Improved separation efficiency of the REFLUX™ Flotation Cell in flotation

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SUMMARY

The capability to enhance flotation performance is a continuous pursuit in the mineral processing industry. Incremental improvements are being pursued by incorporating design changes into established flotation technologies. The industry, however, is demanding advanced technologies to perform better in terms of improved resource utilization while at the same time ensuring that power and water usage is reduced. To meet these demands, it is necessary to make a step change in the performance capability of flotation equipment.

Results from extensive laboratory, pilot and industrial testing are showing that the REFLUX™ Flotation cell is transforming the hydrodynamics of traditional flotation and proving to meet the challenge of delivering as a high efficiency flotation technology. Several pilot testing campaigns have been conducted in cleaning, scavenging and rougher applications across various commodity types including copper, molybdenum, gold, graphite, and coal. Results from this testing consistently show that the technology improves the flotation system kinetics and can shift the grade-recovery curve. The RFC has the capability to produce high grade concentrates while simultaneously increasing recovery.

An overview of the results from these testing campaigns will be discussed along with their impact on flotation circuit design. It will also be shown that the technology is scalable and results at pilot-scale a reproduced at full-scale.

1. Introduction

As head grades continue to decrease operators are pushing tonnages to elevated levels to meet market demand for metals. In response, equipment vendors have traditionally increased flotation cell sizes to accommodate these increased tonnages resulting in commercial units available in sizes more than 600m^3 (Camomile et al.,2013). It is, however, anticipated that a physical upper limit is quickly being approached and the need to reduce flotation volume and improving performance efficiency is increasing.

A novel flotation system has been developed which is proving to transform the hydrodynamics of flotation (Dickinson & Galvin, 2014). This system, known as the REFLUX™ Flotation Cell (RFC) combines several key elements into a single flotation machine that can improve grade and recovery while at the same time reducing the flotation volume required. High intensity pre-contacting of feed promotes enhanced collision and attachment rates, increasing recovery. Operation at elevated air fractions, of 50%, further promote recovery and improved kinetics while the addition of washing water facilitates production of high-grade concentrate. The implementation of a series of inclined channels allows for enhanced bubble liquid segregation further increasing the throughput capabilities of the technology.

Laboratory-, pilot- and full-scale testing has consistently shown that the RFC has the capability to operate beyond the bounds of traditional open tank flotation cells. A selection of pilot and industrial data will be presented in this paper to illustrate the performance enhancements possible utilizing the RFC. These include copper roughing, molybdenum cleaning and coal washing.

2. Technology Description

The REFLUX Flotation Cell technology utilizes several processing mechanisms to enhance flotation kinetics by altering or eliminating rate-limiting features of conventional open tank systems (Parkes et al., 2022). These features include:

- increasing operating bubble surface area flux by as much as ten times of that which is possible with existing technologies (Dickinson et al., 2019),
- operating without a discernible froth/pulp interface, with gas fraction in the order of 50%, eliminating drop back of particles into the pulp phase
- generating a very fine bubble distribution and contacting these bubbles with floatable material

in a high a shear environment at the inlet of the device

- applying wash/fluidization water counter-current to bubbly flow of floatable material to enhance product quality and allow for bias flow control.

A schematic of the RFC is shown in Figure 1. The RFC is essentially a staged flotation device where feed is pre-contacted in a high shear rate sparger system ensuring elevated collision and attachment rates. This contacted bubbly mixture is transported downwards into the main chamber of the RFC where air fractions in the order 50% are present. This consequently provides an order of magnitude greater bubble surface area for further collection of floatable material within the main chamber. The system is frothless, with the bubbly mixture transported to the overflow while being washed with fluidization water producing high grade concentrates. The cell operates with a strong positive bias or downward volumetric flow. The presence of inclined channels allows for enhanced bubble liquid segregation affording downward velocities well in excess of bubble terminal rise rates which enables it to process feed fluxes much greater than the typical industrial limit of about 1 cm/s. The machine is not flux curve constrained and can operate at feed and gas fluxes much higher than in conventional systems, in the order 5-7cm/s.

