

Article

Cell-Specific Relationships Between Froth Parameters and Flotation Performance: Insights from the Flash and Rougher Cells

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Abstract

Recent advances in machine vision systems make froth image analysis a promising tool for real-time monitoring, evaluating, and controlling flotation performance. This study investigates the characteristics of the froth in two mechanical industrial flotation cells: a Flash Cell and Cell 6, which is the final cell in the rougher stage of a gold-bearing sulfide ore processing plant. Froth parameters, including bubble velocity (BV) and bubble size (BS), were measured online using the Stone Three Froth Camera System under varying operating conditions such as air flow rate and froth height. The results showed that BV was the most predictive froth parameter in both cells. BS exhibited predictive value only in the Flash Cell, where gold grade increased linearly with BS. In Cell 6, however, no significant relationship was found between BS and performance. These findings demonstrate that froth monitoring strategies must be cell-specific. BS is a useful control parameter in Flash flotation, but not in Cell 6, where entrainment dominates. Overall, the study shows that, effective optimization requires simultaneous consideration of froth parameters and feed characteristics, rather than reliance on a single indicator.

Keywords: froth image analysis; bubble size; bubble velocity; froth flotation; machine vision; flash flotation



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1. Introduction

The top of the froth surface is the only visible part of the flotation cell and is formed by mineralized air bubbles. Froth appearance reflects the behavior of particles within the collection zone [1–3] and is closely linked to flotation performance [4–7].

In flotation, machine vision technology refers to the use of digital imaging systems to capture and analyze the froth phase at the surface of flotation cells, providing continuous, real-time monitoring. High-resolution cameras, often combined with laser sensors, record froth images in real time [8–11]. These images are then processed using image analysis algorithms to extract quantitative froth descriptors such as bubble size distribution, bubble velocity, froth color, and froth thickness (from the lip of the cell). Each of these parameters reflects different aspects of froth stability, particle attachment, and entrainment. For instance, bubble velocity is strongly linked to air dispersion and froth mobility [12–14], bubble size relates to drainage and selectivity, and froth color can provide indirect information on mineral composition and surface chemistry [7–11]. By converting visual froth features into numerical data, machine vision systems allow operators and control algorithms to infer flotation performance—such as mass pull, concentrate grade, and recovery—without

the need for direct sampling. Early studies demonstrated the potential of image analysis for flotation monitoring [2,3], while more recent work has advanced towards industrial-scale prediction models [5,8]. As a result, machine vision has become a valuable tool for real-time monitoring [15,16], control, and optimization of flotation circuits, complementing conventional sensor-based measurements such as air flow, pulp level, and reagent dosage.

Flotation circuits consist of different banks of cells with distinct roles. The rougher flotation banks are formed by several flotation cells and are operated for a high recovery. The tailings of the rougher bank represent about 90% of the overall plant loss [17]. Thus, control of this stage is crucial for minimizing metal loss. In general, high-quality products that possess high surface liberation and hence higher flotation rate constants are recovered in the first cells of the rougher bank, and the product quality decreases along the bank [18–22]. In addition, it is known that for a given liberation class, the rate constant changes as a function of particle size [21,23]. Below and above a particular particle size range, the flotation rate constant and recovery decrease [20,21,24]. Thus, the particle size distribution of the concentrates obtained from each cell varies along the bank. While the fine and intermediate-sized particles are mostly collected in the first cells, the coarse fraction in the concentrate increases through the last cells [18,20]. Also, top-of-froth (TOF) measurements revealed the increase in coarse size classes in the mass fraction of collected materials down the bank [18]. The particle hydrophobicity and particle size affect froth phase stability, thus the metallurgical performance of the cell [25–30]. Consequently, from the first cell to the last cell of the rougher bank, the visual appearance of the froth and flotation performance varies.

Besides conventional mechanical cells, specialized flotation machines such as the Flash Cell have been developed commercially to enhance overall plant performance. The primary role of the Flash Cell is to recover liberated valuable minerals as early as possible, minimizing overgrinding of particularly gold/gold-bearing sulfide minerals [31,32]. The Flash Cell is designed to treat coarse materials from hydrocyclone underflow or ball mill discharge streams. Therefore, the operating conditions are completely different from the tank flotation cells. It is important to consider the differences between the Flash Cell and the conventional flotation cells, such as the feed size, feed solid content, residence time (shorter in the Flash Cell), reagent conditioning procedure, and cell design [33,34]. As a result, the froth appearance in the Flash Cells is expected to be different from tank cells, and relationships between the machine vision parameters (such as bubble velocity, bubble size, froth color, etc.) would be different, and a generic froth model may not be used for control purposes. This makes it essential to identify the most effective froth parameter(s) for each cell type and to develop cell-specific closed-loop control models.

In this study, the relationships between the froth appearance, machine vision parameters, and flotation performance were investigated using the data collected from a Flash Cell and Cell 6 (the last cell of the rougher flotation bank) in a gold-bearing sulfide ore plant. These two cells were deliberately chosen because they represent two flotation environments with fundamentally different roles, feed characteristics, and operating conditions, making them ideal for examining the cell-specific applicability of froth parameters. Flash Cell treats coarse, dense ball mill discharge (~56% solids), where rapid recovery of liberated minerals is the objective. Cell 6 treats hydrocyclone overflow and is critical for minimizing gold losses; its performance is largely influenced by entrainment of fine particles. By comparing these two extreme cases—selective recovery of coarse particles in the Flash Cell versus entrainment-dominated recovery in Cell 6—this study provides new insights into how froth parameters differ in predictive value across flotation environments. This comparison illustrates why universal froth monitoring models are inadequate and why cell-specific strategies are required for effective flotation control.

Previous machine vision studies have generally treated froth analysis generically, applying the same indicators across all cells. Few have explicitly compared Flash and conventional rougher cells under industrial conditions. The objectives of this study were therefore to:

1. Quantify the effects of operating parameters (air flow rate and froth height) on froth characteristics, namely bubble velocity (BV) and bubble size (BS).
2. Assess the predictive power of BV and BS in relation to mass pull, gold grade, and recovery in the Flash Cell and Cell 6.
3. Compare cell-specific differences in froth–performance relationships and identify which froth parameters are most effective as control indicators.
4. Develop regression-based models linking froth parameters to concentrate grade and recovery, with the aim of improving real-time flotation control strategies.

2. Materials and Methods

This study investigated the froth parameters, bubble velocity (BV), and bubble size (BS), in a Flash Cell and in Cell 6 (the last cell of the rougher flotation bank), under varying operating conditions of airflow rate and froth height. The objective was to evaluate their predictive value for mass pull, concentrate grade, and recovery in a gold-bearing sulfide ore flotation circuit.

The machine vision system measured the froth parameters (bubble velocity and bubble size) of the Flash Cell and Cell 6 in real time. Flotation cell parameters such as air flow rate and froth height were adjusted to generate different froth structures. The froth cam analyzed changes in froth characteristics (bubble velocity, bubble size, froth color, and froth depth from the lip of the cell), and Stone Three software processed the images to provide froth parameter values. These parameters were then related to flotation performance metrics (mass pull, gold grade, sulfur grade, and recovery). Mathematical equations were developed to establish the relationship between operating parameters (air flow rate and froth height), froth parameters (bubble velocity and/or bubble size), and flotation performance of both the Flash Cell and Cell 6. A summary of the test work program is shown in Figure 1.

