ON THE SCALE-UP OF INTENSIFIED FLOTATION CELLS FROM EXHAUSTING TESTS TO CONTINUOUS PLANT OPERATION

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ABSTRACT

The collection of fine and ultra-fine particles requires a high level of energy dissipation, for which intensified flotation cells have emerged. A new type of intensified cell is the Concorde Cell, a pneumatic device that operates under moderate pressure, increasing the efficiency of particle/bubble aggregates formation.

This paper presents a modelling structure to characterize the Concorde Cell, considering the flotation kinetics occurring in the core component, the so-called Concorde Blast Tube, the hydrodynamic characteristics of the different cell components (feed tank, Blast Tube, separation chamber), and the froth transport. Firstly, a comparison between the exhausting and continuous operation, of the same laboratory cell was performed. Then, an analysis relating the laboratory flotation and the expected industrial cell operation, based on simulation, was carried out, from either exhausting or continuous laboratory tests. For this purpose, it was considered that the industrial collection zone (Blast Tube) has similar performance to the laboratory/pilot cell, for the same operating conditions, following a 1:1 scale-up factor typically applied to intensified flotation technologies. However, the overall metallurgical performance at industrial scale also depends on other factors such as cells design, feed tank volume, froth transport distance, and operating conditions.

In this case, a realistic prediction of industrial cells performance can be obtained by using the new pneumatic flotation model previously developed, assuming the same collection kinetics and depending on industrial cell design and operating conditions.

1. INTRODUCTION

The Concorde Cell technology described in Figure 1 is an intensified pneumatic forced-air flotation technology. Figure 1(a) shows the Concorde Cell system, including the feed tank, internal recirculation, and Blast Tubes entering on the top of the cell. Figure 1(b) shows an internal view of the Blast Tubes installation, where the pulp feed and air enter under pressure and discharge at supersonic speed through a constriction at the bottom (Yañez et al., 2024). Figure 1(c) shows a schematic representation of the plunging jet of pulp inside the Blast Tube, together with the entrance of pressurized air and the exiting of the Blast Tube in a shock wave, that impact the impingement bowl, generating vortex rings with high local energy dissipation of around 100 kW/m³ (Jameson, 2010). These conditions facilitate the collection of fine and ultrafine particles that normally are lost in conventional cells.

