

## Article

# Characterization of Hydrodynamics and Mixing Regime of a HydroFloat<sup>®</sup> Cell

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## Abstract

A study was conducted to characterize the performance of a HydroFloat<sup>®</sup> coarse particle flotation (CPF) cell using rougher tailings samples from an industrial copper mining operation. The work involved measuring internal hydrodynamic variables under a wide range of operating conditions. The effect of different operational and hydrodynamic conditions on the metallurgical performance of the HydroFloat<sup>®</sup> cell was also evaluated. Gas dispersion measurements, such as bubble size distribution, superficial gas velocity ( $J_g$ ), superficial area flux ( $S_b$ ), and residence time distribution (RTD), were recorded, enabling a detailed analysis of the cell's operation. Results show that copper recovery is strongly influenced by the superficial gas velocity ( $J_g$ ) and the superficial liquid velocity ( $J_l$ ). It was observed that the bubble diameter ( $d_{32}$ ) remained relatively constant at 0.5 mm across all operating conditions, which is well below typical bubble sizes for conventional flotation cells. This suggests that contrary to what may be expected, in this kind of machine, small bubbles are able to float coarse particles. Bubble image inspection suggests that the HydroFloat<sup>®</sup> cell creates conditions conducive to bubble–particle aggregates, which would explain how small bubbles can float coarse particles. This study contributes to the understanding of CPF and establishes a framework for optimization in copper concentrators.

**Keywords:** coarse particle flotation; hydrodynamics; residence time distribution

## 1. Introduction

The depletion of high-grade copper deposits has forced the mining industry to process lower-grade and more complex ores. Harder ores have increased energy consumption in comminution circuits, which account for up to 50% of a concentrator's operating cost. Coarse particle flotation (CPF) has emerged as a disruptive technology to reduce overgrinding, reject gangue early, and recover valuable minerals at particle sizes above 150  $\mu\text{m}$ —beyond the effective range for conventional mechanical flotation cells. Fluidized-bed flotation devices such as the Eriez (Erie, PA, USA) HydroFloat<sup>®</sup> have demonstrated successful recovery of particles up to 600  $\mu\text{m}$ , enabling significant improvements in throughput, energy efficiency, and, potentially, water recovery from the process. Industrial studies [1,2] have demonstrated that, by integrating HydroFloat<sup>®</sup> cells into the processing circuit, it is possible to reduce overall energy consumption by approximately 20%–30% while maintaining—or even improving—overall copper recovery.



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Regarding water recovery, the production of a coarser tailings stream enables an increase in thickener water recovery efficiency of approximately 10%–25%, thereby reducing freshwater demand and allowing higher levels of process water recirculation [3].

As observed across all flotation technologies, the performance of HydroFloat® cells is critically dependent on internal hydrodynamics, including air dispersion, bubble–particle interactions, and the mixing regime. Few studies have explored CPF hydrodynamics and surface chemistry, therefore it remains a lack of standardized methodologies to define optimal operating conditions. Similar challenges and the need for robust protocols have also been emphasized in recent fluidized-bed hydrodynamic studies [4,5].

The present work aims to fill this gap by conducting a characterization study on HydroFloat® performance using rougher tailings samples from an industrial copper mining operation. The objectives of this study were to characterize key hydrodynamic variables using a laboratory HydroFloat® flotation cell under different operating conditions; identify optimal operating conditions and provide insight into the mechanisms of coarse particle flotation in this kind of equipment.

## 2. Materials and Methods

### 2.1. Sample Characterization

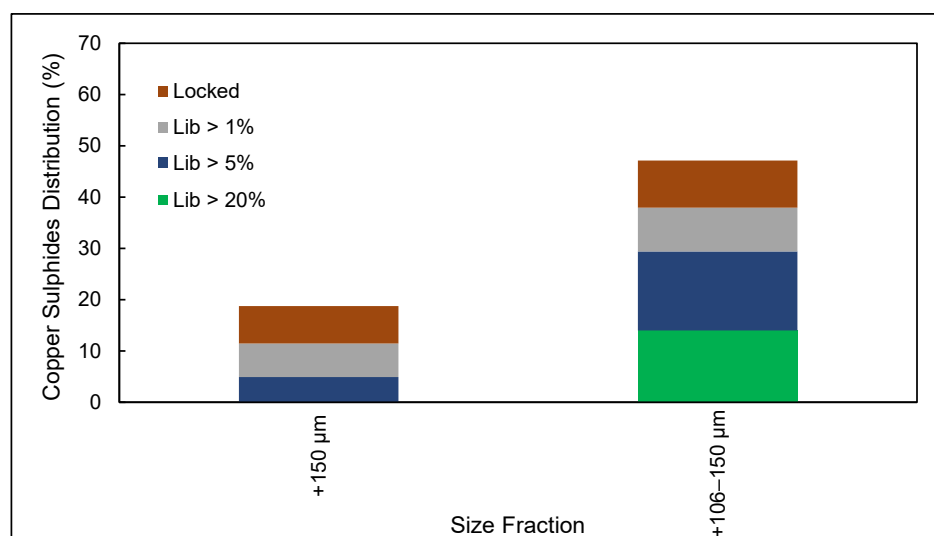
Approximately 10 m<sup>3</sup> of slurry, corresponding to rougher tailings with 30% solids percentage from an industrial copper mining operation were homogenized and used as feed for coarse particle flotation testing. The sample was characterized in terms of chemical composition, particle size distribution, copper distribution by size, and mineralogy. Results are presented in Table 1. As can be observed, the average copper grade of the tailings sample was 0.1% Cu, with copper primarily present as 53% chalcocite and 39% chalcopyrite. Additionally, 44% of the total copper mass was found in the +106 µm coarse fraction.

**Table 1.** Mineralogy, particle size and copper distribution by size fraction of tailings sample.

| Main Minerals                   | (%)              | Rougher Tail Sample |           |      |              |                               |
|---------------------------------|------------------|---------------------|-----------|------|--------------|-------------------------------|
| Cu Sulphides                    | 0.2              | Mesh                | Size (µm) | PSD  | Grade Cu (%) | Element Mass Distribution, Cu |
| Other Cu Mins                   | 0                |                     |           |      |              |                               |
| Pyrite                          | 2.9              |                     |           |      |              |                               |
| Molybdenite                     | 0                | 28                  | 600       | 100  | 0.3          | 0.7                           |
| Muscovite                       | 29.9             | 35                  | 425       | 99.8 | 0.3          | 4.2                           |
| Kaolinite                       | 1.8              | 48                  | 300       | 97.9 | 0.3          | 11.8                          |
| Chlorite                        | 0.2              | 65                  | 212       | 92.3 | 0.2          | 16.7                          |
| Pyrophyllite                    | 4.6              | 100                 | 150       | 83.9 | 0.1          | 10.9                          |
| Other Clays                     | 0.6              | 150                 | 106       | 74.4 | 0.1          | 9.1                           |
| Quartz                          | 51.6             | 200                 | 75        | 65.9 | 0.1          | 6.8                           |
| Feldspar                        | 4.6              | 270                 | 53        | 58.2 | 0.1          | 2.5                           |
| Gypsum/Anhydrite                | 0.4              | 325                 | 44        | 54.8 | 0.1          | 1.7                           |
| Others/Gangue                   | 3.2              | 400                 | 38        | 52.1 | 0.1          | 35.6                          |
| Total                           | 100              | −400                | 0         | 0    |              |                               |
| <b>Main copper Minerals (%)</b> |                  |                     |           |      |              |                               |
| Chalcocite (%)                  | Chalcopyrite (%) | +106 µm             |           |      | 0.1          | 44                            |
| 53.2                            | 38.5             | −106 µm             |           |      | 0.1          | 56                            |

Given that the  $P_{80}$  observed in the particle size distribution of the rougher tailings sample was approximately 145  $\mu\text{m}$ , a cut size of 106  $\mu\text{m}$  was selected to separate the fine and coarse fractions in the feed to the HydroFloat<sup>®</sup> cell. Using 106  $\mu\text{m}$  as the cut size, it was observed that, for this sample, approximately 44% of the copper is contained within only about 25% of the total tailings mass.