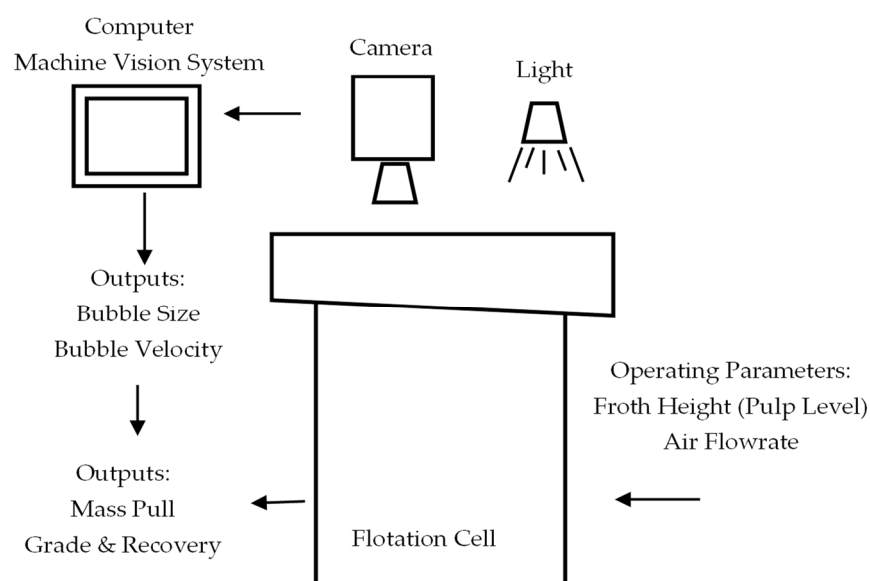


Figure 1. Flowsheet diagram of testwork program.

The testing was performed in a flotation plant treating a gold-bearing sulfide ore. The ore consists mainly of pyrite (11%), galena (0.5%), sphalerite (1.6%), and chalcopy-

rite (0.1%) as sulfide minerals. The non-sulfide gangue minerals are quartz (40%), Mn-silicate/carbonate (20%), feldspar (7.4%), and small amounts of calcite, siderite, mica group, and epidote group. A gold-bearing pyrite concentrate is produced by bulk sulfide mineral flotation. A mixture of SIBX (sodium isopropyl xanthate) and Aero 8045 was used as collectors, and small dosages of CuSO_4 and NaSH were used as activators. The flotation was performed at about pH 9. The ball mill discharge stream was treated in the Flash Cell of 10 m^3 volume. Table 1 shows the percent solid ($w/w\%$) and feed grade of the two flotation cells used in this study.

Table 1. The solid content and feed grade of the Flash Cell and the last cell of the rougher bank.

	Cell Type and Volume (m^3)	Solid (% w/w)	Au, ppm	S, %
Flash Cell	Dorr Oliver, 10	56.20	11.1	1.87
Rougher Cell 6	Wemco, 20	38.09	0.51	0.10

The plant consists of four main sections: Flash Cell, scavenger flotation cells, cleaner flotation cells, and column flotation cells. The ball mill discharge stream was treated in the Flash Cell of 10 m^3 volume, where approximately 60–65% gold recovery is generally achieved. Therefore, control of the Flash Cell is very important. In the rougher flotation bank, six flotation cells of 20 m^3 volume were used to treat the hydrocyclone overflow stream. The tailing stream of the rougher flotation bank was the final tailing stream, and the insufficient control of the last cell could cause gold loss, given that the control of the last cell (Cell 6) of the rougher bank and Flash Cell is a critical stream to maintain high gold recoveries.

The feed grade, %solid (w/w) values, and volume of cells for Flash and Cell 6 are given in Table 1. Gold grade, sulfur content, and solid density in flash flotation were relatively higher than those in the rougher cells, according to Table 1.

The study was conducted using the Stone Three Froth Sensor System MK5 (Stone Three, Somerset West, South Africa). The system consists of a megapixel IP camera with remote zoom/focus, housing for protection, a laser for froth height measurements, and lighting. Bubble velocity, bubble size, froth color, and the froth height from the cell lip were measured online during the sampling surveys.

The froth camera must view both the froth surface and the lip of the flotation cell for proper froth monitoring. Hence, it was mounted to the best location of each cell by Stone Three, and froth camera images taken for Flash and Cell 6 are given in Figure 2. The camera system was protected and sealed against the steam coming from the flotation cell and vibration. After the installation, the camera system was calibrated for online measurement and monitoring. The measurement and sampling work was started after ensuring the froth camera system was providing accurate online data.

The plant work comprises three different phases, which include setting cell operational conditions, sampling, and measurement. Setting cell operational conditions manipulates the froth structure of the investigated cell by changing pulp level and air flow rate. The effects of froth height and air flow rate were investigated at three levels, such as low, intermediate (the standard plant operation), and high. The tests were performed at three different pulp levels: 85 (deep froth, 14 cm), 90 (medium froth height, 10 cm), and 93 (shallow froth height, 4 cm). In the Flash Cell, the air flow rate was varied from about $10 \text{ m}^3/\text{h}$ to $35 \text{ m}^3/\text{h}$ in the medium froth height. The maximum air flow rate was about $20 \text{ m}^3/\text{h}$ in the shallow froth depth and $28 \text{ m}^3/\text{h}$ in the deeper froth. In Cell 6, the air flow rate could be changed between $160 \text{ m}^3/\text{h}$ and $250 \text{ m}^3/\text{h}$ at low pulp levels, but not at the higher pulp levels. The maximum air flow rate tested was $180 \text{ m}^3/\text{h}$, because the slurry

overflowed from the lip at higher air flow rates. The pulp level and air flow rate were controlled by the plant instruments via the SCADA system in the control room. The pulp level (i.e., the froth height) could be adjusted and measured online. Superficial gas velocity and gas hold-up measurements were conducted for hydrodynamic characterization of the flotation cells 8 [35].

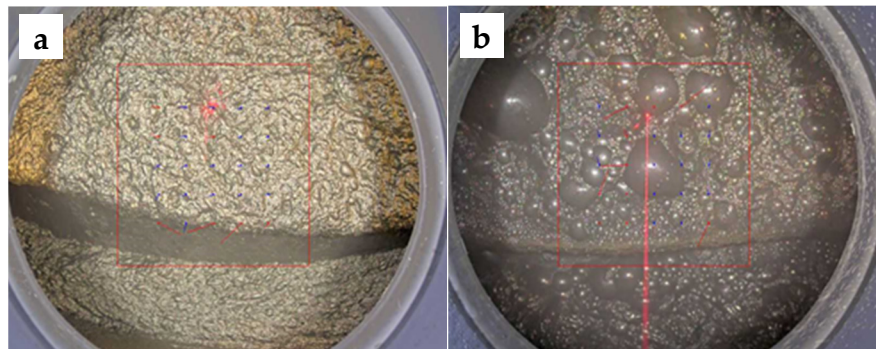


Figure 2. Froth camera image from the top of Flash Cell (a) and Rougher Cell 6 (b).

The sampling survey was conducted after 30 min of changing the cell operating conditions (i.e., air flow rate, froth height, or frother dosage) to ensure the flotation cell was under a steady state condition. Slurry samples were taken from the feed, concentrate, and tailing streams of each cell. The froth parameters (bubble velocity, bubble size) were measured continuously during the sampling survey. The mean values of the froth parameters corresponding to the time of the sampling survey were used in the data analysis. The samples were weighed wet and then dried to calculate the solid content. The dry samples were analyzed for Au by fire assay and S by LECO analysis.

The mass-balance calculations were performed for each test condition by using the JKSimFloat version 6.1. After mass-balancing, the relationship between the froth properties and the flotation performance under changing conditions was investigated. The mean values of the bubble velocity and bubble size were used in the representation of the froth surface of each test.

3. Results

The relationship between froth surface parameters and flotation performance was investigated in Flash Cell and Cell 6 by varying operational conditions. Bubble velocity and bubble size were measured as key froth parameters, while froth color parameters were also recorded but were not included in this paper.