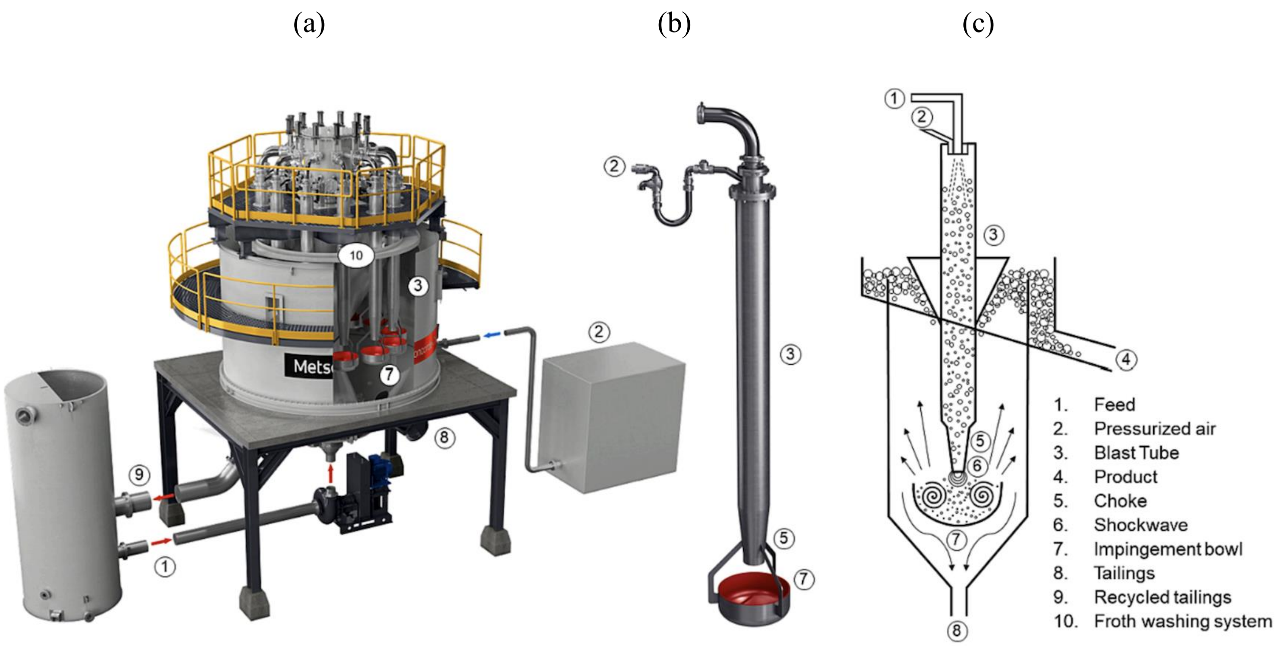

Figure 1. (a) Concorde Cell system, (b) Blast Tubes, and (c) representation of Concorde Cell (Yañez et al., 2024).

This new equipment features a more sophisticated design than conventional flotation cells, incorporating additional elements such as Blast Tubes and an impact bowl, as well as, new operating variables including the air-pulp ratio (APR), defined by the air and pulp flowrates entering the Blast Tube, the Blast Tube pressure, and the ratio between tailings recirculation and the pulp flowrate entering the Blast Tube. While this more complex cell design brings challenges for flotation modelling, it also provides several advantages. For instance, the effective collection process can be identified and characterised, independently from the separation and froth transport zones, allowing for a deeper understanding of the process and a more detailed and accurate metallurgical modelling.

A previous study presented a first approach to modeling the Concorde Cell, in which metallurgical performance depends on operating conditions, feed characteristics, and cell's dimensions (Benítez and Vallejos, 2025). The main particles collection in the Concorde Cell is associated with the processes occurring inside the Blast Tube, which consists of a pipe with top and bottom nozzles, and the discharge impacting the impingement bowl. Three contact zones for bubble-particle attachment are thus identified: the Blast Tube pipe, the shockwave region, and the bowl. At the same time, some particle detachment may occur at the discharge point, where supersonic velocities are reached, and upon impact on the bowl. This probability is expected to be low for fine/ultrafine particles, but it cannot be actually measured (Jameson, 2010). For modelling purposes, a net attachment–detachment process was assumed to occur throughout the entire collection system (Blast Tube plus impingement bowl), represented by a rectangular distribution of rate constants. Additionally, the collection zone was modelled as a plug flow reactor. Then, the separation zone was characterised as a perfect mixer with a detachment efficiency factor, and froth recovery was modelled as a function of froth stability, residence time, and transport distance. Water recovery and gangue entrainment were also modelled to estimate concentrate grades.

Another important challenge associated with emerging flotation technologies is the scale-up process, particularly given the limited availability of industrial data and the inherent complexity of scale-up, even for conventional cells. The scale-up of intensified flotation cells is distinctive, as a 1:1 scale-up factor can be applied to the collection process when comparing laboratory and industrial operations. However, flotation equipment scale-up depends on multiple variables, and different approaches have been described in the literature (Yianatos et al., 2022).

This study evaluates the modelling, simulation, and scale-up of the Concorde Cell, aimed at representing its performance at both laboratory and industrial scales. The flotation model, previously developed by Benítez and Vallejos (2025), was calibrated using data from a batch exhausting test. Then, a continuous laboratory operation was simulated and compared with the batch results. Finally, the metallurgical performance of an industrial cell was simulated, and a sensitivity analysis was performed to assess the effects of froth recovery (represented by the froth transport distance) and recirculation ratio (represented by the number of passes through the Blast Tube) on overall metallurgical performance.

2. SCALE-UP OF FLOTATION CELLS

2.1. Scale-up of mechanical cells

The flotation scale-up process involves the dimensioning and selection of industrial scale equipment based on laboratory or pilot scale testing, for a certain duty, considering minerals characteristics, treatment capacity (tph), and metallurgical performance (recovery and grade).

The typical scale-up procedure for mechanical cells consists of using empirical factors, relating the times required at plant site and laboratory/pilot operation to reach the same mineral recovery (Mesa and Brito-Parada, 2019). These factors implicitly account for the following key aspects:

- Hydrodynamics (flow regime and solids segregation).
- Froth transport (depending on superficial gas and wash water rates (J_G and J_W), froth depth (H_F), mean transport distance, froth stability).
- Mineral drop-back from the froth to the collection zone.
- Effective collection time.

Typical scale-up factors of mechanical cells are around 2.0-2.5, and almost 50% of the difference between laboratory and industrial operations can be explained by the froth transport, otherwise the froth recovery. In addition, the scale-up factor has shown a strong dependence with particle size and liberation. (Yianatos et al., 2022).