Regarding the liberation of copper sulfide particles in the rougher tailings sample, it was found that in the +106  $\mu\text{m}$  size fraction, the particles are approximately evenly distributed among the following categories: fully locked particles, and particles with liberation degrees in the ranges of 1%–5%, 5%–10%, and 20%–50%. This observation aligns with recent mineralogical characterizations for coarse flotation feed streams reported by Ozsoy et al. [5]. Figure 1 presents the copper sulfide particles liberation by size fraction.



**Figure 1.** Liberation by size fraction of copper sulfide particles.

This observation is also consistent with the findings reported by Ding et al. [6], whose work demonstrated that coarse particles exhibit lower surface exposure of the valuable mineral phases, thereby reducing the probability of particle–bubble attachment during the flotation process.

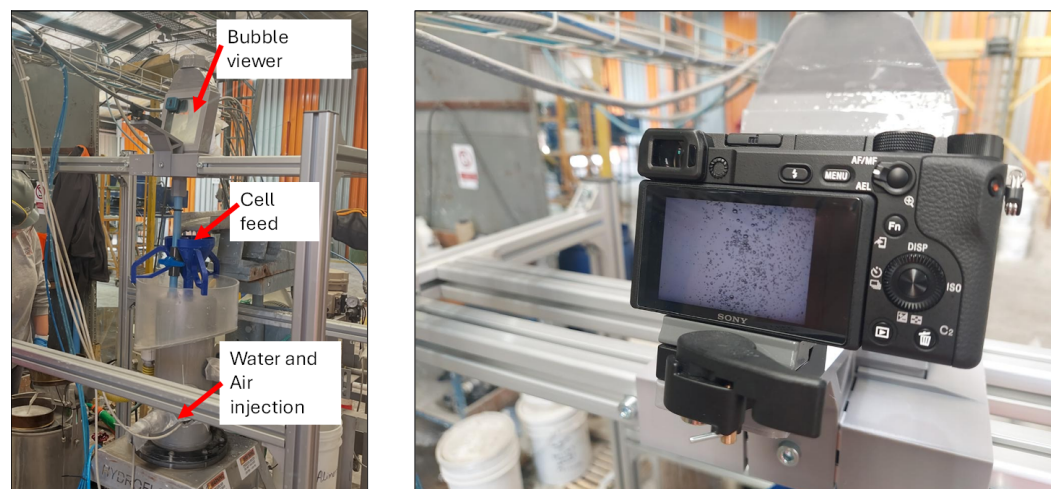
The sample was subjected to a rigorous homogenization process in an agitated tank and subsequently divided into equal portions to ensure identical feed conditions for each flotation test.

## 2.2. Coarse Particle Flotation Cell and Bubble Viewer

All tests were carried out in a HydroFloat<sup>®</sup> cell (15 cm diameter, 37 cm height) equipped with a bubble viewer system for in situ measurement of hydrodynamic variables. The flotation cell and bubble viewer configuration were similar to those used in previous hydrodynamic explorations of fluidized flotation systems [5,7]. Figure 2 shows the flotation cell used in the experimental campaign and the Bubble Viewer System installed for measuring the aerohydrodynamic behavior of the HydroFloat<sup>®</sup> flotation cell. The Bubble Viewer System was manufactured by FT Ingenieria, Santiago, Chile.

The HydroFloat<sup>®</sup> coarse particle flotation technology based its operation on a fluidized bed produced with the very same coarse particles being fed to the flotation cell. The fluidized bed is formed with the aid of a water flow. Air is injected into the water line, and both phases pass through the bubble generator as they enter the cell. To have proper performance, the fine fraction of the feed to the HydroFloat<sup>®</sup> is removed through a classification stage performed before the flotation tests. This is done to ensure low viscosity

within the fluidized bed and to minimize hydraulic entrainment. Knowing that the presence of fine particles in the feed of the flotation cell may have an impact, such a variable was considered as part of this study.



**Figure 2.** HydroFloat® cell and bubble viewer used in the testing campaign.

The bubble viewer consists of a sampling tube through which bubbles ascend into a viewing chamber filled with process water. The water inside the bubble viewer has the same chemical conditions that are present in the cell, pH and frother concentration, to prevent any alteration in bubble size upon entering the viewer. The bubble images are then captured by an automated camera system. The images obtained are subsequently analyzed using ImageJ 1.54g to yield bubble size distribution and statistical diameters, such as  $d_{32}$ . Superficial gas velocity ( $J_g$ ) was estimated from the gas flow rate and cross-sectional area of the cell, which allowed, together with  $d_{32}$ , for the calculation of bubble surface area flux ( $S_b$ ).

### 2.3. Residence Time Distribution Measurement

Radioactive tracer tests were conducted to measure the residence time distribution (RTD) and assess the internal mixing regime of the CPF cell. The RTD was measured under a single operating condition, which served as the baseline for evaluating the effect of other operating conditions. RTD for the tailings and concentrate streams were determined using tracer samples of tailings and concentrate, which were activated in a nuclear reactor and subsequently injected as a pulse into the feed stream of the HydroFloat® cell. The temporal evolution of the detected radiation was recorded with NaI(Tl) detectors integrated with an ALTAIX data acquisition system. This methodology is consistent with tracer-based RTD analyses applied in fluidized-bed flotation systems by Liu et al. [7]. Figure 3 shows photographs of the RTD measurement campaign carried out during the experimental test program.



**Figure 3.** RTD measurement performed in the experimental campaign.

#### 2.4. Operating Conditions Used in the Testing Campaign

Different operating conditions were analyzed. Metallurgical recoveries and concentrate enrichment ratio were also obtained to establish the relationship between hydrodynamics and metallurgical performance. The selection of operating conditions followed a systematic framework similar to recent studies on HydroFloat<sup>®</sup> hydrodynamics and performance evaluation [4,5]. Table 2 shows the operating conditions tested in the experimental campaign. The bed depth corresponds to the distance measured from the top of the cell (concentrate discharge lip) to the top interface of the fluidized bed within the cell.

**Table 2.** Operating conditions tested in the experimental campaign.

| Operating Variable | Test | Conditioning | Water Flow (lpm) | Air Flow (lpm) | Fines Content %<br>–106 µm | Bed Depth (cm) | PAX (gpt) | Diesel (gpt) | Aerofroth 65 (gpt) |
|--------------------|------|--------------|------------------|----------------|----------------------------|----------------|-----------|--------------|--------------------|
| Water Flow         | 1    | 10 min/pH 8  | 2.5              | 1              | 10                         | 3              | 150       | 10           | 100                |
|                    | 2    | 10 min/pH 8  | 3                | 1              | 10                         | 3              | 150       | 10           | 100                |
|                    | 3    | 10 min/pH 8  | 4                | 1              | 10                         | 3              | 150       | 10           | 100                |
|                    | 4    | 10 min/pH 8  | 5                | 1              | 10                         | 3              | 150       | 10           | 100                |
| Air Flow           | 5    | 10 min/pH 8  | 2.5              | 0.5            | 10                         | 3              | 150       | 10           | 100                |
|                    | 6    | 10 min/pH 8  | 2.5              | 1.2            | 10                         | 3              | 150       | 10           | 100                |
|                    | 7    | 10 min/pH 8  | 2.5              | 1.5            | 10                         | 3              | 150       | 10           | 100                |
| Water/Air Ratio    | 8    | 10 min/pH 8  | 4.5              | 1.8            | 10                         | 3              | 150       | 10           | 100                |
|                    | 9    | 10 min/pH 8  | 3                | 1.2            | 10                         | 3              | 150       | 10           | 100                |
|                    | 10   | 10 min/pH 8  | 3.8              | 1.5            | 10                         | 3              | 150       | 10           | 100                |
| Bed Depth          | 11   | 10 min/pH 8  | 2.5              | 1              | 10                         | 2              | 150       | 10           | 100                |
|                    | 12   | 10 min/pH 8  | 2.5              | 1              | 10                         | 5              | 150       | 10           | 100                |
|                    | 13   | 10 min/pH 8  | 2.5              | 1              | 10                         | 7              | 150       | 10           | 100                |
| Fines Content      | 14   | 10 min/pH 8  | 2.5              | 1              | 15                         | 3              | 150       | 10           | 100                |
|                    | 15   | 10 min/pH 8  | 2.5              | 1              | 20                         | 3              | 150       | 10           | 100                |
|                    | 16   | 10 min/pH 8  | 2.5              | 1              | 25                         | 3              | 150       | 10           | 100                |
| PAX Dosage         | 17   | 10 min/pH 8  | 2.5              | 1              | 10                         | 3              | 30        | 10           | 100                |
|                    | 18   | 10 min/pH 8  | 2.5              | 1              | 10                         | 3              | 300       | 10           | 100                |
| Diesel Dosage      | 19   | 10 min/pH 8  | 2.5              | 1              | 10                         | 3              | 150       | 0            | 100                |
| Frother Dosage     | 20   | 10 min/pH 8  | 2.5              | 1              | 10                         | 3              | 150       | 10           | 50                 |
| Cond. Time         | 21   | 2 min/pH 8   | 2.5              | 1              | 10                         | 3              | 150       | 10           | 100                |
| Duplicate Test 1   | 22   | 10 min/pH 8  | 2.5              | 1              | 10                         | 3              | 150       | 10           | 100                |
| DTR 1              | DTR  | DTR          | 2.5              | 1              | 10                         | 3              | 150       | 10           | 100                |