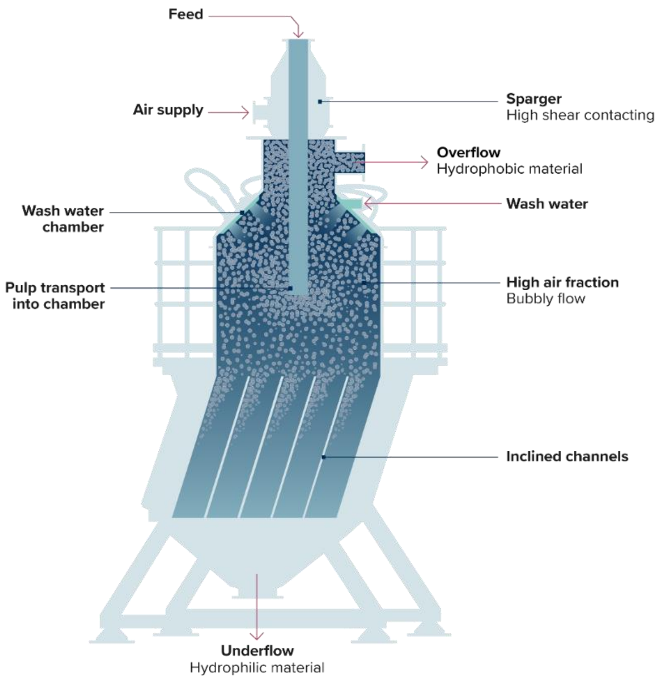

Figure 1. *Schematic of RFC*

3. Piloting and Full-Scale Trial

An extensive volume of test work has been conducted utilizing the RFC technology. Work has been conducted using pilot-scale machines as well as a full-scale industrial cell.

3.1. Testing Equipment

3.1.1. Pilot-Scale test system

In order to demonstrate the performance capability of the RFC a pilot scale system was constructed in a manner to facilitate ease of transport, installation and operation. Figure 2 shows an image of the dual RFC100 pilot system. The system consists of two collapsible RFC units each with a cross sectional area of 80cm^2. Each RFC has a dedicated feed tank and pump arrangement along with a discharge pump. The system is controlled through a local PLC. The entire rig is transportable in a standard 20ft shipping container.

Figure 2. *RFC Dual pilot system*

The test system requires the following feed and utility supply:

- Feed: 50-100l/min
- Process Water: 20l/min at 200kPa
- Instrumentation Air: 100sl/min at 700kPa

The volumetric flow rates of feed, tailings, wash water and air are set to a defined set point and controlled via the local PLC. The natural flow balance of the slurry process variables determines the concentrate volumetric rate, therefore overcoming any need for formal process control of the concentrate rate. That is, the concentrate rate = feed rate + fluidization water rate – tailings rate (Dickenson et al.). Hence, for a tailings rate set equal to the feed rate, the fluidization water simply reports to the overflow producing, in effect, a neutral or zero bias flux through the top of the cell (not accounting for the solids loading in the concentrate flow). Bias flux is utilized as a process control variable and is typically set to a positive value for cleaning applications and neutral for rougher applications.

3.1.2. Industrial Scale Test System

To validate performance of the RFC technology at an industrial scale, a 2m diameter machine was constructed and installed along with ancillary pumps, reagent systems and tanks. Figure 3 shows the RFC2000 system in place prior to commencing with testing.

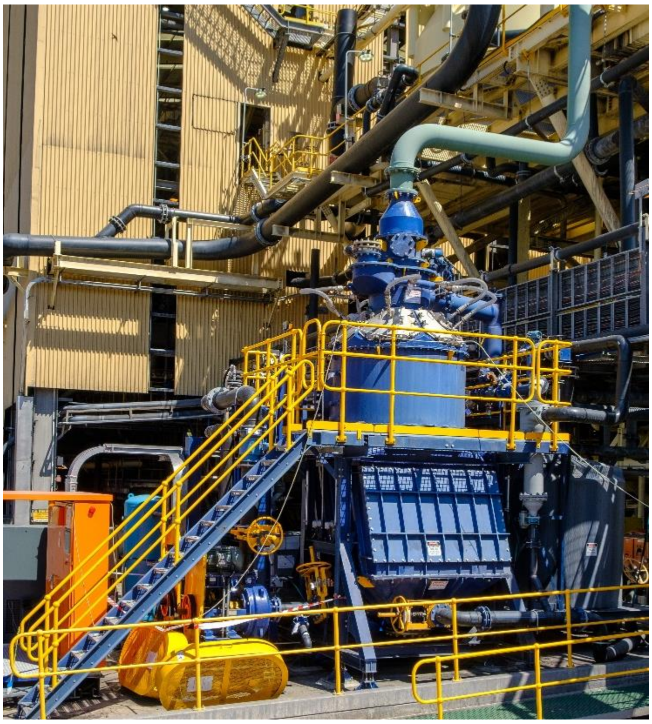

Figure 3. *RFC2000 installed on-site*

Feed to the RFC2000 in this installation was supplied by gravity flow and metered using a control valve and flow meter. A local PLC system is utilized to control the underflow, feed, wash water and air supply as with the smaller pilot system.