2.2. Scale-up of intensified flotation cells

The scale-up of this type of cells, particularly the Concorde Cell, is distinctive, because the collection zone (Concorde Blast Tube) is confined and can be operated under similar conditions at both industrial and laboratory scales. Otherwise, a scale-up factor 1:1 can be considered for the collection process. This is a key factor, because it allows for an independent characterization of the flotation kinetics, by identifying the true collection time. However, the overall metallurgical performance also depends on other parameters such as, feed tank volume, cell design, froth transport characteristics and operating conditions.

If the scale-up process were performed following the conventional approach, i.e., relating the residence times between laboratory and industrial scales, the total system residence time should be considered rather than only the collection time in the Blast Tube. However, this approach is difficult to apply because the total residence time depends on the combined volumes of all system components, including the feed tank, the cell, and any other elements, for both laboratory and industrial configurations. To address this challenge, the concept of the number of passes was introduced to represent the number of times the pulp goes through the core component Blast Tube, providing a consistent basis for comparing laboratory and industrial operations (Jameson, 2010). This is an alternative way for representing the flotation time, typically used in kinetic models' response. Under this framework, same collection recoveries are obtained for the same time, while overall recoveries may differ due to the effect of froth recovery, cell dimensions, and hydrodynamic conditions (for batch exhausting operation).

3. PROCESS MODELLING AND SIMULATION APPROACH

3.1. Model structure for the Concorde cell

The flotation process has two main objectives, recovery and grade. The equipment designed to reach these objectives comprises two distinctive zones: the collection zone, associated with the aerated pulp zone, and the separation zone, associated with the froth-cleaning zone. This description mainly applies to mechanical cells. However, the development of intensive flotation cells has changed the design approach by separating the pulp zone performance into two different stages: the pulp collection zone (Blast Tube) and the pulp separation zone. The main objective of this distinction is to physically separate and identify the effective collection zone, where bubble-particle aggregation occurs, from the separation stage, in which the aggregates rise through the pulp and enter the froth zone due to their lower density (Yianatos and Vallejos, 2024). This is relevant to evaluate the true collection rate in a flotation equipment, which requires the identification of the effective collection residence time for kinetics characterization (Hernández, 1992; Benítez et al., 2024).

Figure 2 shows the different stages in the Concorde Cell considered for modelling (Benitez and Vallejos, 2025). Four stages are identified: The feed tank, the core component Blast Tube with a bowl, the separator tank, and the froth zone.

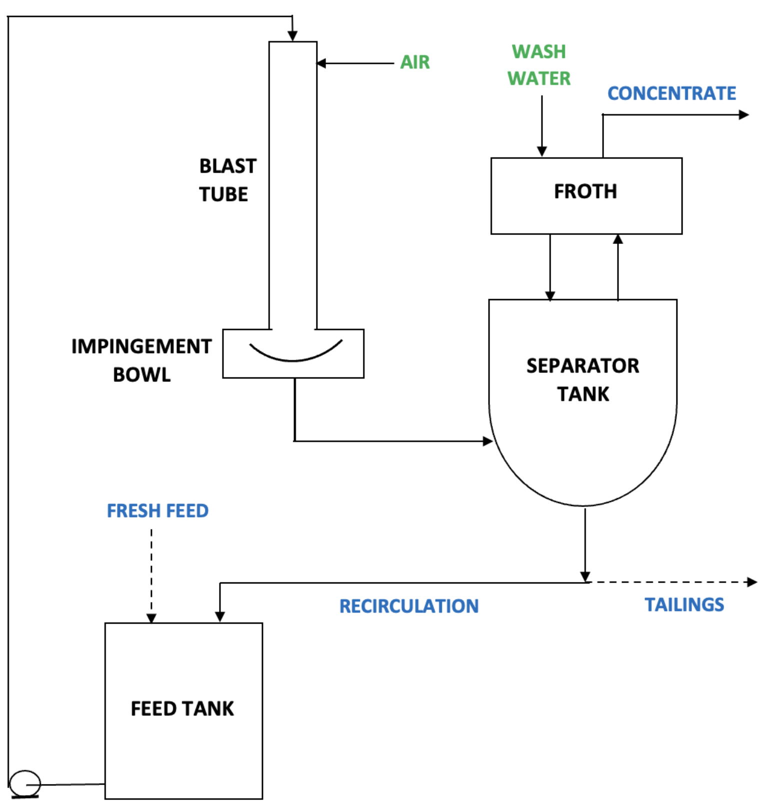

Figure 2. Model structure of the Concorde Cell in exhausting batch and continuous flotation (dashed lines).

