship between d90 and air recovery, figure 4a, is linear but negative, meaning that, in the range tested, the presence of larger particles destabilizes the froth. The relationship seen here is observed in other studies that use varying types of ore (Aktas et al., 2008 and McFadzean et al., 2016). The effect of the impeller speed, figure 4b, is also linear, but positive in that increasing impeller speed, within the range tested, will increase the stability.

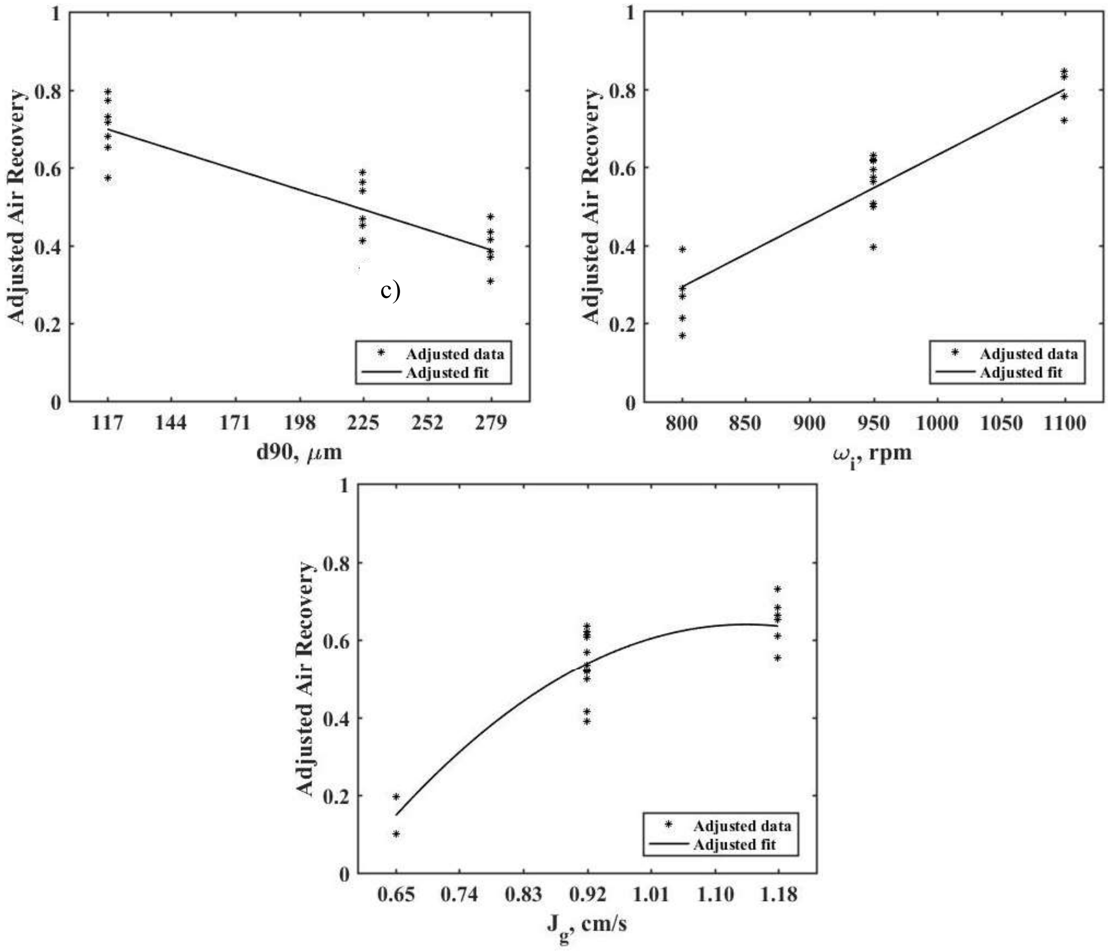


This is due to an increase in the overflowing froth velocity.

a) b)

Figure 4 – Adjusted response the three different predictors on air recovery, a) Particle size, *d90*, b) Impeller speed, ω_i, c) Superficial gas velocity, J_g,

Unlike the other two variables, superficial gas velocity has a self-interaction, resulting in the quadratic



relationship with air recovery as seen in figure 4c. Here there is a turning point in air recovery at a superficial gas velocity of approximately 1.13 cm/s. This indicates the presence of a peak in air recovery, as previously seen in Hadler & Cilliers (2009). This is also similar to the values of superficial as velocity where a peak in air recovery is seen at industrial scale (Hadler et al., 2010) as well as seen in the same cell using only silica as the feed (Norori-McCormac et al., 2017).

These results show that using the recirculating cell with a copper tailings ore gives results that are comparable in performance, i.e. operating at steady state and displaying a peak in air recovery, to those seen by Norori-McCormac et al. (2017) when using the same cell but with a single species silica feed. As well as this there are also similar tends to those seen by other authors, especially in an industrial setting. In addition, this is the first time that some of these trends, e.g. peak in air recovery, have been analysed for a non-standard industrial ore such as copper tailings. The results indicate there is scope to optimise the stability of flotation tailings froths, which would be expected to be linked to enhanced metallurgical performance. This work also demonstrates that the bench-scale cell developed is useful for conducting laboratory research in which the froth behavior is comparable to that of industrial cells.

CONCLUSIONS

This work has investigated the effects of particle size, impeller speed and superficial gas velocity on the air recovery, or froth stability, of a copper tailings ore. These experiments were performed using a novel bench scale recirculating cell which has previously only been used to investigate effects with a single species and two species, idealised systems. Even when using a complex ore such as copper tailings this cell has been shown to operate at steady state for a long period of time.

A linear regression model has been fitted to the data with a good and statistically significant fit. This model is simple, with no interactions between variables and only one self-interaction. It has been shown that the effects of particle size and impeller speed are linear, and thus the behaviour of the system is in agreement with the literature, including previous work done in the same rig. It is also clear that varying the superficial gas velocity results in a peak in air recovery, something not yet seen for a tailings ore. The froth stability for this copper tailings ore, quantified through air recovery, can be optimized by using the finest particle size and highest impeller speed, within the range tested, and with a superficial gas velocity of 1.13 cm/s.

This work has shown that the novel rig that has been developed not only behaves well and can be run at steady state with an idealised, single species ore, but with a complex ore. It has also been shown that the stability of the froth in the system matches that of previous studies, including those from industrial trials. The recirculating cell is therefore a good system to use to conduct steady state, laboratory experiments to further our understanding of the processes occurring in froth flotation.

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