3.2. Pilot testing in a copper rougher application

3.2.1. Pilot-Scale test overview

Piloting test work was completed in four campaigns over a three-month period utilizing the RFC100 test system. The system was configured such that a rougher-scavenger flow arrangement was utilized. Tailings from the first RFC was transferred as feed to the second RFC. Feed to the plant first rougher cell was used as feedstock for all four campaigns and was collected from a spear sampler used for producing representative samples for metallurgical accounting purposes. The sample collection point was after the addition of reagents and consequently no further collector was added during testing. Frother (IF50) was added to the first RFC mixing tank using a small positive displacement pump.

The objective of the test was to replicate plant conditions of the first two cells in the rougher circuit which consisted of nine WEMCO® 128m^3 flotation cells. Figure 4 shows the circuit arrangement and the placement of the RFC test system.

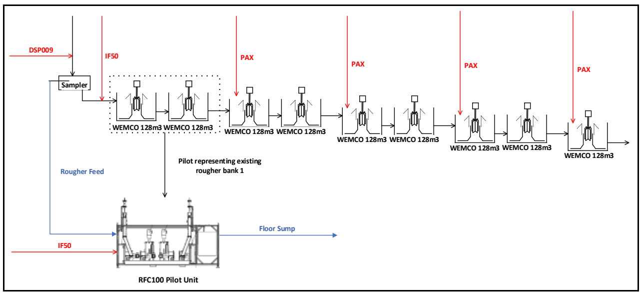

Figure 4. *Rougher circuit and RFC test location*

The existing rougher bank first two cells have a combined residence time of 9minutes and consistently produce a concentrate grade of 28-30% Cu at approximately 80% recovery.

During testing daily comparative bench top kinetic tests were conducted to form a baseline for comparison to the RFC tests and normalize any variation in mineralogy/grind size, and for scale-up purposes.

Various operating conditions were utilized where feed, wash water and bias were adjusted. I wide range of operating conditions were utilized in order to produce a statistically significant data set that could be used for system modeling.

3.2.2. Pilot-Scale test results

The biggest advantage of this technology is fast flotation kinetics, shown in the depiction of recovery versus residence time for all tests in Figure 5. Throughout the testing, this characteristic was exhibited regardless of the testing conditions. This included tests that were outside the expected normal operating conditions which were required to generate a model of the system. The minimum recovery observed for a single stage RFC was ~40%, with a maximum of up to 80% in a single stage in under 25 seconds. A two stage RFC further increased recovery to a minimum of ~70% and a system maximum of 90% in under 60s of residence time. Compared to the same flotation conditions at nine minutes residence time in conventional flotation cells, this improves flotation kinetics by up to 10 times.

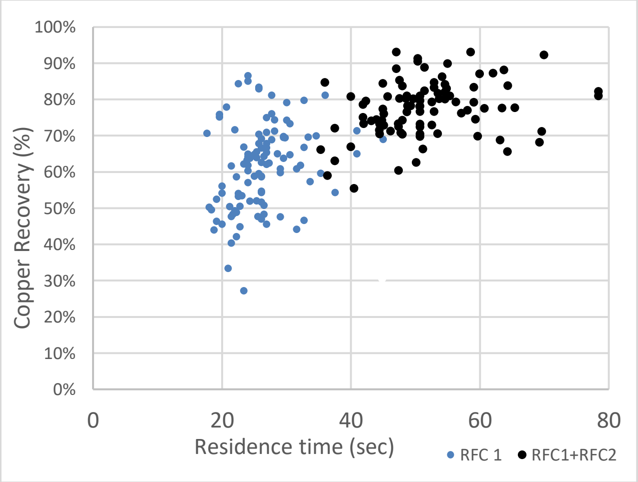

Figure 5. *Combined Tests Cu Grade vs Retention time*

The ability to achieve a suitable concentrate grade while also achieving fast kinetics has long been a challenge. Figure 6 shows the grade and recovery performance of all the tests with the plant performance of the first WEMCO bank represented also. It should be noted that scattering of data is primarily due to a wide range of operating conditions selected for testing.