It is important to note that all flotation tests were conducted at basic conditions (pH 8), which favors the adsorption of xanthate collectors on copper sulfide mineral surfaces. These results highlight that reagent dosage must be carefully balanced to avoid overdosing effects while ensuring sufficient hydrophobicity and aggregate stability under the prevailing hydrodynamic conditions.

Table 3 presents a description of the reagents used in this study.

In addition to hydrodynamic considerations, the role of reagents is critical in governing the efficiency of bubble–particle interactions in the HydroFloat<sup>®</sup> system. The collector used in this study, potassium amyl xanthate (PAX), is a well-established sulfide collector that promotes hydrophobicity of copper mineral surfaces through chemisorption, thereby

increasing the probability of particle–bubble attachment. Diesel, used as a secondary collector or promoter, enhances hydrophobicity, particularly for coarse particles, by improving surface coating and contributing to the formation and stability of bubble–particle aggregates within the fluidized bed. The frother employed, Aerofroth 65, is a glycol-based frother specifically designed to generate relatively small and stable bubbles while maintaining moderate froth persistence. This property is particularly relevant in HydroFloat® operation, as it contributes to the generation of fine bubbles (approximately 0.5 mm, as observed in this study) and supports the stability and transport of coarse particle aggregates. The combined action of these reagents is essential in coarse particle flotation systems, where attachment probability is inherently limited by reduced liberation and surface exposure. Therefore, reagent selection and dosage must be carefully optimized to balance hydrophobicity, aggregate stability, and froth transport, particularly under conditions where hydrodynamic forces may promote detachment of weakly attached particles.

**Table 3.** Reagents description.

| Reagent Type                     | Reagent Name                  | Dosage Range | Composition/Chemical Nature                                                                                 |
|----------------------------------|-------------------------------|--------------|-------------------------------------------------------------------------------------------------------------|
| Collector                        | PAX (Potassium Amyl Xanthate) | 30–300 g/t   | Alkyl xanthate (ROCS <sub>2</sub> K), sulfur-based collector for sulfide minerals.                          |
| Secondary Collector/<br>Promoter | Diesel                        | 0–10 g/t     | Hydrocarbon mixture (paraffinic/aliphatic compounds).                                                       |
| Frother                          | Aerofroth 65                  | 50–100 g/t   | Polyglycol-based frother (glycol ethers), designed for controlled bubble size and moderate froth stability. |

### 3. Results

Table 4 provides a summary of the results obtained during the experimental campaign.

**Table 4.** Summary of the results obtained from the testing campaign and main operating conditions used in each test.

| Test | Feed P80 (µm) | Mass Rec (%) | Cu Concentrate Grade (%Cu) | Cu Rec (%) | Enrichment Ratio | Jg (cm/s) | d <sub>32</sub> (mm) | Sb (1/s) |
|------|---------------|--------------|----------------------------|------------|------------------|-----------|----------------------|----------|
| 1    | 241           | 18.4         | 0.75                       | 70.0       | 3.8              | 0.09      | 0.60                 | 9.1      |
| 2    | 246           | 21.9         | 0.66                       | 73.9       | 3.4              | 0.09      | 0.53                 | 10.3     |
| 3    | 240           | 25.7         | 0.58                       | 75.5       | 2.9              | 0.09      | 0.47                 | 11.7     |
| 4    | 246           | 28.9         | 0.54                       | 79.8       | 2.8              | 0.09      | 0.48                 | 11.4     |
| 5    | 248           | 15.3         | 0.85                       | 61.8       | 4.1              | 0.05      | 0.56                 | 4.9      |
| 6    | 247           | 23.6         | 0.67                       | 75.0       | 3.2              | 0.11      | 0.56                 | 11.7     |
| 7    | 249           | 19.0         | 0.83                       | 76.6       | 4.0              | 0.14      | 0.43                 | 19.1     |
| 8    | 224           | 32.0         | 0.48                       | 78.3       | 2.4              | 0.16      | 0.49                 | 20.1     |
| 9    | 246           | 23.0         | 0.66                       | 72.6       | 3.2              | 0.11      | 0.52                 | 12.7     |
| 10   | 233           | 25.4         | 0.59                       | 76.3       | 3.0              | 0.14      | 0.54                 | 15.2     |
| 11   | 236           | 26.4         | 0.67                       | 79.2       | 3.0              | 0.09      | 0.57                 | 9.6      |
| 12   | 243           | 19.4         | 0.7                        | 68.0       | 3.5              | 0.09      | 0.56                 | 9.8      |
| 13   | 245           | 16.7         | 0.73                       | 56.9       | 3.4              | 0.09      | 0.58                 | 9.5      |
| 14   | 240           | 21.4         | 0.63                       | 66.0       | 3.1              | 0.09      | 0.60                 | 9.1      |
| 15   | 237           | 21.2         | 0.54                       | 59.5       | 2.8              | 0.09      | 0.59                 | 9.3      |

Table 4. Cont.

| Test | Feed P80 ( $\mu\text{m}$ ) | Mass Rec (%) | Cu Concentrate Grade (%Cu) | Cu Rec (%) | Enrichment Ratio | Jg (cm/s) | d <sub>32</sub> (mm) | Sb (1/s) |
|------|----------------------------|--------------|----------------------------|------------|------------------|-----------|----------------------|----------|
| 16   | 237                        | 17.5         | 0.54                       | 49.4       | 2.8              | 0.09      | 0.54                 | 10.2     |
| 17   | 246                        | 24.3         | 0.69                       | 81.9       | 3.4              | 0.09      | 0.52                 | 10.5     |
| 18   | 246                        | 17.9         | 0.76                       | 65.8       | 3.7              | 0.09      | 0.56                 | 9.8      |
| 19   | 239                        | 18.4         | 0.73                       | 65.5       | 3.6              | 0.09      | 0.64                 | 8.6      |
| 20   | 239                        | 9.9          | 0.21                       | 10.2       | 1.0              | 0.09      | 0.65                 | 8.4      |
| 21   | 239                        | 16.5         | 0.19                       | 15.1       | 0.9              | 0.09      | 0.62                 | 8.8      |
| 22   | 217                        | 19.5         | 0.75                       | 71.6       | 3.7              | 0.09      | 0.61                 | 9.0      |

### 3.1. Copper and Mass Recoveries Obtained

The results of copper recoveries are shown on Figure 4. These results are plotted against the mass recoveries obtained in each test. Figure 5 shows the grade enrichment ratio (ER) of the concentrates obtained in each test, plotted against the corresponding mass recoveries.