3.1. Bubble Velocity (BV)

The relationship between air flow rate and bubble velocity was investigated at three different froth heights or pulp levels. Pulp level was adjusted to 93, 90, and 85 set values from the control room of the plant, which corresponds to shallow, medium, and deep froth for the Flash Cell. The froth height was also measured manually in each survey. The flotation plant is a dynamic environment, and despite adjusting the operating parameters to certain set values, they vary continuously within a certain range. Given that the measured values are used in the data analysis.

The bubble velocity measured in the Flash Cell and Rougher Cell 6 is illustrated in Figures 3 and 4, respectively. In general, the bubble velocity increases by increasing the air flow rate and decreasing the froth height [9,36]. Similar trends were observed in both the Flash Cell and Cell 6.

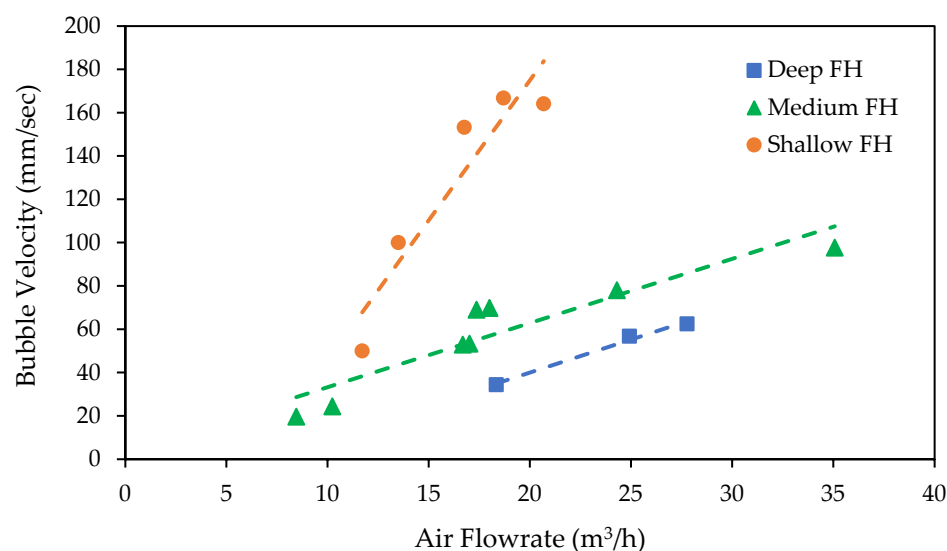


Figure 3. The relationship between air flow rate and bubble velocity in Flash Cell.

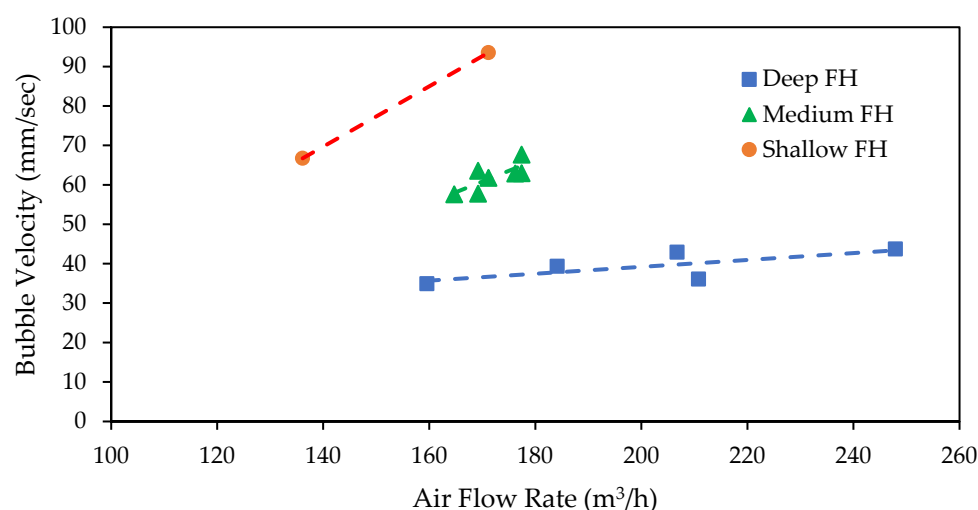


Figure 4. The relationship between air flow rate and bubble velocity in Cell 6.

The operational characteristics of the two cells were completely different [33,34]. The air flow rate could be changed between 10 m³/h and 35 m³/h in the Flash Cell (Figure 3). The maximum air flow rate in the shallow froth depth was 20 m³/h, because the froth phase disappeared at higher values and the pulp flowed over the lip. The influence of the froth height was negligible at very low air flow rates (10 m³/h), but the bubble velocity increased substantially at about 15–20 m³/h air flow rate, particularly at the shallow froth height. The bubble velocity changed between 20 mm/s and 170 mm/s at the shallow froth height. The maximum bubble velocity was about 100 mm/s at the medium froth height and 60 mm/s at the deep froth.

The bubble velocity values of Cell 6 were different from those of the Flash Cell. The air flow rate was changed between 140 m³/h and 250 m³/h (Figure 4), depending on the froth height. The froth appearance of Cell 6 was very sensitive to the froth height, and hence the froth height (i.e., pulp level) could be adjusted between 35 mm and 85 mm in this cell. The froth stability was very low at deeper froth heights, at which froth concentrates could not be obtained. In the 160–180 m³/h air flow rate range, the bubble velocity was measured at about 90 mm/s at the shallow froth, 60–65 mm/s at the medium froth, and 40 mm/s at the deep froth. The effect of air flow rate was very small at the deep froth heights. The results

show that the froth height had a stronger impact on the bubble velocity than the air flow rate in Cell 6.

Cell performance was evaluated based on mass pull, gold and sulfur grade, and recovery. Mass pull and recovery were calculated in reference to the feed of the flotation cells. Figure 5 illustrates the relationship between the bubble velocity and mass pull. In the Flash Cell, the mass pull ranges from approximately 0.5% to 1%, increasing linearly with bubble velocity. In Cell 6, however, the scale was different, and the maximum mass pull was calculated as 35%. As mentioned above, the mass pull and the recoveries were calculated in reference to the feed of each flotation cell. The feed to the Flash Cell was the ball mill discharge, and the tonnage was higher than that of the feed to the Rougher Cell 6. The mass pull increases linearly with bubble velocity in both flotation cells.

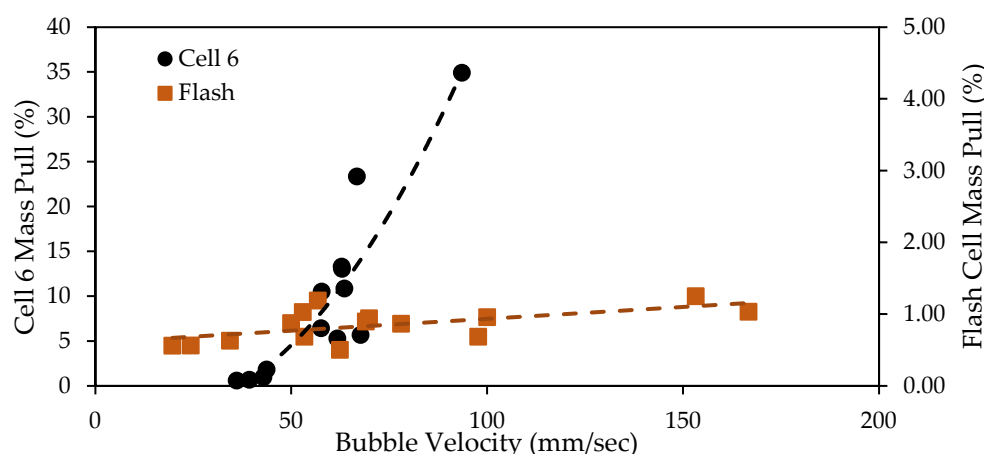


Figure 5. The relationship between bubble velocity and mass pull.