The feed tank receives the fresh feed pulp and a fraction of tailings pulp that recirculates from the separator tank. From the feed tank, a pump elevates the pulp into the inlet of the Blast Tube, which enters under pressure (around two bar), while an air flowrate also enters through the top of the Blast Tube, after the top nozzle.

The Blast Tube plus impact bowl discharge the collected and non-collected minerals inside a separator tank. On the top of this tank, there is a froth zone, which allows for selective separation of minerals collected by true flotation from the pulp, favouring that most of non-floatable minerals and gangue goes to tailings. On top of the froth, wash water is typically added to favour the froth cleaning by preventing the fine gangue entrainment.

From the froth, mineral drop-back to the separation tank occurs because of bubbles coalescence and collapse, and the liquid drainage by gravity. This mineral has a low opportunity of collection in the separator tank and mostly ends up in the tailings. A partial tailings recirculation to the feed tank, as in case of continuous operation, allows for a new opportunity of collection. This recirculation gives rise to the parameter known as number of passes, accounting for the number of times the pulp passes through the Blast Tube.

It should be noted that in the batch exhausting operation, the tailings from the separator tank are completely recirculated to the feed tank, and there is no fresh feed pulp flowrate.

The modelling of the Concorde Cell characterises each zone in Figure 2 independently, considering mineral collection occurs mainly in the core component Blast Tube. Actually, particle-bubble collection can occur in three zones: in the plunging jet inside the Blast Tube, in the shock wave downstream of the choke and in the impact bowl (Jameson, 2010). However, as there is no available data to evaluate these effects separately, the kinetic modelling considers a net overall kinetic constant (k), based on residence time in the Blast Tube. Additionally, a detachment efficiency factor was considered to account for the separation zone performance, and a froth recovery model depending on froth stability, residence time, and transport distance was used. The feed tank was treated as a flow mixer between fresh feed and tailings recirculation, without direct contribution to the metallurgical performance.

For the flotation process modelling, the main assumptions were: (i) the overall particles collection follows a first order kinetic, (ii) the Blast Tube operates under plug flow, and (iii) perfect mixers described the separator and feed tanks mixing conditions.

3.2. Simulation of the Concorde cell

From the flotation model, a series of simulations were carried out to evaluate metallurgical performance in a Concorde Cell, at laboratory and industrial scales.

Data from a batch exhausting test (copper mineral) was used to calibrate de flotation model, to then simulate a continuous laboratory operation, keeping the same feed characteristics, cell design, operating conditions, and kinetic parameters. Next, the metallurgical performance of an industrial cell was simulated, and a sensitivity analysis was performed to assess the effects of froth transport distance and recirculation ratio (number of passes) on the overall metallurgical performance.

All simulations performed in this study considered the same feed characteristics, and operating conditions, as shown in Table 1.

Table 1. Mineral characteristics and operating conditions for simulations.

Feed Cu Grade, %	Feed solid content, %	APR	Jw, cm/s	Froth Depth, mm
8.5	13.3	0.6	0.02	400

<u>Laboratory cell simulation</u>

Experimental kinetic results from a batch exhausting operation were used to calibrate the model, which are represented by white dots in Figure 3. The corresponding modelled kinetic curve is shown as a solid black line. In this analysis, the kinetic responses are represented with respect to the number of passes. Each pass through the Blast Tube corresponds to 6 seconds. Overall, a good agreement was observed between experimental and modelled results.

Then, using the kinetic parameters obtained from calibration, a continuous laboratory operation was simulated, considering the same cell, mineral characteristics and operating conditions. The simulated kinetic responses for continuous operation are shown as a solid red line in Figure 3. This curve represents the Cu recoveries when operating at different fresh feed flowrates (recirculation ratios) in a laboratory cell in continuous operation, which generates different number of passes of pulp through the Blast Tube. Hence, discrete recoveries are obtained for each continuous operating condition, while cumulative recovery over time is presented for the batch operation.

On the other hand, the vertical dotted lines in Figure 3 indicate the range of 1.0-2.5 passes, which corresponds to recirculation ratios from 0 to 67% in continuous operation. In pilot and industrial operations, typical recirculation ratios range from 30 to 60%, whereas a ratio of 0% indicates that the entire tailings stream exits the system, meaning the pulp passes only once through the Blast Tube.

