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The impact of batch flotation tests on the industrial plant prediction

Paulina Vallejos

Department of Chemical and Environmental Engineering, Universidad Técnica Federico Santa María, Valparaíso, Chile.

Corresponding author: paulina.vallejos@usm.cl

Abstract: To predict the metallurgical results of industrial plants, laboratory batch flotation tests are carried out, relating both operations through scale-up factors. However, robust scale-up procedures and well-defined laboratory protocols are necessary to reach reliable results at industrial scale. In this paper, results from different flotation batch tests are presented, analysing the effect of batch protocol in terms of operating conditions, operator, ore type, water quality, and others on the metallurgical response. Additionally, the ability of batch responses to describe industrial operations and determine scale-up factors was analysed. Then, a sensitivity analysis was carried out, considering the effect of batch and industrial conditions on the estimation of scale-up factors. Results showed that the batch response significantly changes, depending on the operating conditions, flotation operator, and batch flotation machine, even for the same cell design. Additionally, it was observed that the batch recovery significantly changes when modifying ore type and water quality, which can cause changes in batch and/or industrial operation, affecting the scale-up factors. In addition, results showed that the scale-up factors varied significantly by changing operating conditions in a batch cell. This also occurs in plants when metallurgical performance changes, for example, due to a modification in launder design and/or operating condition, to increase recovery, or due to control limitations that prevent efficient metallurgical performance.

Keywords: batch flotation, rougher banks, standard protocol, operating conditions

1. Introduction

The significant rise in demand for minerals with lower grades in recent decades has led to a substantial increase in the size of flotation cells. This has resulted in concentrator plants now being equipped with mechanical flotation cells of 300 m^3 (Yianatos et al., 2008; Govender et al., 2014), and more recently, cells of over 600 m^3 have been installed and are operating in flotation plants (Lelinski et al., 2017; Romero, 2018). While the use of larger flotation machines has brought about various economic benefits, it has also presented new challenges in terms of correlating laboratory results with metallurgical performance at industrial scale.

The scale-up process in flotation is complex as it encompasses not only different equipment dimensions and arrangements, but also diverse flow regimes, transport phenomena and operational conditions. Predicting the industrial circuit performance from batch flotation tests requires a comprehensive understanding of the variables involved to establish more robust scale-up procedures. Unfortunately, the definition of a standard protocol for laboratory tests remains a concern. The conventional procedure involves using a time scale-up factor to compare laboratory and plant flotation performances (Yianatos et al, 2022). However, several subprocesses exhibit significant differences at both scales, which are not fully understood. Scale-up factors observed in practice typically range from 1.5 to 4.3 (Yianatos et al., 2006; Boeree, 2014; Thompson, 2016; Mesa and Brito-Parada, 2019) and it is common practice to use values around 2-2.5 (Amelunxen et al., 2018). Additionally, the lack of standard conditions in laboratory flotation tests, as well as abnormal operating conditions in plants prevent a proper identification of scale-up factors.

Commonly, each laboratory follows its own flotation protocol, consequently leading to scale-up factors that are influenced by each batch test. The selection and management of operating variables,

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such as gas flow rate and impeller speed (rpm), produces varying metallurgical responses, thereby impacting scale up factors (Yianatos et al., 2003). Furthermore, using the same type of machine with same operator for a flotation test can also result in different metallurgical responses (Runge, 2010; Aro, 2013; Valdés, 2014).

This paper analyses the impact of batch flotation protocols and industrial flotation operations on metallurgical responses and scale-up factors, considering four case studies of experimental tests conducted in industrial flotation plants. The study covers the effects of gas flowrate, impeller speed, batch equipment, operator, and makeup water volume within the batch flotation protocol. Additionally, the influence of ore type and water quality on the batch protocol and scale-up procedure was discussed. Finally, the effect of batch and industrial conditions on scale-up factors was analysed, through a sensitivity analysis.

2. Methodology

2.1. Case studies

Four case studies are presented (cases A, B, C and D), which correspond to experimental tests, at batch and industrial scale, carried out in four different flotation plants in Chile. Batch studies were carried out in all four cases, while metallurgical studies at industrial scale were performed in cases A, C and D. These case studies were used for the following objectives:

- Cases A and B: To study the effect of batch operating conditions on the metallurgical response.
- Cases A, C and D: To analyse the effect of batch response to describe the industrial operation and scale-up factors.
- Case A: To carry out a sensitivity analysis, considering the effect of batch and industrial conditions on the estimation of scale-up factors.

2.2. Flotation batch tests

Table 1 shows the operating conditions of the flotation batch tests for each case. It can be observed that all the flotation protocols have different operating conditions, which determine the batch metallurgical responses.

It must be mentioned that changes in the ore type and water quality in each flotation test can significantly modify the metallurgical response, using the same flotation protocol. This is relevant when flotation batch tests are used to represent the industrial operation.