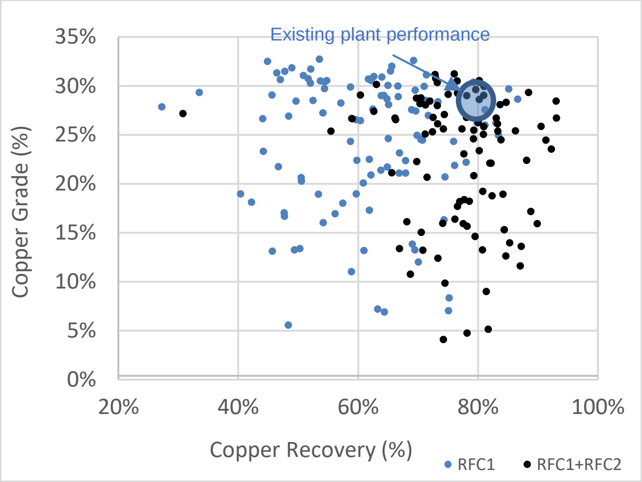

Figure 6. *Combined Tests Cu Grade vs Recovery*

Although there is significant scatter in the data, it shows that under ideal conditions the plant performance can be met or exceeded for the liberation and reagent conditions of the flotation feed (i.e. high selectivity towards liberated chalcopyrite) during the testing, it was found that a positive wash bias is required to maintain selectivity within the system without hindering recovery. This results in the grade produced by the system being highly sensitive to the wash water flow and overflow mechanisms. The optimum will be discussed further in the modelling section.

3.2.3. Modeling and optimization

To illustrate the potential benefits of implementing the RFC into a full-scale circuit, a response surface statistical method was used to generate models. Collected data allowed generation of statistically significant models for single (rougher or scavenger) and two-stage (rougher-scavenger) flotation using RFC technology. Later, the models were used to identify optimum operating conditions for the RFC units, to simulate full scale circuit and compare with conventional flotation technology.

The RFC models (rougher and scavenger) were developed utilizing a commercially available statistical software package which allows for investigation of vital factors and components to characterize interactions between system variables. Operating variables including feed rate, air rate, wash water rate and bias flux were adjusted to determine optimum performance levels, these variables were maintained to values within the original test matrix. Optimization algorithms in the software were utilized to identify operating conditions leading to best performance at highest desirability.

The conventional flotation system was modelled utilizing data from a set of fourteen standard benchtop kinetics tests. These tests were performed over the period of the campaign and an averaged kinetics response was generated to predict conventional flotation response. The recovery model utilized for this model is shown by equation 1 below.

$$Rec = m_f\left[1 - e^{(-k_f t)}\right] + m_s\left[1 - e^{(-k_s t)}\right] \ldots\ldots\ldots\ldots\ldots..(1)$$

Where m_f and k_f = mass % and rate constant of fast floating species, m_s and k_s = mass % and rate constant of slow floating species and t = retention time.

A grade versus recovery relationship was developed utilizing statistical curve fitting software to predict product grade based on the recovery from the kinetics model above.

Models were reviewed to ensure validity based on the experimental data generated. Figure 7 and 8 below show a summary of the averaged laboratory kinetics data, the RFC experimental data showing combined rougher scavenger performance as well as modelled RFC and full-scale conventional circuit performance. Circuit simulations shown utilize an averaged feed grade of 0.9% copper, which is reflective of the average feed grade for the 14 kinetics tests performed. RFC circuit simulations show operating conditions to produce a set of data optimized to produce maximum grade and recovery values for various operational parameter values. Conventional simulation reflects plant conditions based on existing flotation cell configuration. It should be noted that the conventional circuit requires additional cleaning to meet product specification of copper grades in excess of 28% copper.