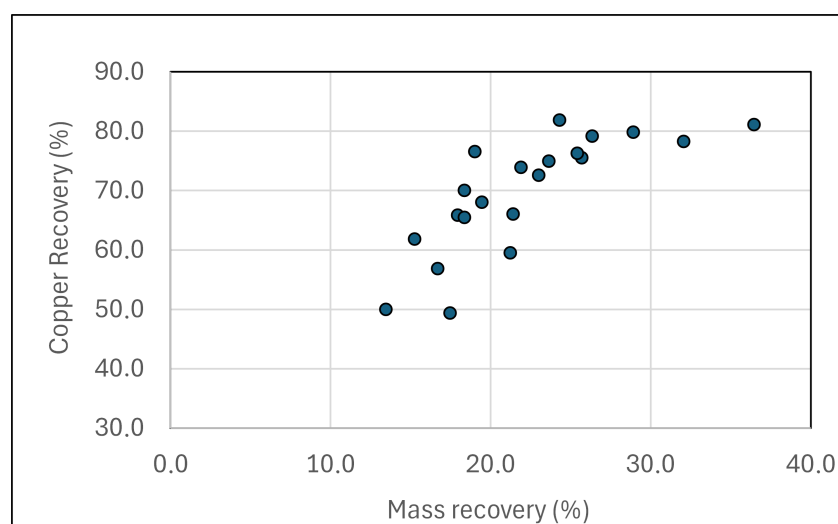


Figure 4. Copper recoveries versus mass recoveries.

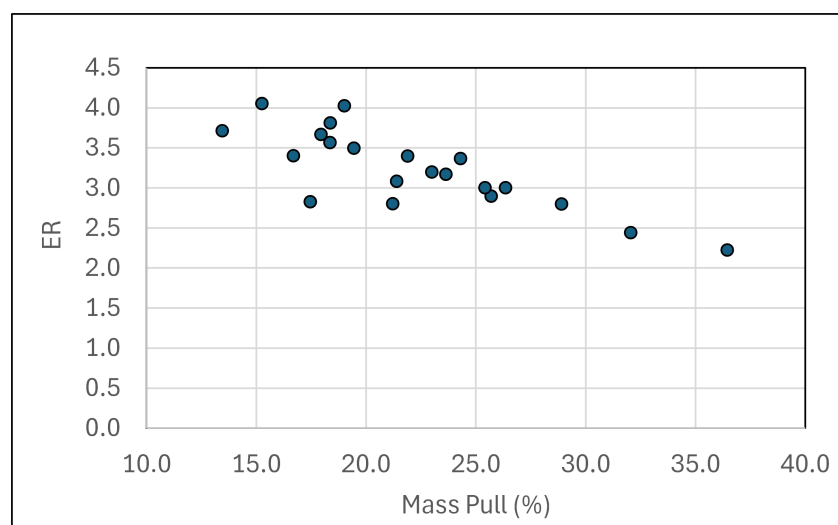


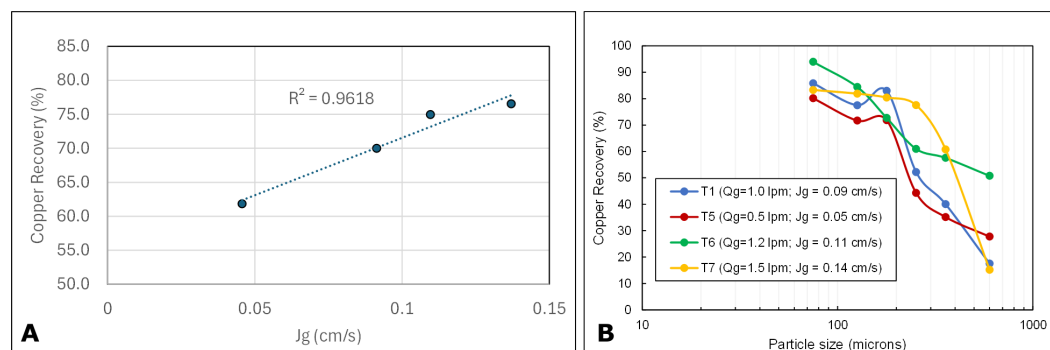
Figure 5. Enrichment ratio (ER) versus mass recovery.

From Figure 4, it can be observed that certain operating conditions result in improved metallurgical recoveries. However, for high mass recoveries, specifically, above 25%, copper recovery no longer increases. This suggests that at the operating conditions that make the mass recovery increases above 25%, there is an increasing effect of non-selective flotation taking place that report gangue to the concentrate. The results observed in Figure 4 can be divided in three ranges: a range in which the equipment exhibits selectivity or where the slope is greater than 1, followed by an intermediate range in which selectivity is diminished or when the slope approaches 1 and a final range where recovery of the valuable mineral appears to be limited, with the response predominantly governed by gangue (the flat region of the graph towards the end).

Figure 5 shows that increases in metallurgical and mass recoveries are accompanied by a reduction in concentrate quality (enrichment ratio, ER), as indicated by the slope shown in the figure. This trade-off between recovery and grade is consistent with hydrodynamic and kinetic evaluations of CPF devices in the literature [4].

### 3.2. Effect of Air Injection

Higher air flow rates increased copper recovery and enabled the recovery of coarser particles. Figure 6 shows the effect of gas flow rate on global recovery and recovery by size.

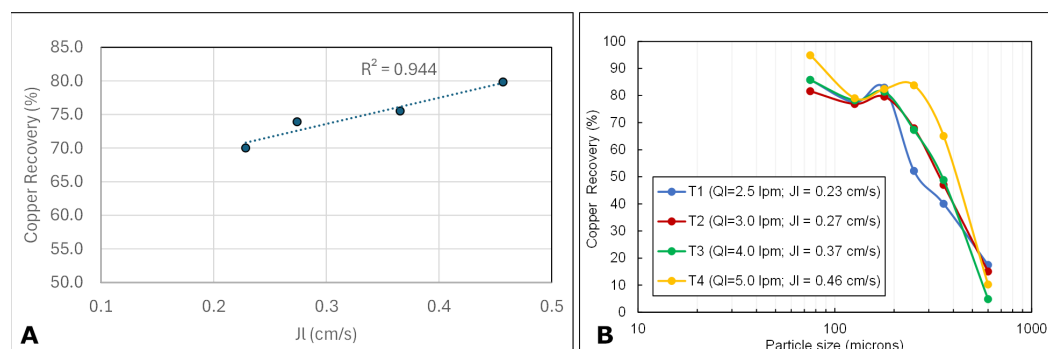


**Figure 6.** Effect of  $J_g$  on copper recoveries. Global copper recovery vs.  $J_g$  (A) and recovery by particle size at different  $J_g$  (B).

Figure 6B shows the copper recovery curves by particle size, indicating that higher air flow rates tend to improve the recovery of the coarser size fractions. This behavior is consistent with the fundamental role of gas dispersion reported in HydroFloat<sup>®</sup> hydrodynamic studies. Increasing the gas injection rate increases the number of bubbles available within the fluidized bed and therefore the bubble surface area flux ( $S_b$ ), which enhances the probability of bubble–particle collision and attachment. Furthermore, the visual observations obtained during this study suggest that a higher bubble population may facilitate the formation of chain-like bubble–particle aggregates, increasing the effective buoyancy of coarse particles and promoting their upward transport through the fluidized bed. This mechanism may explain the improved recovery of coarse particles observed at higher gas flow rates [8].

### 3.3. Effect of Water Injection Rate

Copper recovery also improved with water injection rate. Figure 7A shows the correlation between water injection and copper recovery. Figure 7B shows the copper recovery curves by particle size, indicating that higher water injection rates tend to enhance the recovery of the coarser size fractions. However, it was also found that excessive water injection reduced selectivity by entraining fine gangue particles.



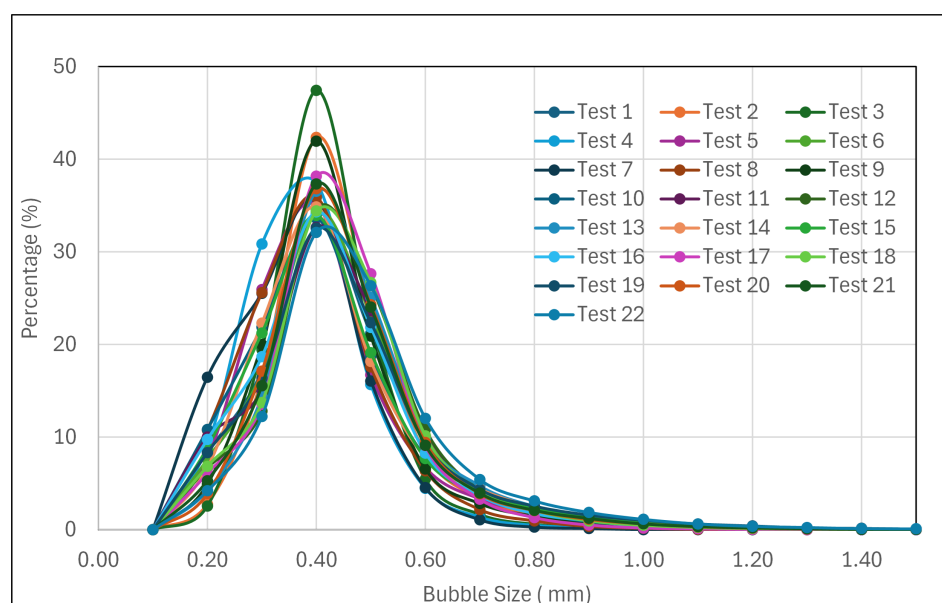
**Figure 7.** Effect of  $J_L$  on copper recoveries. Global copper recovery vs.  $J_L$  (A) and recovery by particle size at different  $J_L$  (B).