Then, Table 2 shows the feed characteristics for each flotation batch test. The minerals used to run each batch test correspond to feed samples from the respective industrial bank. The ore analysed in all cases corresponds to Cu sulphides, with Cu feed grades in the range of 0.3-1.3%Cu. The feed streams had a P_{80} of 150 – 285 μm, and a solid content of 30 – 36%.

Table 1. Operating conditions of flotation batch cells (flotation protocol), cases A to D

	CASE A	CASE B	CASE C	CASE D
Cell type	Agitair	Denver	Denver	(*)
Volume (L)	2.7	2.3	2.6	5.4
Impeller speed (rpm)	1300	1500	1200	800
Air Flowrate (L/min)	12	7	6	5
Scraping frequency (s)	20	10	3 - 5	(*)
Flotation times (min)	1, 3, 5, 8, 12.5, 20	1, 3, 6, 12, 20, 25	1, 2, 4, 8, 16	1, 3, 5, 10, 14

(*) Information not available

Table 2. Characteristics of Cu ore fed to flotation batch cells, cases A to D

	CASE A	CASE B	CASE C	CASE D
Feed grade (Cu%)	1.3	0.6	0.3	0.5
P_{80} (μm)	210	250	285	150
Solid content (%)	30	36	34	35.3

Fig. 1 shows two examples of batch flotation cells: Agitair cell (Fig. 1a) and Denver cell (Fig. 1b), to illustrate the equipment used in the flotation tests shown in Table 1.

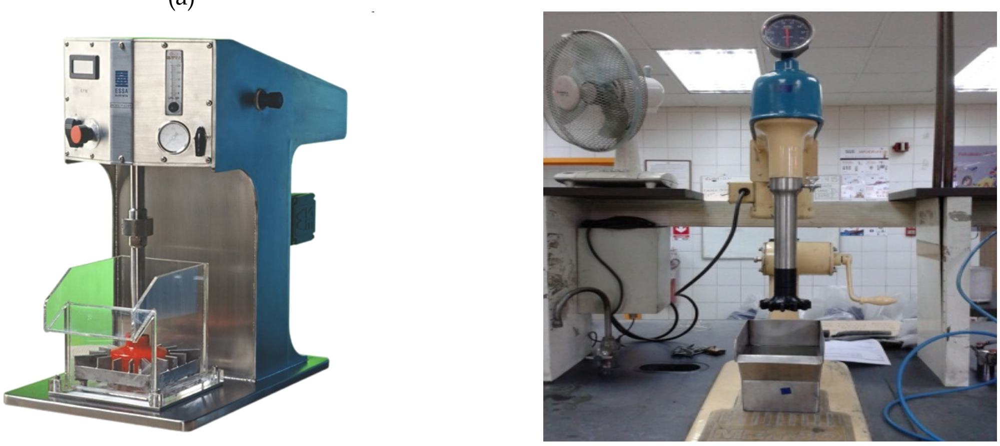

Fig. 1. Examples of batch flotation cells: (a) Agitair and (b) Denver

2.3. Flotation industrial operation

Sampling surveys were carried out in the industrial banks of cases A, C and D to characterize the metallurgical performance. This was performed by sampling some streams of the process, gathering composites that were then submitted to chemical analysis. Fig. 2 shows the rougher bank of case D, as an example, with the sampling points (circles), from where the composites were obtained.

Table 3 shows the characteristics of the flotation banks and ore feed, and the Cu recovery obtained from the sampling surveys. The feed tonnage was in the range of 1250 – 1800 (tph), with a wide range of feed Cu grades, between 0.3% and 1.3%. The Cu recoveries were also diverse, between 74 and 94%.

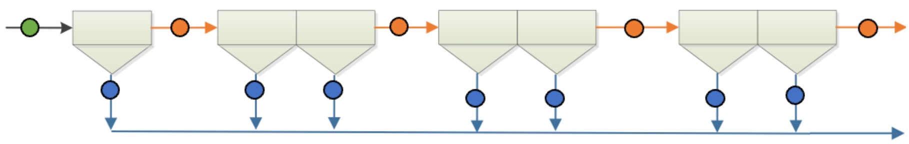

Fig. 2. Sampling points in the industrial bank of case D, for metallurgical characterization

Table 3. Characteristics of industrial flotation banks, cases A, C, and D

	CASE A	CASE C	CASE D
Feed tonnage (tph)	1250	1300	1800
Feed Cu grade (%)	1.3	0.3	0.5
Solid content (%)	30	34	35.3
Number of cells	6	8	7
Cell volume (m^3)	300	250	300
Cu recovery (%)	94.4	74.4	92.0

2.4. Scale-up to relate batch and industrial operation

2.4.1. Flotation batch tests using the same ore fed to industrial banks

For the experimental tests of cases A, C, and D, flotation batch tests and industrial surveys were carried out in the same period, to estimate scale-up factors, considering that the batch test represents the industrial operation. Thus, the ore fed to the flotation batch cells corresponds to a sample from the feed of the industrial bank ("hot flotation").