Under this condition, the fresh feed flowrate reaches a maximum. These results clearly demonstrate the significant influence of recirculation on mineral recovery in this type of equipment. As the recirculation ratio increases, the feed flowrate and cell throughput decrease, while the recovery improves due to the longer effective residence time in the Blast Tube (higher number of passes).

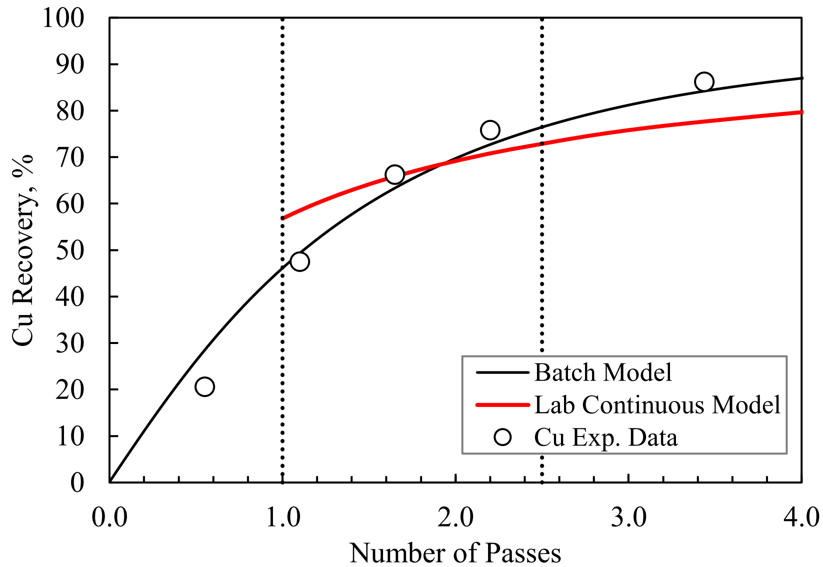

Figure 3. Cumulative Cu recovery of Concorde cells in batch and continuous laboratory flotation.

The results in Figure 3 show that Cu recovery increases with the number of passes for both operations, as expected due to the corresponding increase in residence time. In the batch operation, the cumulative recovery increases with flotation time until reaching the final point, similar to the behaviour observed in conventional batch exhausting cells. In contrast, for the continuous operation, increasing the number of passes, i.e., longer residence time in the Blast Tube, means a decreasing in the fresh feed flowrate, which leads to higher recoveries.

In the batch operation, the Cu recovery starts at its maximum value, with a constant flowrate from the feed tank entering the Blast Tube at the initial feed grade. Then, as the number of passes increases, the incremental recovery continuously decreases, while the cumulative Cu recovery gradually increases, approaching the maximum recovery. Thus, the mineral grade entering the Blast Tube progressively decreases due to mineral depletion (exhaustion). Conversely, in a continuous laboratory operation (under steady-state conditions), the feed grade entering the Blast Tube remains constant, for a given operating point, but decreases as the fresh feed flowrate is reduced to increase the number of passes. This effect results from the higher proportion of tailings recirculation from the separation tank, which have a lower grade.

Industrial cell simulation

In order to predict the industrial operation of a Concorde cell, key kinetic parameters identified from batch testing were used to evaluate its performance. For this simulation, a sensitivity analysis was performed, while varying the design and operating conditions at industrial scale.

In industrial flotation cells, a critical parameter is the froth transport distance, which affects the froth recovery, and therefore the overall cell recovery in a similar way than in mechanical cells (Yianatos et al., 2022). In this sense, as an example, Figure 4 shows the effect of varying the froth transport distance on the grade-recovery curve for Cu, to illustrate the space of potential operation of an industrial Concorde Cell, using the kinetics parameters previously identified from batch tests. These results show that decreasing the nominal froth transport distance will increase the overall recovery, by improving the froth recovery.