### 3.4. Bubble Size

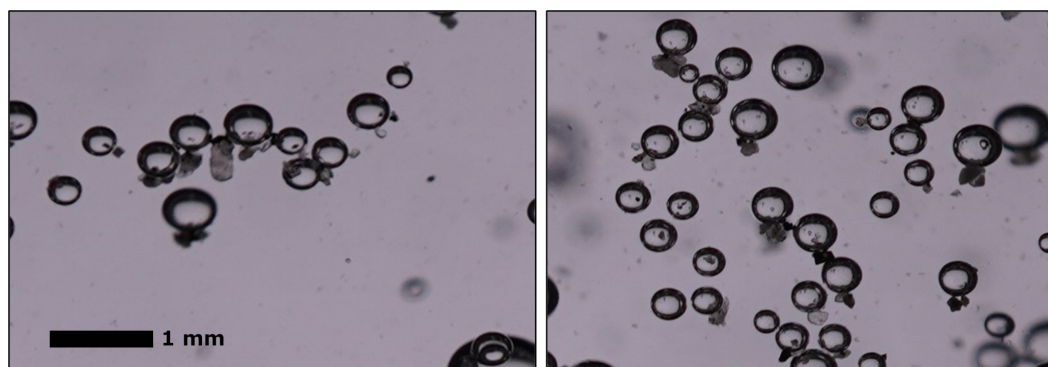
An interesting finding was that the bubble diameter remained nearly constant at approximately 0.5 mm ( $d_{32}$ ), regardless of the operating conditions. Figure 8 shows the bubble size distributions for all tests conducted, showing that in all cases, bubbles generated in the HydroFloat<sup>®</sup> cell are much smaller than those produced in conventional flotation machines (ca. 1.0 mm). This finding is counterintuitive as it is expected that coarse particles require large bubbles to be collected.

The use of the bubble viewer during the experimental campaign made it possible to visually observe the bubbles and collected particles captured by the sampling tube. It was consistently observed, in the different sets of images, that bubbles can form chain-like bubble–particle aggregates, which appear to collaborate in increasing the buoyancy of coarse particles within the fluidized bed. These observations are consistent with reports of bubble–particle aggregate formation in fluidized-bed flotation columns [7].

Although the purpose of this work is to present the behavior of the cell under different operating conditions, and not to analyze the underlying mechanisms in coarse particle flotation, it is worth emphasizing this finding as it suggests a possible advantage of a fluidized bed in the bubble–particle collection. Figure 9 presents images of loaded bubbles and chain-like bubble–particle aggregates as they appeared in the bubble viewer.



**Figure 8.** Bubble size distribution measured from the testing campaign.



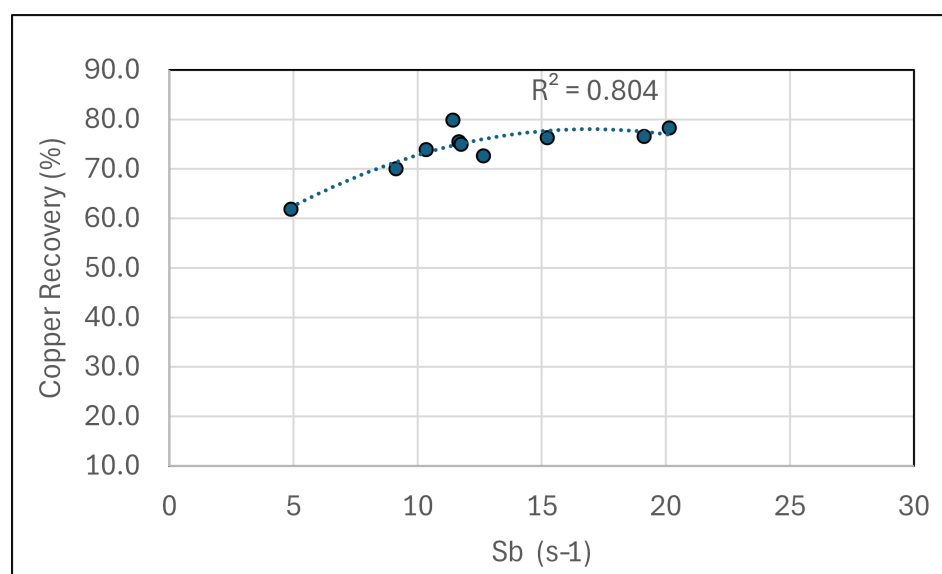
**Figure 9.** Chain-like bubble–particle aggregates observed in the bubble viewer under the operating conditions of Test 1.

The chain-like bubble–particle aggregates presented in Figure 9 were observed in all the experiments and suggest a possible mechanism of multi-bubble–particle collection and upward transport of coarse particles via aggregation within the fluidized bed of the flotation cell. These observations provide evidence of a possible distinctive operating mechanism governing this type of technology.

### 3.5. Effect of Bubble Surface Area Flux ( $S_b$ )

Figure 10 shows the correlation between copper recoveries and superficial area flux ( $S_b$ ). This graph includes only those tests in which the fluidized-bed level was maintained at 3 cm below the cell concentrate lip, the fines content ( $-106\ \mu\text{m}$ ) was constant at 10%, and both the type and dosage of reagents was kept constant. In other words, Figure 10 presents the effect of  $S_b$  on copper metallurgical recoveries under different  $J_g$  and  $J_l$  levels.

Figure 10 shows that at  $S_b$  values above  $17\ \text{s}^{-1}$ , copper recovery does not increase further, suggesting that higher values of  $S_b$  do not contribute to a better metallurgical performance. Beyond this point, further increases in  $S_b$  result primarily in the entrainment of gangue into the concentrate.