Similar trends were observed for both Au recovery and S recovery as a function of bubble velocity (Figure 6). The increase in bubble velocity increased the recovery of both Au and S in Cell 6. However, in the Flash Cell, the bubble velocity had no effect on gold or sulfur recoveries. Gold recovery varied between 6% and 17% with an average of 10%, while the sulfur recovery varied between 10% and 23% with an average of 16%. Both the gold and sulfur recoveries varied within a relatively narrow range (compared to Cell 6), and a statistically significant relationship could not be derived as a function of bubble velocity.

Figure 7 shows the gold grade of the concentrate as a function of bubble velocity in the Flash Cell and Cell 6. As expected, there was a large difference between the gold grade of the Flash concentrate and Cell 6, which is the last cell of the rougher flotation stage. In Cell 6, Au grades changed from 0.78 g/t up to 15.2 g/t. A power decay relationship was observed between bubble velocity and the gold grade of the concentrate. The Au grade decreased from 15.25 ppm to 4.08 ppm when the bubble velocity increased from approximately 40 mm/s to 60 mm/s. The concentrate grade remained stable at about 0.9–1.8 g/t at bubble velocities above 60 mm/s. The large variation in the concentrate grade was attributed to the changes in the mass pull (Figure 5). The froth height was considered as the main operating parameter affecting the mass pull in Cell 6, and hence the concentrate grade.

Figure 8 shows the concentrate grade as a function of bubble velocity at three froth heights. There was a linear relationship between the bubble velocity and concentrate grade at the deep froth, and the grade decreased from about 15 g/t to 4 g/t at a very narrow bubble velocity range. The grade values were close in the medium and shallow froth depths and decreased linearly from about 2 g/t to 1 g/t as a function of bubble velocity.

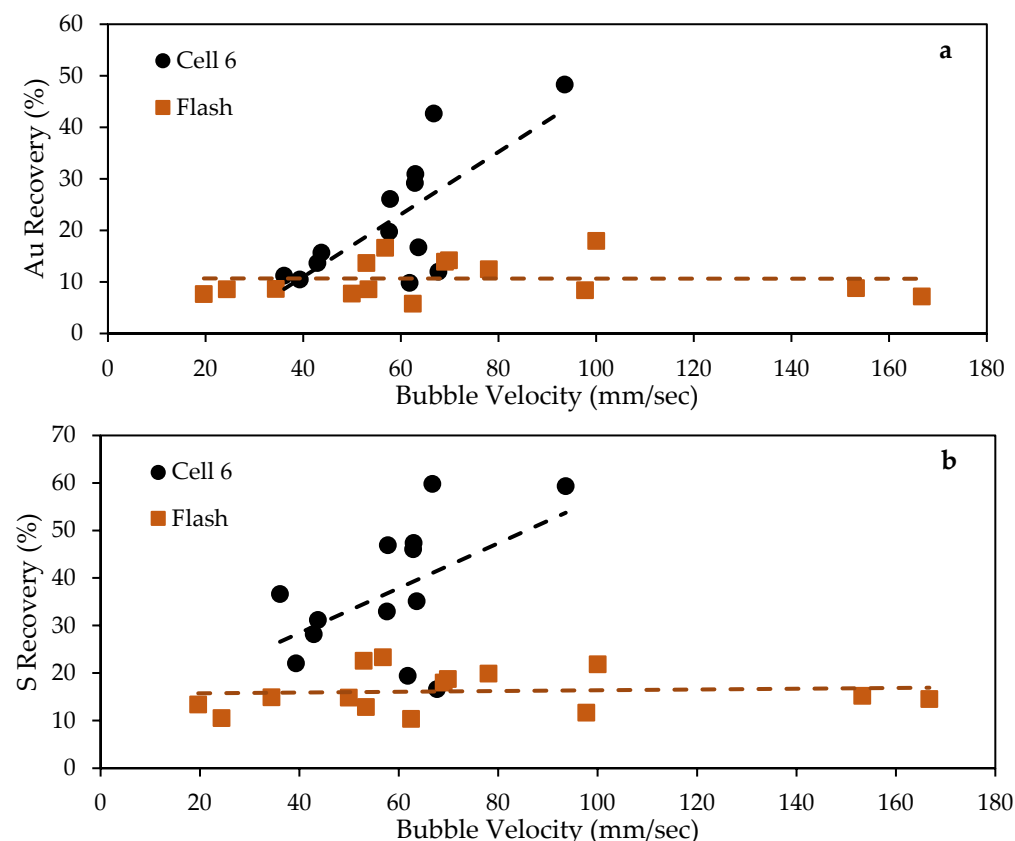


Figure 6. Au (a) and S (b) recoveries as a function of bubble velocity in the Flash Cell and Cell 6.

The gold and sulfur grades of the flash concentrate decreased linearly as a function of bubble velocity. The data was highly scattered, presumably due to the other operating parameters such as froth height, feed grade, and flow rate. These parameters affect the mass pull and hence the concentrate grade. It is obvious that bubble velocity is not enough to estimate the concentrate grade in the Flash Cell. The other independent operating parameters should be considered to derive a mathematical equation with strong predictive power.

There is a linear relationship between bubble velocity and solids content of the concentrate (Figure 9). The solid content of the flash concentrate decreased with increasing bubble velocity and varied between 63.71% and 53.02%. However, a different behavior was observed in Cell 6, and the solids content increased with increasing bubble velocity. The solid content was about 10% at 40 mm/s bubble velocity and increased to about 30% at 90 mm/s. This was attributed to the differences in the solid content of the pulp and the operational characteristics of the cells.

The feed stream of the Flash Cell contains 11 g/t Au and 2%–3% S. The pulp density and particle size were 56% *w/w* and $d_{80} = 190 \mu\text{m}$, respectively. Cell 6, on the other hand, had a feed stream assaying 0.47 g/t Au, 0.1% S, $d_{80} = 60 \mu\text{m}$, and 38% *w/w* pulp density.