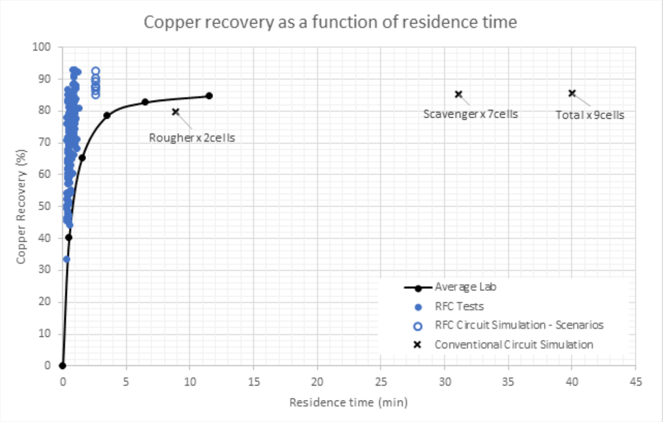

Figure 7. *Copper recovery as a function of residence time*

Figure 8 shows that copper recovery equal to or greater than bench and production scale flotation systems are achieved in less than 3minutes where industrial systems require in excess of 30minutes residence time. This finding is not unique to this test campaign and study with similar results reported (Ref: Cole, M J, 2020) It should be noted that the residence time achieved by the RFC circuit simulation is larger than the pilot testing due to the fact that the industrial system geometry is of such a nature, that to maintain wash, feed and bias fluxes the effective circuit residence time is larger than the pilot.

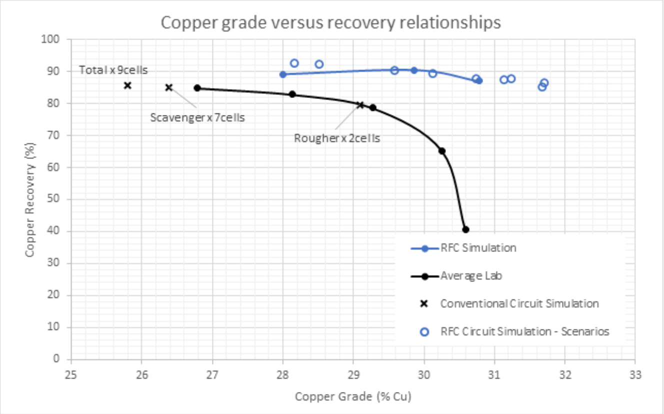

Figure 8. *Cu Grade vs recovery*

In addition to achieving superior recovery the RFC circuit shows improved product quality when compared to rougher flotation. In this case, where the required product specification of 28% copper is required, the RFC circuit will not require additional cleaner flotation.

3.2.4. Implication on circuit design

When considering an alternative RFC circuit compared to the existing conventional circuit, the RFC circuit offers the following advantages:

- An approximate 5-8% recovery improvement could be realized to produce on specification concentrate in excess of 28% copper
- The need to perform additional cleaning of the rougher flotation product is not required, negating the need for additional cleaning flotation capital equipment and associated flotation volume
- Flotation volume is reduced up to 10-fold when considering the conventional rougher system only. This translates into reduced plant footprint and associated capital and installation cost savings
- Reflux flotation machines do not require direct power input with power consumption limited to transfer pumping of slurry and wash water supply only. The comparative power value in Table 1 accounts for these in the power calculation.

Table 1 below shows a summary of key areas where savings can be made when comparing the RFC and conventional flotation circuits.

Table 1. *Comparison of key circuit variances*

	Existing Circuit	RFC Circuit
Flotation Equipment	9 x WEMCO® 130 cells	4 x RFC-2350
Configuration	2 x Rougher, 7 x Scavenger	1 x Rougher, 1 x Scavenger
Rows	One	Two
Power	100%	30%
Flotation Volume	100%	17%

3.3. Pilot testing in a molybdenum cleaner application

3.3.1. Pilot-Scale test overview

Continuous feed pilot scale testing utilizing the RFC100 test system was performed in a molybdenum cleaner circuit. A slip stream of the feed to the 2nd cleaner column was diverted to an existing mixing tank located in the basement. The mobile unit was fed from that tank on a semi-batch basis. This arrangement allowed for changing feed % solids and adjustment of pH/ORP for individual tests. Additionally, wash water, feed flow, air flow and bias flow were controlled and recorded for each test.

For each test feed ORP was recorded and adjusted, if needed, using NaSH solution. In addition, pH and ORP of wash water was adjusted to match the feed. Wash water solution was reagentized in a 275-gal IBC tote tank each day before testing. About 20 ppm of MIBC concentration was maintained in wash water.

Testing included operation of the skid in two-stage (rougher-scavenger) and in a single stage continuous mode. In addition, testing in a batch mode was completed to generate kinetics curves.