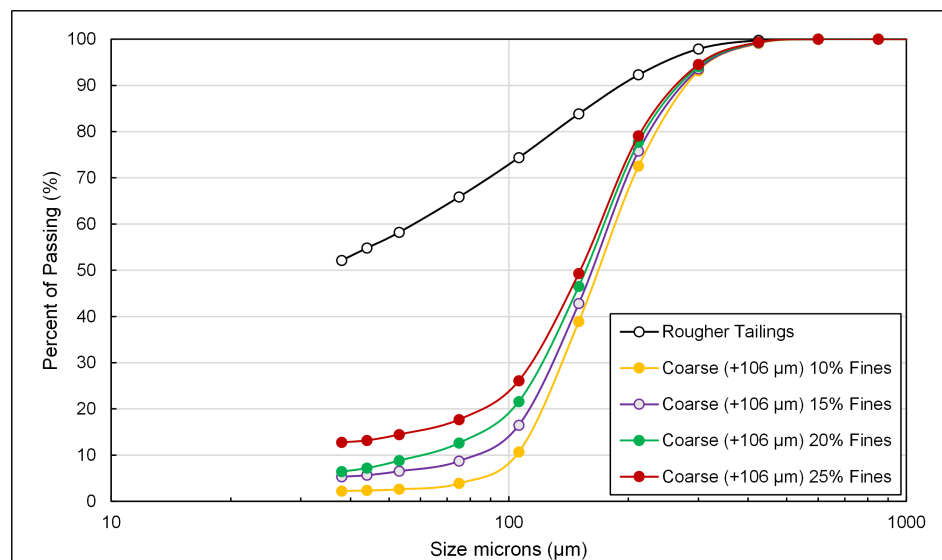


**Figure 10.** Copper recovery versus bubble surface area flux  $S_b$ .

### 3.6. Effect of Fines Particles Content on Feed

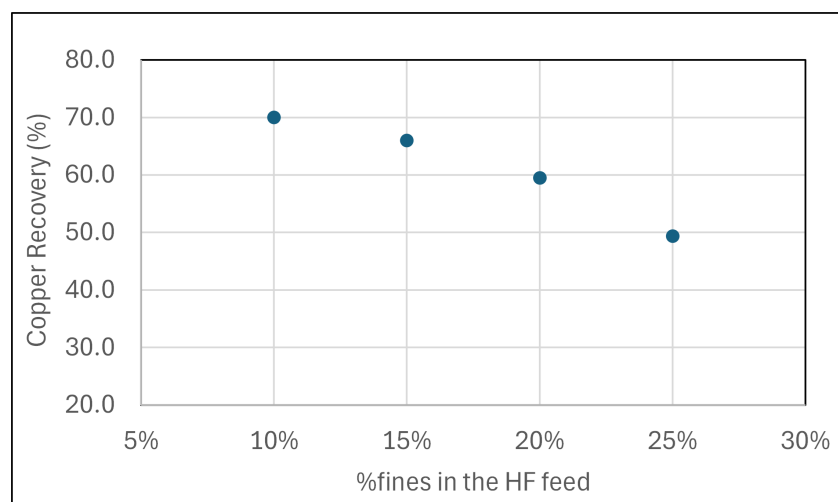
As previously explained, the HydroFloat<sup>®</sup> coarse particle flotation technology requires the classification or separation of fine and coarse particles upstream of the flotation cell to ensure a low viscosity within the fluidized bed. Different fine contents ( $\% -106\ \mu\text{m}$ ) were

tested during the experimental campaign. To generate the particle size distribution curves used in the laboratory, various classification efficiencies in hydrocyclones were simulated using the Weir Minerals software Cavex Cyclone Selector. Figure 11 shows the particle size distribution of the total rougher tailings sample used in the experimental campaign. It also shows the size distribution of the fine fraction ( $-106\ \mu\text{m}$ ) after tailings classification, as well as the feed size distributions to the HydroFloat<sup>®</sup> cell corresponding to 10% fines content (base case) and 15%, 20%, and 25% fines.



**Figure 11.** Particle size distributions of sample received and HydroFloat<sup>®</sup> feeds.

Figure 12 shows the effect of fines content in the metallurgical performance of the HydroFloat<sup>®</sup> flotation cell (HF). As can be observed, the presence of fines ( $<106\ \mu\text{m}$ ) has a negative impact on CPF performance. Copper recovery decreases significantly when the fines exceed 10% of the feed by weight. The presence of fine particles may adversely affect the mobility of bubble–particle aggregates within the fluidized bed, likely due to increased slurry viscosity and hindered settling effects associated with a higher fines fraction. This may result in a higher apparent bed viscosity, reduced permeability, and increased interparticle interactions, thereby limiting aggregate transport and overall flotation performance. These results highlight the importance of investigating the incorporation of a classification stage upstream of the HydroFloat<sup>®</sup> cells.



**Figure 12.** Effect of fines content on copper recoveries.

### 3.7. Effect of Collector and Diesel Dosages, Bed Level, and Conditioning Time

From Table 4, test results revealed that the lowest collector dosages yielded the highest copper recoveries, which is likely due to overdosing of the collector caused by the presence of residual reagents in the process water, which may lead to adverse effects. These results are consistent with the surface chemistry findings that demonstrated that coarse particle flotation is highly sensitive to bubble–particle attachment conditions. Results showed that the probability of attachment decreases with increasing particle size due to the larger inertia of coarse particles and the shorter collision contact times available for attachment. Under these conditions, the induction time required for successful attachment becomes a critical parameter and can be significantly influenced by reagent dosage and particle surface hydrophobicity. Excessive collector addition may not necessarily improve flotation performance and, in some cases, may adversely affect selectivity and bubble–particle interactions. These findings support the results obtained in the present study, where lower collector dosages produced higher copper recoveries and where proper reagent conditioning was found to be essential for effective coarse particle flotation [9]. Diesel addition enhanced the HydroFloat® performance. This effect is likely related to the role of diesel as a hydrophobic extender, increasing the effective hydrophobicity of partially liberated sulfide particles and improving bubble–particle attachment efficiency. For coarse particles, where attachment and aggregate stability are often limiting factors, enhanced surface hydrophobicity may increase both the probability of attachment and the resistance of bubble–particle aggregates to detachment. Consequently, diesel addition may contribute to improved recovery of coarse particles within the fluidized bed. As observed in most industrial-scale coarse particle flotation (CPF) operations, the use of diesel is a common practice in coarse particle recovery.

The results obtained from the experimental campaign show that bed levels lead to higher copper and mass recoveries. Additionally, the enrichment ratios indicate that operating at a lower bed level does not necessarily result in lower concentrate grades.

Regarding conditioning time, it was found that proper reagent conditioning is critical to achieving good metallurgical recoveries. Laboratory tests applied a standard conditioning time of 10 min. When this time was reduced, a noticeable negative impact was observed on the effectiveness of coarse particle attachment to bubbles within the fluidized bed. This is likely because coarse particles exhibit a lower degree of liberation and a reduced exposed surface area of the target mineralogical species. Therefore, longer conditioning times may increase the probability of hydrophobization of the exposed mineral surfaces.

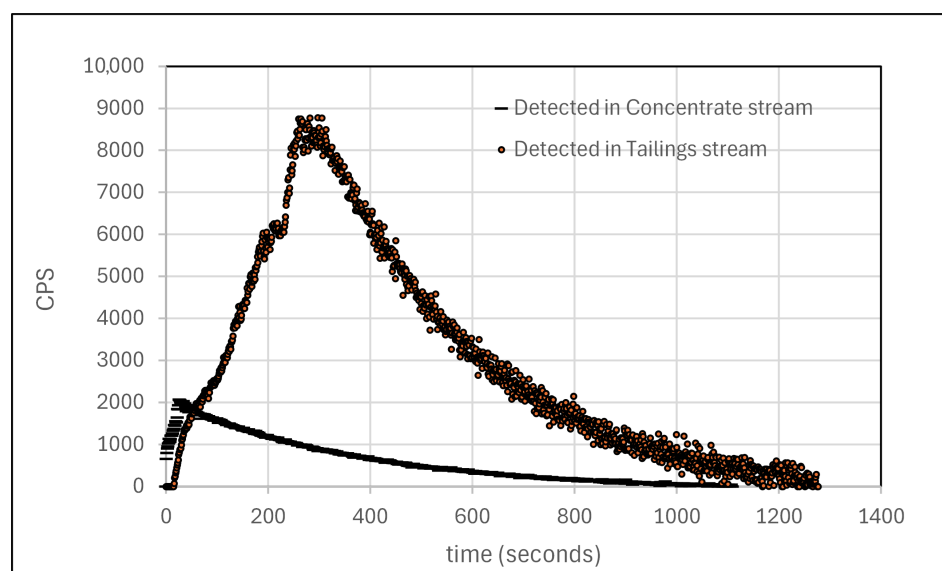
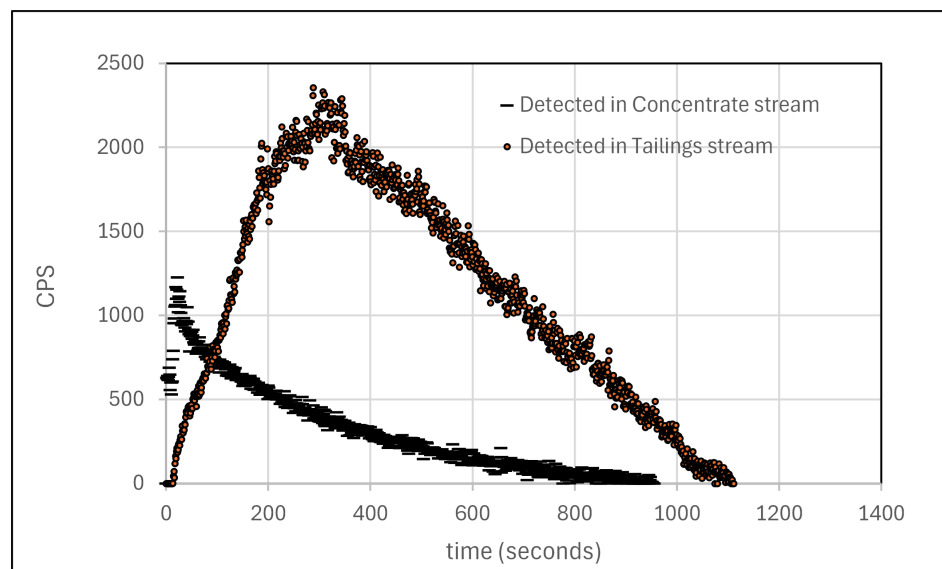
### 3.8. Residence Time Distribution (RTD)