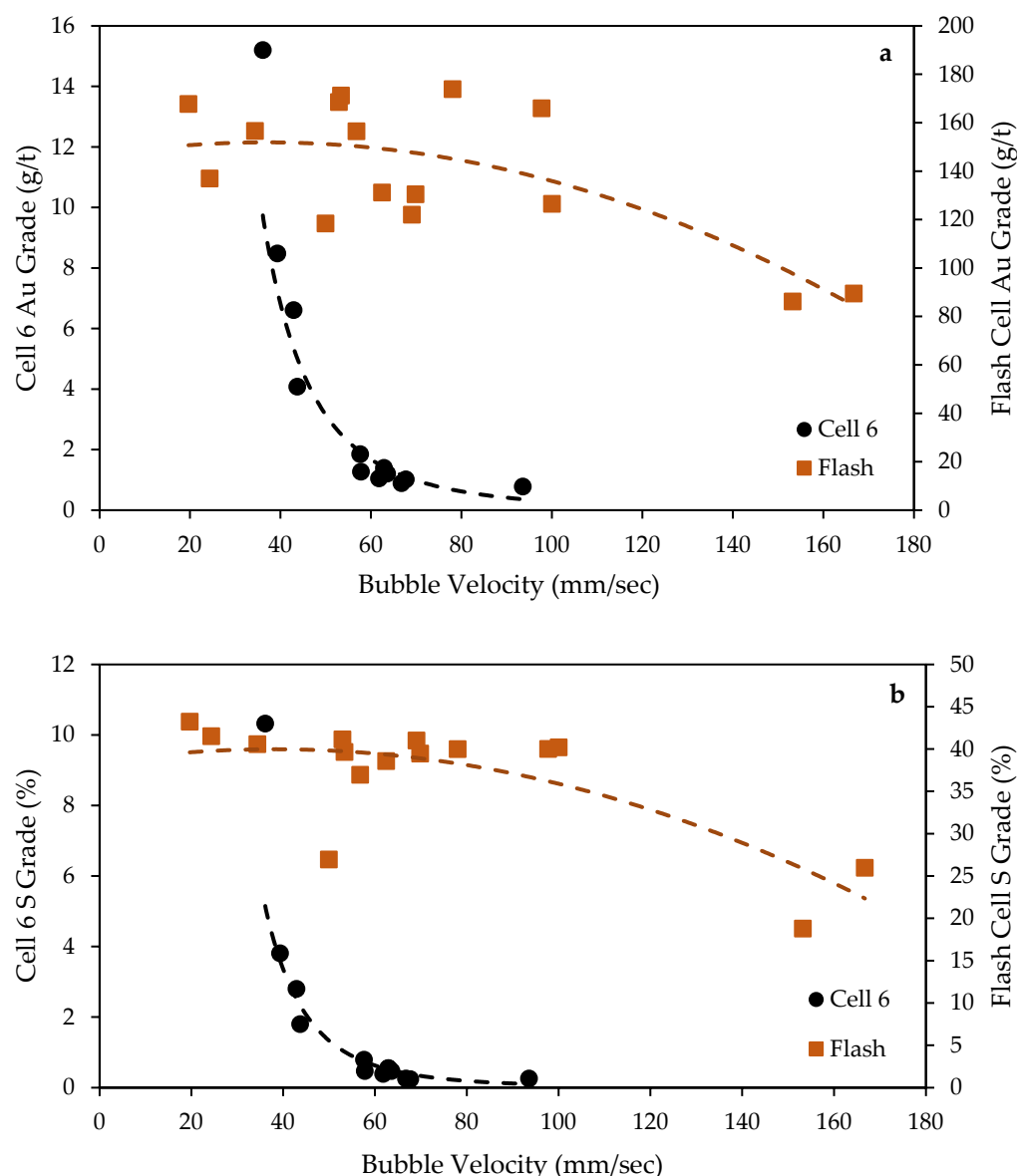


Figure 7. Au (a) and S (b) grades as a function of bubble velocity in the Flash Cell and Cell 6.

The particle size distribution of the Flash Cell is very coarse, and hence the recovery by entrainment would be at negligible levels. The aim is to recover the liberated gold and sulfide mineral particles [31,32]. Despite large variations in the bubble velocity, the solid content of the concentrate decreased from about 60% *w/w* to 55% *w/w*, which means a limited increase in water recovery to the concentrate [34,37].

In Cell 6, the relationship between the bubble velocity and concentrated solid content was just the opposite of the Flash Cell. This was attributed to the differences in the feed streams and operating parameters of the cells. The froth stability, in other words, water recovery, increases with increasing bubble velocity in Cell 6. The recovery by entrainment was the dominant recovery mechanism due to the fine particle size and resulted in an increase in mass pull and hence higher solid content in the concentrate with increasing bubble velocity. It is obvious that the froth parameters should be interpreted differently for the two cells.

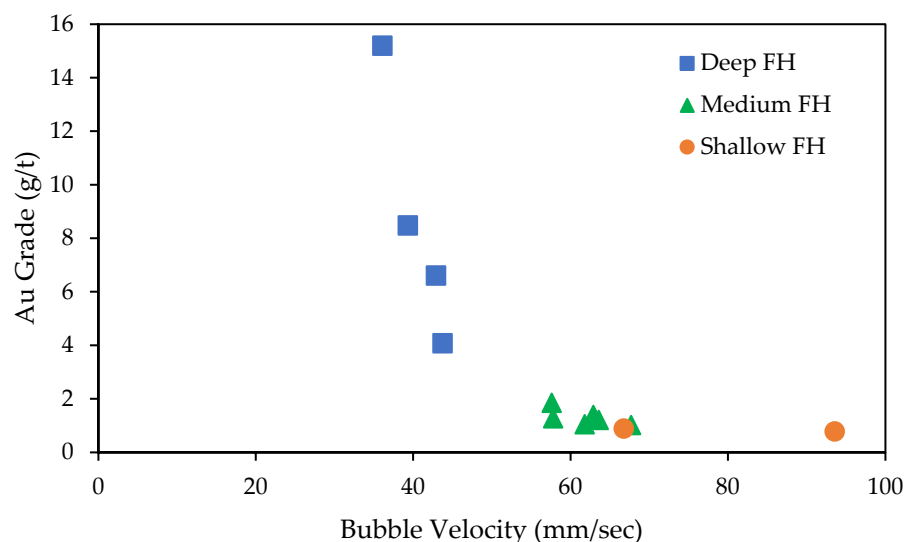


Figure 8. The Au grade of the concentrate as a function of bubble velocity at three froth heights of Cell 6.

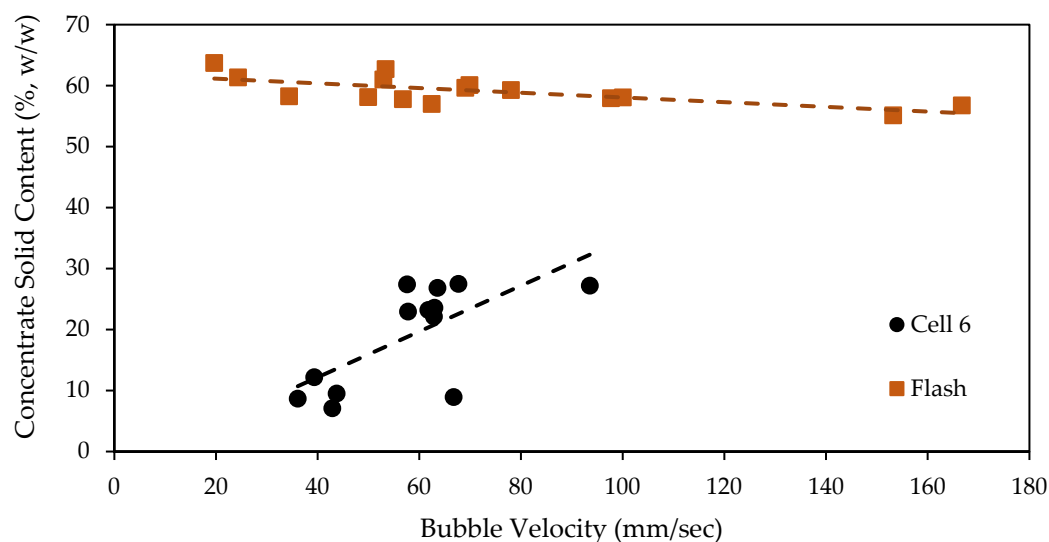


Figure 9. The relationship between bubble velocity and concentrate % solid.

3.2. Bubble Size

Bubble size distribution of the froth phase was also measured during the surveys. The Stone Three MK5 program measured bubble size every second during sampling, and sampling took approximately 10 min. Therefore, histograms were illustrated in every test, and the mean bubble size was calculated. An example for the calculation of the mean bubble size by using histograms is given in Figure 10. The figure shows a typical bubble size distribution of the Flash Cell (Test 5). The distributions were close to a normal distribution. The mean bubble size was calculated for each condition and used to represent the appearance of the froth phase.

The relationship between bubble size and air flow rate is illustrated for different froth heights in Figures 11 and 12 for the Flash Cell and Cell 6, respectively. There was no statistically significant relationship between the bubble size and the operating parameters, air flow rate, and froth height. However, there were differences between the Flash Cell and Cell 6. The bubble size ranges between 50 mm and 60 mm in the Flash Cell and between 60 mm and 70 mm in Cell 6. The difference could be attributed to the differences in the froth structure of the two cells. The froth was heavily loaded with hydrophobic particles in

the Flash Cell with a more uniform bubble size distribution (Figure 2a). The froth of Cell 6, however, was different, with a wide range of bubble size distribution (Figure 2b).