For each test, composite samples of the feed, concentrate and tails were collected to quantify metallurgical response. Bench kinetic tests using Denver D-12 flotation machine were performed for each sampling campaign as a reference. In addition, the 2nd and the 3rd testing campaign included sampling of feed, concentrate and tails form the 2nd moly cleaner to compare testing data with actual plant performance.

The objective of the work was to determine the performance efficiency of the RFC in a moly cleaner application. The existing circuit comprises of five stages of cleaning utilizing column flotation cells. Plant target molybdenum grade is 51.5% Mo.

3.3.2. Pilot-Scale test results

Figure 9 shows the kinetic response of the continuous runs, batch runs and bench top tests. It is seen that the RFC has improved kinetics over that of the standard bench top tests, in fact RFC continuous runs showed faster kinetics than corresponding RFC batch mode tests.

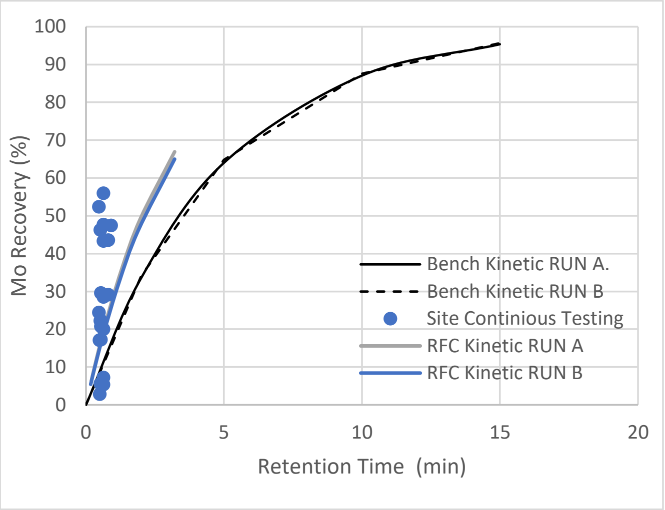

Figure 9. *Kinetics data for continuous, batch and bench scale tests*

Figure 10 shows the grade recovery relationship for the same tests as those in Figure 9. It can be seen that the RFC was capable of achieving plant target grade in a single stage of cleaning. A range of recoveries were achieved and it should be noted that the testing approach utilized a design of experiment software package to define operating conditions, consequently less than ideal results were achieved in some of the runs due to poor operating conditions. Optimized runs showed improved recoveries.

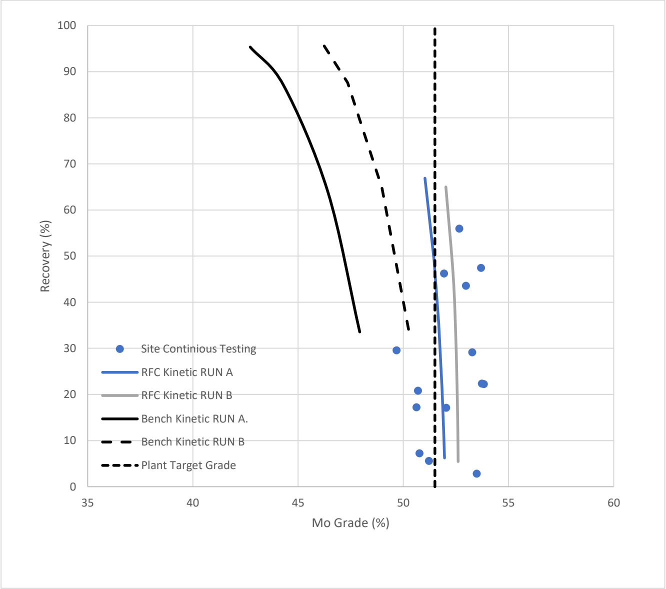

Figure 10. *Grade vs recovery data for continuous, batch and bench scale tests*

3.3.3. Implications on the circuit

The existing facility has multiple stages of cleaning, with poor performance resulting in a gradual buildup of circulating loads. Inclusion of the RFC has the ability to produce on specification concentrate. This is achieved early on in the circuit with the result that the remainder of the circuit could be offloaded and eliminating the build up of circulating loads.