Radioactive tracer tests indicated that the mean residence time for the baseline case is 7 min for gangue particles and ca. 5 min for non-floatable particles reporting to the concentrate. Table 5 presents a summary of the results obtained from the RTD measurements. Using the equation presented by Fogler [10], the number of ideal tanks in series (N) was calculated ( $N = MRT^2/\sigma^2$ ). The results are consistent with the operation principle of the HydroFloat® cell as particles that form the fluidized bed will tend to stay longer inside the cell as those reaching the concentrate.

The interpretation of the RTD curves suggests that HydroFloat® cells operate under an intermediate mixing regime, ensuring sufficient particle–bubble interaction without the excessive back-mixing. Figures 13 and 14 show the RTD curves obtained from the measurements conducted in this study.

**Table 5.** Mean Residence Time (MRT), variance and N values obtained from RTD measurements.

| Measurement | Tracer          | MRT (min) |       | Variance (min <sup>2</sup> ) |                  | Number of Ideal Tanks in Series ( $N = MRT^2/\sigma^2$ ) |         |
|-------------|-----------------|-----------|-------|------------------------------|------------------|----------------------------------------------------------|---------|
|             |                 | Conc.     | Tails | $\sigma^2$ Conc.             | $\sigma^2$ Tails | N Conc.                                                  | N Tails |
| 1           | Tails Particles | 4.7       | 7.1   | 14.6                         | 16.0             | 1.5                                                      | 3.2     |
| 2           | Conc. Particles | 4.3       | 7.5   | 12.0                         | 15.0             | 1.6                                                      | 3.7     |
| Duplicate   | Tails Particles | 5.1       | 7.2   | 17.6                         | 17.6             | 1.5                                                      | 2.9     |

**Figure 13.** RTD using radioactive gangue particles.**Figure 14.** RTD using radioactive concentrate particles.

This is consistent with the observations reported by Zhao et al. [11], who proposed that the fluidized bed provides a quasi-laminar and low-turbulence environment that promotes the formation and stability of particle–bubble aggregates.

The residence time distribution (RTD) curves presented in Figures 13 and 14 indicate that the HydroFloat<sup>®</sup> cell does not conform to either ideal plug flow or perfectly mixed reactor behavior. Instead, the observed responses are characteristic of an intermediate hydrodynamic regime, combining axial dispersion with a moderate degree of back-mixing.

The presence of delayed peaks together with extended tails towards longer residence times suggests the coexistence of multiple transport pathways within the fluidized bed, in other words, the presence of internal recirculation within the bed. For the gangue tracer (Figure 13), the RTD is dominated by the signal measured in the tailings stream, exhibiting a well-defined peak at approximately 250–300 s followed by a gradual decay with a pronounced long tail. In contrast, the concentrate stream shows an early-time response of significantly lower magnitude. This behavior confirms that most gangue particles follow the expected pathway towards tailings, while a minor fraction is rapidly recovered to the concentrate, likely due to hydraulic entrainment or non-selective transport mechanisms. The broad and asymmetric nature of the tailings distribution further indicates that gangue particles experience substantial residence times within the system, rather than undergoing short-circuiting.

For the concentrate tracer (Figure 14), a similar trend is observed, with the dominant response appearing in the tailings stream, while the concentrate signal is characterized by an earlier and less intense response. A fraction of valuable particles follows a rapid flotation pathway and reports to the concentrate at short residence times, whereas a significant proportion is either not captured or only weakly attached and ultimately reports to tailings after prolonged residence times.

The combined interpretation of both RTD curves provides a detailed insight into the hydrodynamic behavior of the HydroFloat<sup>®</sup> cell, revealing that the system operates far from an ideal plug flow regime. This conclusion is supported not only by the qualitative shape of the RTD responses shown in Figures 13 and 14, but also by the statistical dispersion of the residence time distributions reported in Table 5. In particular, the measured variances for the tailings show a significant spread of residence times around the mean values. Such levels of dispersion are incompatible with plug flow behavior and instead reflect a hydrodynamic regime dominated by axial dispersion and internal recirculation. This is further evidenced by the presence of asymmetric profiles, delayed maxima, and extended tails at longer residence times in the tailings responses, all of which are characteristic of systems in which particles experience multiple transport pathways and partial back-mixing within the fluidized bed.

A more detailed examination of the RTD curves also reveals a clear differentiation between the behavior of the upper and lower regions of the cell. The responses measured in the concentrate stream exhibit an early-time peak, with maximum CPS values occurring close to the initial time, which strongly suggests that the upper section of the HydroFloat<sup>®</sup> behaves approximately as a single, well-mixed region, as suggested by *N* values around 1.5. This behavior is consistent with a short-circuit flow path, in which any particle reaching this upper zone—regardless of its hydrophobicity—can be rapidly transported to the overflow with minimal additional residence time. From a process perspective, this has important implications for selectivity: while it enables fast recovery of hydrophobic particles, it also creates a pathway for hydrophilic gangue particles to report to the concentrate through non-selective transport mechanisms such as entrainment. Consequently, improving the concentrate grade would likely require strategies to limit the upward transport of hydrophilic particles into this highly mixed overflow region while preserving efficient recovery kinetics for hydrophobic particles.

In contrast, the RTD responses measured in the tailings stream display broader, more symmetric distributions with delayed peaks and pronounced long tails, indicating a fundamentally different hydrodynamic regime. These profiles are consistent with the behavior of multiple ideal mixers operating in series, as supported by the calculated values of *N* shown in Table 5. This range of *N* implies that particle transport within the fluidized bed and lower regions of the cell can be effectively described by a distributed mixing model with a limited

number of mixing stages, rather than by either a perfectly mixed reactor or a plug flow system. In physical terms, this behavior reflects the presence of internal recirculation loops, heterogeneous flow structures, and zones of varying mobility within the bed, all of which contribute to prolonging particle residence times and broadening the RTD. The existence of these hydrodynamic features explains why both gangue and valuable particles may remain in the system for extended periods without necessarily achieving separation.

From an operational and scale-up perspective, these findings highlight the importance of controlling both mixing intensity and flow structure within the HydroFloat® cell. The co-existence of a highly mixed overflow region and a partially mixed fluidized bed implies that performance is governed by the balance between rapid transport pathways and distributed residence time processes. Excessive dispersion and recirculation may reduce selectivity by increasing gangue carryover, whereas insufficient mixing may limit particle–bubble contact and reduce recovery efficiency. Furthermore, the presence of long residence time tails suggests the existence of poorly mixed or low-velocity regions within the bed, which may act as dead zones or regions of limited flotation activity. Addressing these limitations during scale-up may require improvements in fluidization uniformity, air distribution, and hydrodynamic design, with the objective of enhancing phase segregation, reducing non-selective transport to the overflow, and achieving a more controlled residence time distribution that optimizes both recovery and concentrate grade.

#### 4. Discussion

The hydrodynamic and metallurgical results obtained in this study confirm that the HydroFloat® cell performance is highly dependent on the water addition, and air rate injection. The identification of a superficial area flux ( $S_b \approx 17 \text{ s}^{-1}$ ) above which metallurgical performance does not further improve might provide a practical guideline for industrial operation. Given that the bubble size remained essentially constant under the different operating conditions tested, the bubble surface area flux ( $S_b$ ) was primarily governed by the injected air flow rate, or superficial gas velocity ( $J_g$ ). An optimal or practical maximum  $S_b$  might ensure high copper recovery without excessive gangue entrainment, a finding consistent with previous observations in fluidized-bed flotation systems [5,7].