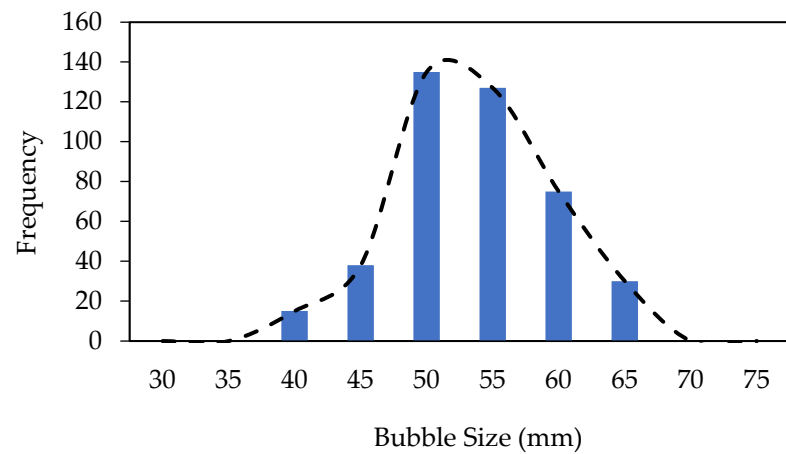


Figure 10. An example of mean bubble size distributions of the froth phase of Flash Cell (Test 5).

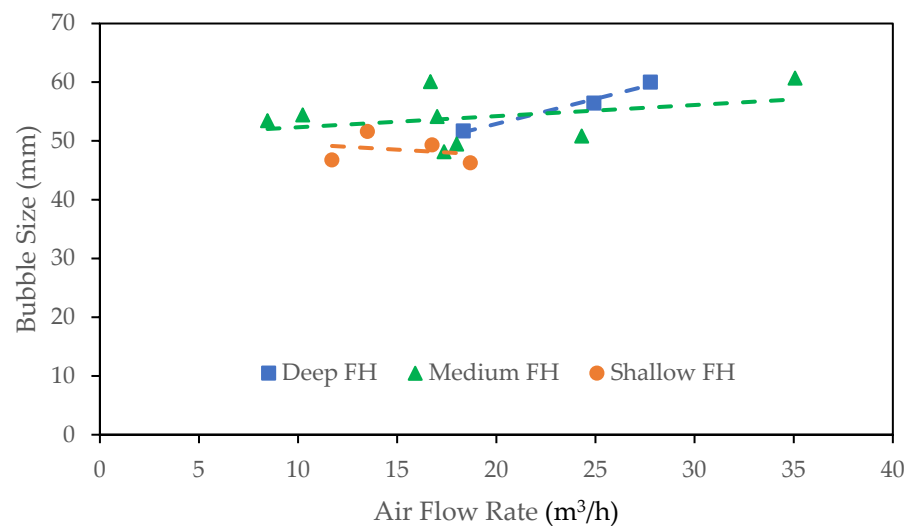


Figure 11. The relationship between bubble size and air flow rate at different froth heights in the Flash Cell.

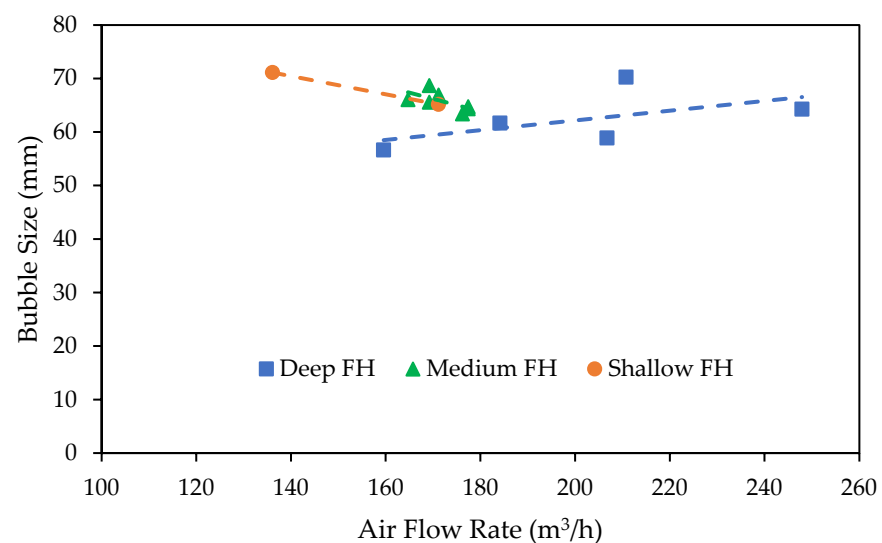


Figure 12. The relationship between bubble size and air flow rate at different froth heights in Cell 6.

In the Flash Cell, the froth is loaded with liberated hydrophobic particles, giving a relatively uniform and stable bubble size distribution. In Cell 6, on the other hand, the froth is highly unstable, dominated by entrainment of fine gangue, and shows a broad bubble size distribution. Because of this, bubble size in the Flash Cell more directly reflects froth stability and selective attachment of liberated particles, while in Cell 6, the bubble size signal is “masked” by entrainment and water recovery effects.

The gold grade of the concentrate increased linearly with bubble size in the Flash Cell (Figure 13). Larger bubbles promoted better drainage, reduced water recovery, and yielded cleaner concentrates. No statistically significant correlation between bubble size and grade, recovery, or mass pull was found in Cell 6. Instead, performance was governed mainly by bubble velocity and froth height (entrainment-driven mechanisms).