3.4. Industrial testing in a coal washing application

3.4.1. Industrial-Scale test overview

Previous laboratory-scale work by Cole et al. (2020) has shown that the RFC is capable of high efficiency flotation of ultrafine coal. Low product ash and high combustible recoveries were possible. In fact, results showed that the performance of the RFC lay to the left of the tree curve, reference Figure 11. A tree curve is an industry accepted method to define the best possible flotation performance in coal applications. Performance producing data points to the left of the tree curve is considered exceptional and rarely achieved by conventional open tank flotation cells.

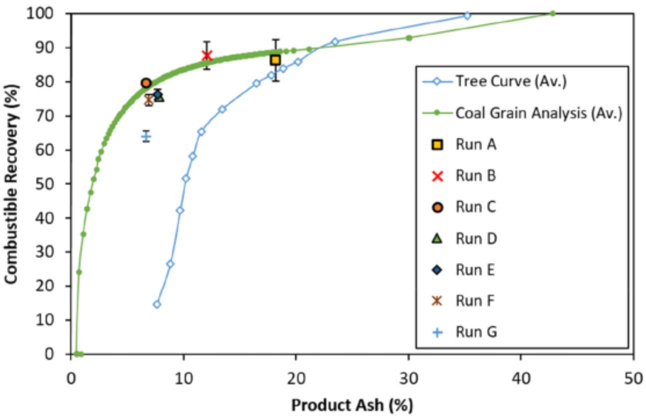

Figure 11. Combustible recovery vs product ash curve showing RFC performance to the left of tree curve (Cole et al. , 2020)

Figure 11 also shows a recently developed optical technique, nm. Coal Grain Analysis (CGA) which more closely matches the RFC performance and has been used to predict RFC performance in coal applications.

Work underway by Iveson et al. (2022) at an industrial scale is being performed to show that performance of the RFC at production scale mirrors that of laboratory scale. This work is utilizing a 2m diameter full scale RFC as shown in Figure 3. It was identified (Iveson et al., 2022) that the feed to the RFC, during the testing campaign reported on in this paper, was ultra-fine in nature with 50 vol% of the feed less than 14.4µm in size. In addition, feed ash values of approximately 60% were present in the feed. As described by Iveson et al. (2022) this feed material presents substantial difficulty in attaining high recovery at low ash content.

Testing was performed over a 4 hour period where the feed rate was maintained in the range of 200 to 220m3/h. This feed rate is equivalent to a feed flux of ~1.9cm/s, approximately double that of an equivalent sized open tank flotation cell. Air, wash water and underflow rates were kept constant at 180m^3/h, 65m^3/h and 235m^3/h respectively. Figure 12 shows the stability in operation where the RFC is consistently producing an averaged product ash of 12.7%.

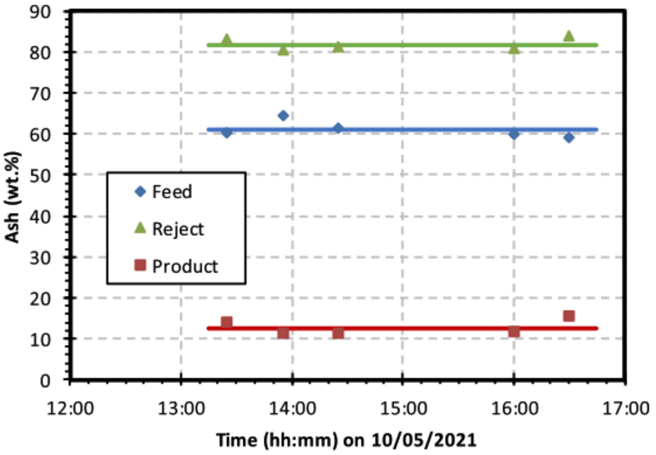

Figure 12. Feed, product and reject ash values over the duration of testing (Iveson et al., 2022)

3.4.2. Test Results

Results reported on here are taken from the first trial of the RFC, current work continues to optimize performance and increase throughput rate.

Five sets of samples were taken over the run period. These samples were labeled A, B, C, D and E and were taken at 13:25,13:55, 14:25, 16:00 and 16:30. These are depicted in Figure 13 which also shows associated tree curves for samples E, C and D. It can be seen that for sample E the RFC was producing product on the tree curve and for runs C and D performance has shifted to the left of the corresponding tree curve.