The results presented in this study demonstrate that each of the operational variables evaluated, namely superficial gas velocity ( $J_g$ ), superficial liquid velocity ( $J_l$ ), bubble surface area flux ( $S_b$ ), fines content, reagent dosage, and bed level, exerts a distinct and measurable influence on the metallurgical performance of the HydroFloat® cell. Gas injection plays a primary role in controlling bubble surface area and collision frequency, thereby directly impacting recovery, particularly for coarse particles. Similarly, water injection regulates bed expansion and particle mobility within the fluidized bed, which can enhance transport but also promote entrainment at excessive levels. The bubble surface area flux ( $S_b$ ) was identified as a key parameter integrating gas and bubble size effects, with an apparent upper limit beyond which performance gains are offset by non-selective recovery. Finally, bed level and conditioning time were shown to affect both residence time and the degree of particle hydrophobization. These results confirm that HydroFloat® performance is governed by a complex combination of hydrodynamic, physical, and chemical factors, rather than by any single variable in isolation.

More importantly, the results highlight that the performance of the HydroFloat® system is controlled by the interaction between hydrodynamic conditions and chemical environment, rather than by independent effects of individual variables. Hydrodynamics define the framework for particle transport, collision frequency, and residence time distribution, while reagent chemistry governs the probability of attachment and the stability of bubble–particle aggregates. For instance, increased gas and water flow rates may enhance

dispersion and collision rates, but at the same time raise shear forces that can promote particle detachment, particularly for weakly hydrophobic particles. Similarly, the effectiveness of collectors and promoters such as PAX and diesel depends not only on their ability to generate hydrophobic surfaces, but also on the capacity of the hydrodynamic environment to preserve aggregate integrity during transport. The frother, in turn, links both domains by controlling bubble size and froth stability, directly influencing both attachment and transport phenomena. Therefore, optimal performance in coarse particle flotation cannot be achieved by maximizing individual variables, but rather by balancing hydrodynamic conditions and reagent chemistry to ensure efficient particle–bubble interaction while minimizing detachment and non-selective transport. This integrated perspective is essential for both process optimization and scale-up of HydroFloat<sup>®</sup> systems.

Although the HydroFloat<sup>®</sup> technology is specifically designed for the recovery of coarse particles, the results shown in Figures 6B and 7B indicate a clear decline in copper recovery for particle sizes above approximately 0.1 mm. This behavior suggests that, despite the enhanced coarse particle flotation capabilities of the system, there are still intrinsic limitations governing the recovery of larger particles. As discussed in Section 2, coarse particles in the +106  $\mu\text{m}$  fraction exhibit relatively low degrees of liberation and reduced exposed surface area of valuable mineral phases, which decreases the probability of effective bubble–particle attachment. In addition, the hydrodynamic conditions within the fluidized bed may impose constraints on the stability and transport of bubble–particle aggregates, particularly as particle mass increases. Therefore, while the HydroFloat<sup>®</sup> cell extends the recoverable size range compared to conventional flotation technologies, the observed recovery drop for coarser particles highlights the competing effects of particle size, liberation, and hydrodynamic transport mechanisms, indicating that optimal performance in CPF systems requires a balance between coarse particle recovery capability and the fundamental limitations associated with particle–bubble attachment and aggregate stability.

An additional aspect that deserves consideration when interpreting the metallurgical performance is the balance between inertial and surface forces acting on the bubbles and bubble–particle aggregates within the fluidized bed. Bubble sphericity is typically maintained when surface tension forces dominate over inertial effects; however, under conditions of increased shear stress—such as those induced by elevated water and air injection rates—bubble deformation may occur. The slight deformation observed in the bubbles shown in Figure 9 suggests that local hydrodynamic shear is present within the fluidized bed. This has important implications for particle–bubble attachment stability, as increased shear forces can promote the detachment of particles from the bubble surface. This effect is expected to be particularly significant for particles with low contact angles, where attachment forces are inherently weaker. Therefore, while higher water and air flow rates may enhance particle suspension and collision frequency, they may simultaneously compromise aggregate stability by increasing detachment rates. This highlights the existence of a trade-off between improving hydrodynamic conditions for particle–bubble contact and preserving the integrity of the formed aggregates, which ultimately governs the recovery of coarse particles in HydroFloat<sup>®</sup> systems.

An important and somewhat counterintuitive observation in this study is that relatively small bubbles, with diameters of approximately 0.5 mm, are capable of recovering coarse particles. This behavior contrasts with the conventional expectation that coarse particle flotation requires larger bubbles to provide sufficient buoyancy force. A plausible explanation lies in the specific hydrodynamic and interfacial conditions established within the fluidized bed of the HydroFloat<sup>®</sup> cell, which differ significantly from those of conventional mechanically agitated systems. In fluidized-bed flotation, the relatively low-turbulence environment reduces detachment rates and allows particle–bubble aggregates to

persist during transport [12]. In addition, visual observations presented in Figure 9 suggest the formation of chain-like bubble–particle aggregates, in which multiple small bubbles interact with a single coarse particle or previously formed aggregates. This mechanism effectively increases the total buoyant force acting on the particle, compensating for the smaller size of individual bubbles and enabling the transport of coarse particles.

From a fundamental standpoint, the ability of small bubbles to float coarse particles can be interpreted as the result of a balance between attachment probability and detachment stability. While larger bubbles provide higher individual buoyancy, smaller bubbles offer higher specific surface area and increased collision frequency, which enhances attachment efficiency. However, for coarse particles, aggregate stability becomes the dominant limiting factor, as detachment probability increases significantly with particle size, particularly under turbulent conditions [13]. In this context, the formation of multi-bubble aggregates and the relatively quiescent hydrodynamic conditions of the fluidized bed enable these aggregates to remain stable during transport. Therefore, the present results suggest that coarse particle recovery in this system is governed not solely by bubble size but by the combined effects of aggregate structure and hydrodynamic conditions, which together allow small bubbles to effectively transport coarse particles.

The residence time distribution (RTD) results highlight that residence time within the laboratory scale HydroFloat<sup>®</sup> cell is ca. 7 min for the tailings stream. This finding is useful information for projects design when estimating HydroFloat<sup>®</sup> units. The residence time distribution (RTD) curves indicate that the HydroFloat<sup>®</sup> cell does not conform to either ideal plug flow or perfectly mixed reactor behavior. The presence of delayed peaks together with extended tails towards longer residence times suggests the coexistence of multiple transport pathways within the fluidized bed, in other words, the presence of internal recirculation and/or stagnant zones within the bed.

Finally, results obtained suggest that reagent dosage and fines content underscores the importance of integrating hydrodynamic and surface chemistry considerations in the optimization of coarse particle flotation. Lower collector dosages were favorable due to residual reagents present in process water, while insufficient frother addition negatively impacted recovery. Similar trends regarding reagent–hydrodynamic interactions and their effect on attachment probability have been reported in surface chemistry studies [9].

## 5. Conclusions

- HydroFloat<sup>®</sup> performance is strongly influenced by the gas and water flows added to the teeter bed.
- A potential optimal bubble surface area flux ( $S_b \approx 17 \text{ s}^{-1}$ ) was identified, beyond which additional air only increases the mass pull and entrainment of gangue.
- Bubble diameter remained nearly constant (ca. 0.5 mm) across all tests, suggesting that in this kind of machine, small bubbles can collect coarse particles.
- The observation of chain-like bubble–particle aggregates suggests a possible mechanism to be considered when modeling the phenomena taking place within the fluidized bed.
- Residence time distribution (RTD) measurements indicated a mean residence time of ca. 7 min for the tailings stream with limited back-mixing.
- HydroFloat<sup>®</sup> performance was negatively affected by excessive fines and collector overdosing, while adequate frother addition is essential to maintain recovery.
- Results suggest that the integration of hydrodynamic and surface chemistry perspectives is key for optimizing HydroFloat<sup>®</sup> performance.

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## Abbreviations

The following abbreviations are used in this manuscript:

|     |                             |
|-----|-----------------------------|
| CPF | Coarse Particle Flotation   |
| RTD | Residence Time Distribution |
| ER  | Enrichment Ratio            |

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