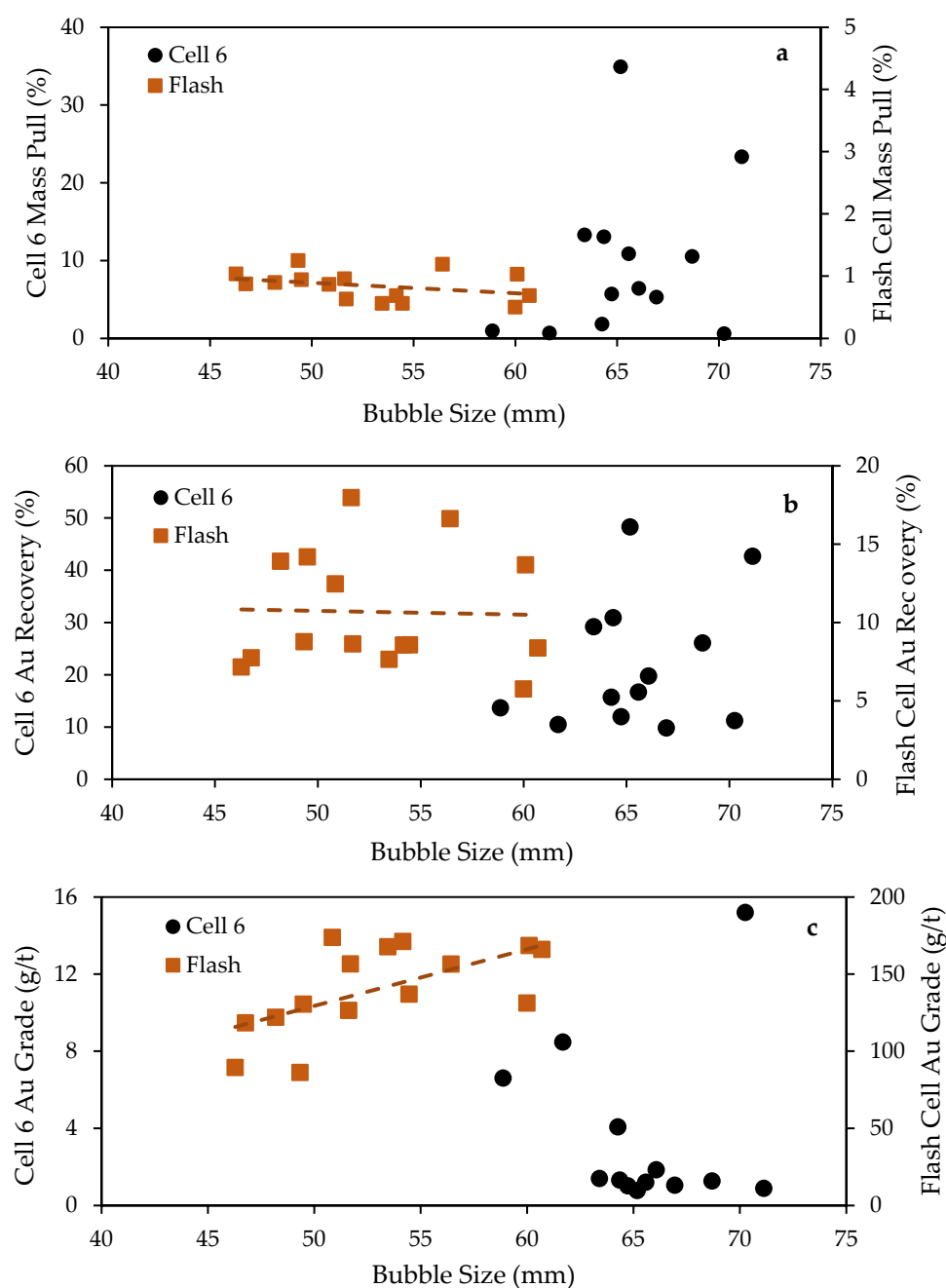


Figure 13. Effects of bubble size on the mass pull (a), gold recovery (b), and gold grade (c) in Cell 6 and Flash Cell.

These findings align with previous reports emphasizing the cell-specific role of froth parameters. In flash flotation, where the objective is early recovery of liberated, coarse valuable minerals, froth structure and bubble size distribution are crucial for selectivity and grade control [31,33,34]. In contrast, in the final, rougher cells operating on fine and poorly liberated particles, entrainment dominates, and bubble size loses predictive value, with froth velocity and froth stability being more critical parameters [25,35].

4. Discussion

The effects of cell operating parameters (air flow rate and froth height) on the froth appearance were measured using a machine vision system in a Flash Cell and a tank cell (the last cell of a rougher flotation bank), which have completely different geometric and hydrodynamic characteristics and functions. The results revealed that operating parameters such as, air flow rate and froth height significantly influence bubble velocity in flotation cells. However, the effects on bubble size were not statistically significant, presumably due to the difficulty of measuring the bubble size in different froth structures and expressing it as a single value (mean bubble size in this case). This study discussed the differences in froth structure appearance between the two cell types, as well as the value and limitations of a froth vision system as a control tool.

4.1. The Relationship Between Cell Operating Parameters and Froth Control Parameters

In both cells, increasing the air flow rate generally increased BV, while increased froth height had a dampening effect. However, the relative importance of these two operational parameters differed; in the Flash Cell, air flow rate played a more direct role, whereas in Cell 6, froth height (pulp level) dominated as the controlling factor. This is likely due to differences in froth stability, particle size distribution, and hydrophobic particle content between the two cells [37,38].

Therefore, a linear regression analysis was performed to derive an equation determining the bubble velocity as a function of air flow rate (A) and froth height (FH). The BV equations for the Flash Cell and Cell 6 are given in Equation (1) and Equation (2), respectively. For the Flash Cell, both air flow rate and froth height were statistically significant at a 95% confidence level. The correlation coefficient is high, indicating the strong predictive power of Equation (1). In Cell 6, however, the air flow rate did not significantly affect bubble velocity but rather froth height (Equation (2)). The number of hydrophobic particles in Cell 6 was very low, so the effect of the air flow rate was expected to be minimal [39,40].

$$BV = 3.04 \times A - 1.04 \times FH + 119.3 \quad \text{AdjR}^2 = 0.91 \quad (1)$$

$$BV = 0.083 \times A - 0.632 \times FH + 83.01 \quad \text{AdjR}^2 = 0.72 \quad (2)$$

Figure 14 illustrates the relationship between the measured and calculated BV for both cells. There is a good agreement between the measured and calculated values, which means that Equations (1) and (2) can be used to calculate bubble velocity as a function of air flow rate and froth height.

The equations indicate that bubble velocity (BV) is directly proportional to air flow rate and inversely proportional to froth height. These findings are consistent with previous reports in the literature. Earlier studies have shown correlations between operating parameters (e.g., air flow rate and froth height) and froth velocity [9,36]. Mehrabi et al. demonstrated that froth velocity increases with air flow rate due to higher bubble surface area flux and water recovery, while slurry level and depressant dosage also play important roles. High slurry levels (low froth heights) produce watery, mobile froths with small bubbles, whereas the addition of depressant leads to less mobile froths with reduced water

recovery and larger bubbles. Massinaei et al., further reported that air flow rate and froth depth strongly influence both froth characteristics and metallurgical performance in coal flotation. Specifically, increasing air flow rate enhances bubble surface area flux (S_b) and combustible recovery, while greater froth depth decreases both combustible recovery and concentrate ash content due to enhanced particle drainage. Overall, these findings emphasize the critical role of air flow rate and froth depth in governing froth stability, structure, and flotation performance.

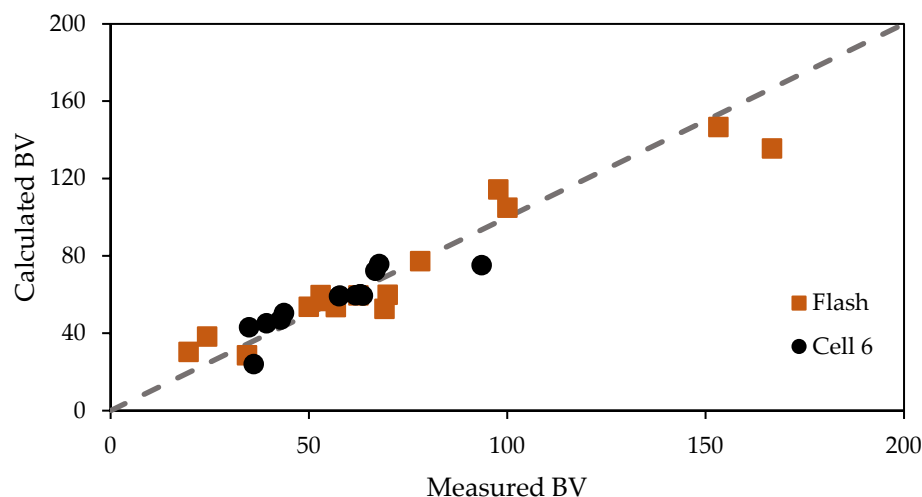


Figure 14. Measured vs. calculated BV of Flash Cell and Cell 6 using Equations (1) and (2).

Although bubble size (BS) was found to be less important than BV, its behavior still offered valuable insights. There was no strong correlation between BS and operating parameters (air flow rate and froth height) across both cells, indicating that BS is more influenced by frother dosage or cell design [39]. The Flash Cell exhibited a more uniform and narrow bubble size distribution, indicative of stable froth containing liberated hydrophobic particles. In contrast, Cell 6 had a wider BS distribution, likely due to the presence of a mixture of finer, less hydrophobic particles in the froth phase.

4.2. The Relationship Between the Froth Parameters and Flotation Performance

A polynomial relationship was observed between bubble velocity (BV) and concentrate gold (Au) grade in the Flash Cell (Figure 7), suggesting that increased bubble mobility beyond a certain velocity threshold may reduce concentrate grade, possibly due to froth instability or increased entrainment of gangue [37–41]. However, in Cell 6, the relationship was better captured by a power decay function, where the concentrate grade declined rapidly with increasing BV and then stabilized. This points to an asymptotic threshold BV of approximately ~34 mm/s, below which high-grade material recovery is more favorable.