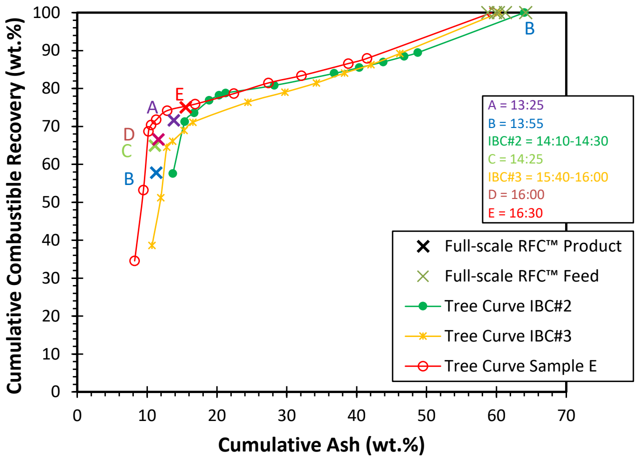

Figure 13. Cumulative recovery vs ash showing results from the full-scale unit with associated tree curves.

Figure 14 below reproduced from Iveson et al. (2022) shows cumulative yield vs ash for the full scale unit along with the associated tree and CGA curves. It can be seen that the tree curves and CGA curves match relatively closely, an indication that the tree curves in this case represent the ultimate flotation response well.

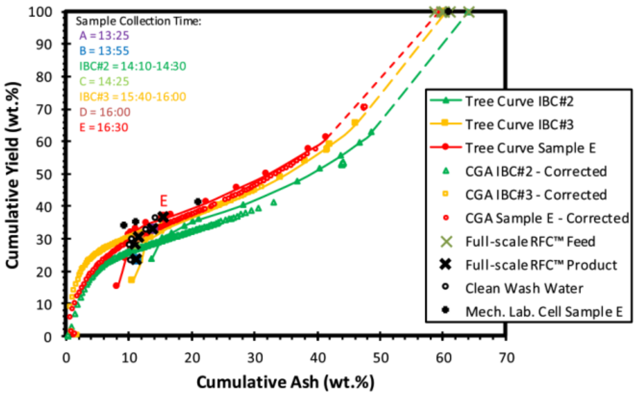

Figure 14. Cumulative yield vs ash showing results from the full-scale unit with associated tree and CGA curves. (Iveson et al., 2022)

These results show that the RFC is capable of performing at industrial scale with performance results in line with expectations when considering the tree and CGA curves. This result is impressive when considering a throughput rate of almost double that of a comparably sized conventional open tank flotation cell.

4. Conclusions

The new RFC technology has been tested in various commodities including, but not limited to, copper, molybdenum and coal. In all cases the technology performs better than conventional evaluation techniques.

Improved grade and recovery is possible at reduced flotation volume. This can therefore present operators with an opportunity for reduced flotation circuit sizes along with improved metallurgical performance.

Results from industrial testing show that that technology is scalable with performance results equal to laboratory and pilot scale RFC testing efforts.

Full scale performance is in line with expectations at feed rates almost twice that of comparable industrial machines.

Acknowledgments

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References

Camomile, A, Weber, A, Lelinski, D, Foreman, D, Traczyk, F, Baker, T, 2013. Development of the largest flotation machine: 600 series Supercell™ from FLSmidth, in Proceedings of 10th International Minerals Processing Conference, pp 233-233 (Procemin 2013)

Parkes, S, Wang, P, Galvin, KP, 2022. Investigating the System Flotation Kinetics of Fine Chalcopyrite in a REFLUX™ Flotation Cell using a Standardised Flotation Cell Reference Method. Minerals Engineering

Dickinson, JE, Galvin, KP, 2014. Fluidized bed desliming in fine particle flotation – Part I. Chemical Engineering Science pp283-298

Dickinson, JE, Cole, MJ, Galvin, KP, 2019. Chalcopyrite flotation using the Reflux™ Flotation Cell. Separation and Purification Technology 240, 2019

Dickinson, JE, Dabrowski, B, Lelinski, D, Christodoulou, L, Galvin, KP, 2019. Pilot trial of a new high rate flotation machine. Proceedings of Flotation ’19.

Cole, MJ, Dickinson, JE, Galvin, KP, 2020. Recovery and cleaning of fine hydrophobic particles using the Reflux™ Flotation Cell. Separation and Purification Technology 240, 2020

Iveson, SM, Sutherland , JL, Cole, MJ, Borrow, DJ, Zhou, J, Galvin, KP, 2022. Full-Scale trial of the REFLUX™ flotation cell. Minerals Engineering 179, 2022