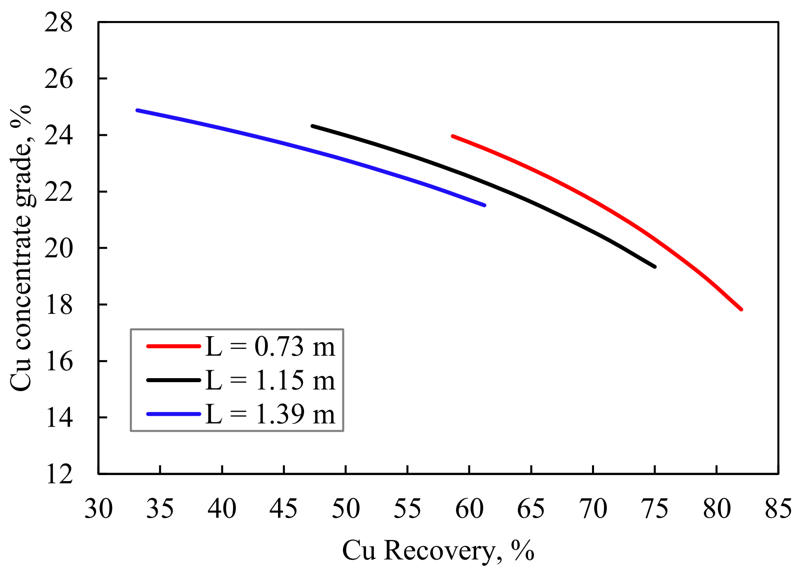

Figure 4. Simulated grade-recovery curves for an industrial operation, at different froth transport distances.

Figure 5 shows the increase in recovery versus number of passes (time) of pulp through the Blast Tube, which depends on the effective flotation rate obtained from batch tests and operating conditions, for the different froth transport distances. This result shows that both the froth transport distance and the number of passes have a significant impact on the overall cell recovery. In addition, the proper manipulation of the gas flowrate, wash water flowrate and froth depth will contribute to reach the best compromise between Cu recovery and grade.

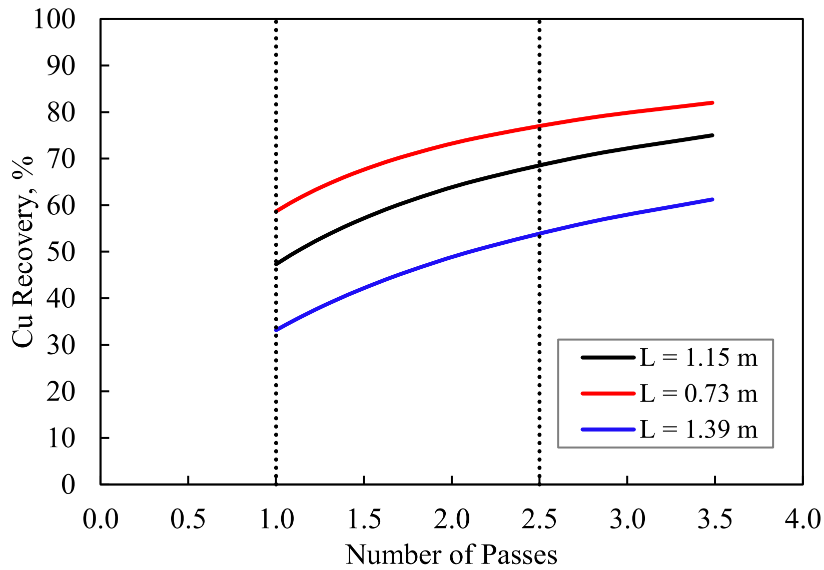

Figure 5. Simulation of the industrial continuous cell recovery, as a function of the Number of passes, at different froth transport distances.

The simulations indicate that, in terms of comparability and robustness, employing batch (exhausting) laboratory tests as a base of reference allows for an effective identification of the true flotation rate for kinetic characterization of the collection process occurring in the Blast Tube. Then, from this kinetic characterization, the scale-up to industrial operations becomes more plausible because it mainly depends on the system hydrodynamics and froth transport characteristics.

CONCLUSIONS

The flotation model for the Concorde Cell was successfully applied to simulate continuous operations at both laboratory and industrial scales. The model effectively represented the metallurgical behavior under different operating conditions, demonstrating its flexibility and good potential for prediction.

At laboratory scale, the continuous simulations revealed differences in recoveries compared to the batch exhaustion system, which were higher or lower depending on the number of passes that represents the effective collection time. These variations arise from the distinct operational modes, particularly the cumulative recovery of the batch operation versus a constant recovery in the continuous operation, at the same collection time.

At industrial scale, the simulations highlighted the effect of cell design on metallurgical performance, identifying the transport distance as a key variable affecting overall recovery through its impact on froth recovery. In addition, the significant impact of tailings recirculation (number of passes) on cell recovery.

Overall, the results demonstrate that batch tests provide a robust basis for determining the true flotation rate and support a reliable scale-up to industrial operations. The flotation model thus represents a valuable tool for predicting the metallurgical response of intensified flotation technologies and for guiding their incorporation into hybrid flotation circuits.

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