It should also be noted that increasing froth velocity directly influences water recovery, which in turn affects mass pull and entrainment. Given that coarse particles are less sensitive to entrainment, the Flash Cell (with a coarser particle size distribution) is expected to show lower froth sensitivity to high froth velocities. In contrast, in the last cells of the rougher bank, where particles are finer and more prone to non-selective recovery, the effect of froth velocity on entrainment is more pronounced. This observation is consistent with the results obtained in this study.

A weak correlation was found between bubble size and flotation performance in Cell 6 (Figure 13). However, in the Flash Cell, a linear relationship was observed between increasing bubble size and Au grade. This suggests that larger bubbles may facilitate better drainage and thus yield higher-grade concentrates. This again emphasizes that

froth structural parameters cannot be universally interpreted across cell types but must be considered in context.

Linear regression analysis was performed to estimate the gold grade of the Flash concentrate as a function of BV and BS (Equation (3)). On the other hand, a power equation was used to estimate the gold grade of the concentrate in Cell 6 as a function of BV.

$$\text{Gau} = 2.62 \times \text{BS} - 0.354 \times \text{BV} + 27.58 \quad \text{AdjR}^2 = 0.55 \quad (3)$$

$$\text{Gau} = 554278 \times \text{BV}^{-3.11} \quad \text{AdjR}^2 = 0.87 \quad (4)$$

Figure 15 shows the measured versus calculated concentrate gold grade of Flash and Cell 6. Equations (3) and (4) were used to calculate the gold grades for Flash and Cell 6, respectively. A value of 15 g/t Au was considered an outlier for Cell 6 during the derivation of the equations and was therefore not included in the model. Generally, there is an acceptable agreement between the measured and calculated values, except for a few points in the high-grade section. Therefore, these equations can be used to estimate the gold grade of the concentrate in Flash and Cell 6 concentrates.

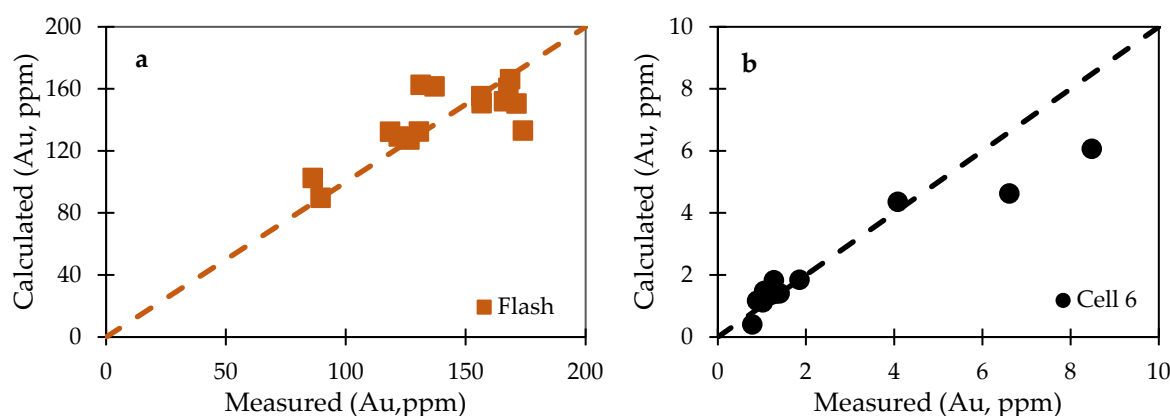


Figure 15. Measured vs. calculated concentrate gold grade of Flash Cell (a) and Cell 6 (b) using Equations (1) and (2).

The same analyses were performed to estimate the gold recovery. Figures 6 and 13 show that the gold recovery changed between 5% and 20% in the Flash Cell as a function of changing air flow rate and froth height. The recovery data was highly scattered in these graphs, indicating no statistically relevant relationship between gold recovery and froth parameters. This was attributed to the specific flotation characteristics of the Flash Cell, which recovers only the liberated particles at a low mass pull from a flotation feed of very coarse particle size distribution [31,32,34].

The gold recovery in Cell 6, on the other hand, increased linearly with increasing BV (Figure 6). BS did not show any statistically significant correlation with gold recovery. Linear regression analysis was also performed using BV and BS as independent variables. The correlation coefficient of the regression equation was lower than the linear equation given in Figure 6. Given that Equation (5) was considered as a better option to calculate the gold recovery in Cell 6.

$$\text{Rau} = 0.6058 \times \text{BV} - 13.218 \quad \text{AdjR}^2 = 0.50 \quad (5)$$

4.3. Operational Strategies for Different Cells

The findings indicate that froth parameters must be contextualized within each cell's unique design and function. The Flash Cell, targeting coarser and more liberated particles,

showed better performance at medium froth heights, where drainage was optimal and froth stability had not yet been compromised. In contrast, shallow froths yielded high mass pulls but lower grades, highlighting the trade-off between recovery and selectivity.

For Cell 6, which operates on a much finer feed with diminished hydrophobicity, shallow froth heights improved both froth mobility and mass pull; however, they also increased water recovery and entrainment. Thus, while higher BV led to greater mass pull, it adversely affected grade due to poor selectivity.

From a process control standpoint, these results validate the use of froth cameras and machine vision systems to infer cell performance in real time. However, a one-size-fits-all interpretation model would be inappropriate due to the variable sensitivity of BV and BS across different cell types. Instead, cell-specific control strategies should be developed with customized regression models (e.g., a polynomial model for the Flash Cell and an exponential model for rougher cells) to link froth parameters to flotation performance.

AI-assisted machine vision control could also be implemented using cell-specific models, since the Flash Cell and Cell 6 should be treated as different control problems. These two-model/two-loop strategies reflect the measured differences between cells, which can be utilized by operators for better control.

Ultimately, effective flotation control should not rely on Bubble Velocity or Bubble Size in isolation. Feed characteristics (such as particle size and hydrophobicity) must be integrated into a multivariate control approach, ideally using adaptive models that can evolve with process conditions.

5. Conclusions

This study demonstrates the role of machine vision-based froth monitoring in evaluating and optimizing the performance of flash and rougher flotation cells. The following conclusions were drawn.

Bubble velocity (BV) was the most predictive froth parameter in both cells. In the Flash Cell, bubble velocity (BV) was significantly affected by both air flow rate and froth height, but the froth height was found to be of secondary importance. BV increased linearly with higher air input and decreased slightly as froth height increased. In Cell 6, however, froth height had a more pronounced effect than air flow rate.

In the Flash Cell, BV increased from 20 to 170 mm/s as the air flow rate increased, while the mass pull rose linearly from 0.5% to 1%. Gold recovery varied from 6% to 17%, while concentrate grade ranged from 80 to 180 g/t Au. In Cell 6, BV ranged from 40 to 90 mm/s, with a mass pull of 35%. Gold recovery increased linearly with BV, ranging from 10% to 50%, while concentrate grade declined from ~15 g/t to 1 g/t as BV increased.

BS served as a valuable control parameter in the Flash Cell, where gold grade increased linearly with BS. However, no significant relationship was found between BS and flotation performance in Cell 6, which was dominated by entrainment.

The Flash Cell and Cell 6 (the last Rougher Cell) exhibited fundamentally different relationships between froth parameters and flotation performance. These findings demonstrate that froth monitoring strategies must be cell-specific.

This study revealed that froth image analysis offers valuable insights for real-time flotation control, but it must be implemented with tailored strategies because it requires customization according to the operational and structural features of individual flotation cells. A multivariate approach incorporating froth parameters and feed characteristics is necessary for robust performance optimization.

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Abbreviations

The following abbreviations are used in this manuscript:

BV	Bubble Velocity
BS	Bubble Size
FH	Froth Height
A	Air Flowrate

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