To represent the industrial operation from batch tests, a flotation batch protocol must be selected, setting the batch times, operating conditions, cell type, and others. Particularly, for the cases A, C and D, the protocols used in the flotation tests were presented in Table 2. It must be mentioned that the batch response is sensitive to changes of any condition of the protocol, which affect the estimation of scale-up factors. At the same time, any change in the industrial plant operation will also affect the scale-up process. Therefore, either the batch protocol or the scale-up factors must be adjusted when changing any operating condition at industrial scale.

2.4.2. Estimation of scale-up factors

The estimation of scale-up factors for each case was carried out using the time ratio between the batch and industrial rougher bank to reach the same recovery, taking the industrial recovery as a reference. This is the typical method for scale-up, used in most flotation plants. This approach directly compares the flotation times, but strongly depends on operating conditions.

3. Results and discussion

3.1. Batch response to flotation protocol changes

3.1.1. Effect of operating conditions

Fig. 3 shows the effect of operating conditions on the batch flotation response for the case A. Thus, the effect of impeller speed (Fig. 3a), gas flowrate (Fig. 3b), volume of makeup water (Fig. 3c), and laboratory used for batch testing (Fig. 3d, considering the same cell replicated in two different laboratories), were analysed. All tests were performed with the same sample and keeping the other conditions constant (see characteristics of case A in Tables 1 and 2).

In Figs. 3c and 3d, the effect of makeup water volume and laboratory was analysed in four tests, including two different conditions for each case: Exp. 1 and 2, and Exp. 3 and 4, respectively. The operating conditions used in each test are shown in Table 4, which includes the four tests (Exp. 1 to 4) to evaluate makeup water volume and laboratory, as well as those to evaluate gas flowrate and impeller speed.

The same trends when changing water volume and laboratory were observed for the different tests. Results showed that the batch response can significantly change when modifying operating conditions, even using the same sample.

Table 4. Characteristics of batch flotation tests to evaluate operating conditions, case A

	Evaluation of variables		Exp. 1	Exp. 2	Exp. 3	Exp. 4
Effect	Gas flowrate	Impeller speed	Makeup water vol.	Makeup water vol.	Lab.	Lab.
Cell type	Agitair	Agitair	Agitair	Agitair	Agitair	Agitair
Volume (L)	2.7	2.7	2.7	2.7	2.7	2.7
Imp. speed (rpm)	1300	1000 – 1200 - 1400	1000	1200	1200	1400
Air flowrate (L/min)	10 – 14 - 18	12	10	14	18	14
Makeup water vol. (mL)	200 - 600	200 - 600	370 - 1240	150 - 490	500 - 800	500 - 800
Laboratory	A	A	A	A	A - B	A - B

Figs. 3a and 3b show that high impeller speed and/or high gas flowrate generate faster responses, reaching high recoveries in few minutes. This occurs because these operating conditions favour the collection process, increasing the kinetic behaviour of valuable minerals in flotation cells. This situation would probably not be a suitable condition to represent most industrial responses. However, in any case, the batch operating conditions should be thoroughly selected to agree with the industrial operation, which will be different according to the characteristics of each plant.

Fig. 3c shows the effect of makeup water volume, and the way it is added throughout the flotation tests on the metallurgical response. The objective of adding water is to maintain the pulp volume and interface level in the flotation cell, but in many cases, this is not achieved. Exp. 1 and 2 in Fig. 3c shows significant differences in the total water volume added to the flotation cell, which generates metallurgical responses that can be slower, when water is not adequately added during the first minutes of the tests (higher mass pull). Additionally, metallurgical responses may not reach a plateau when water is added towards the end of the tests, which also has an impact on the concentrate grades.

Regarding Fig. 3d, the metallurgical response was not suitably replicated in two different laboratories, even using the same ore, flotation machine and operating conditions. This was observed for two different experiences, Exp. 3 and 4.

Another important issue commonly observed in flotation batch tests is that some flotation protocols allow the operator to arbitrarily modify some variables, for example, establishing a maximum gas flowrate instead of a fixed value. Fig. 4 shows the effect of varying the gas flowrate throughout batch flotation tests for the case A. Thus, different batch responses for three different tests (Exp. 5, 6 and 7) were presented, where the gas flowrate was variable. The ore sample and the other operating conditions were the same and remained constant during the tests. The operating conditions used in each test are shown in Table 5, which includes the three tests (Exp. 5 to 7) to evaluate variable gas flowrates throughout batch tests.

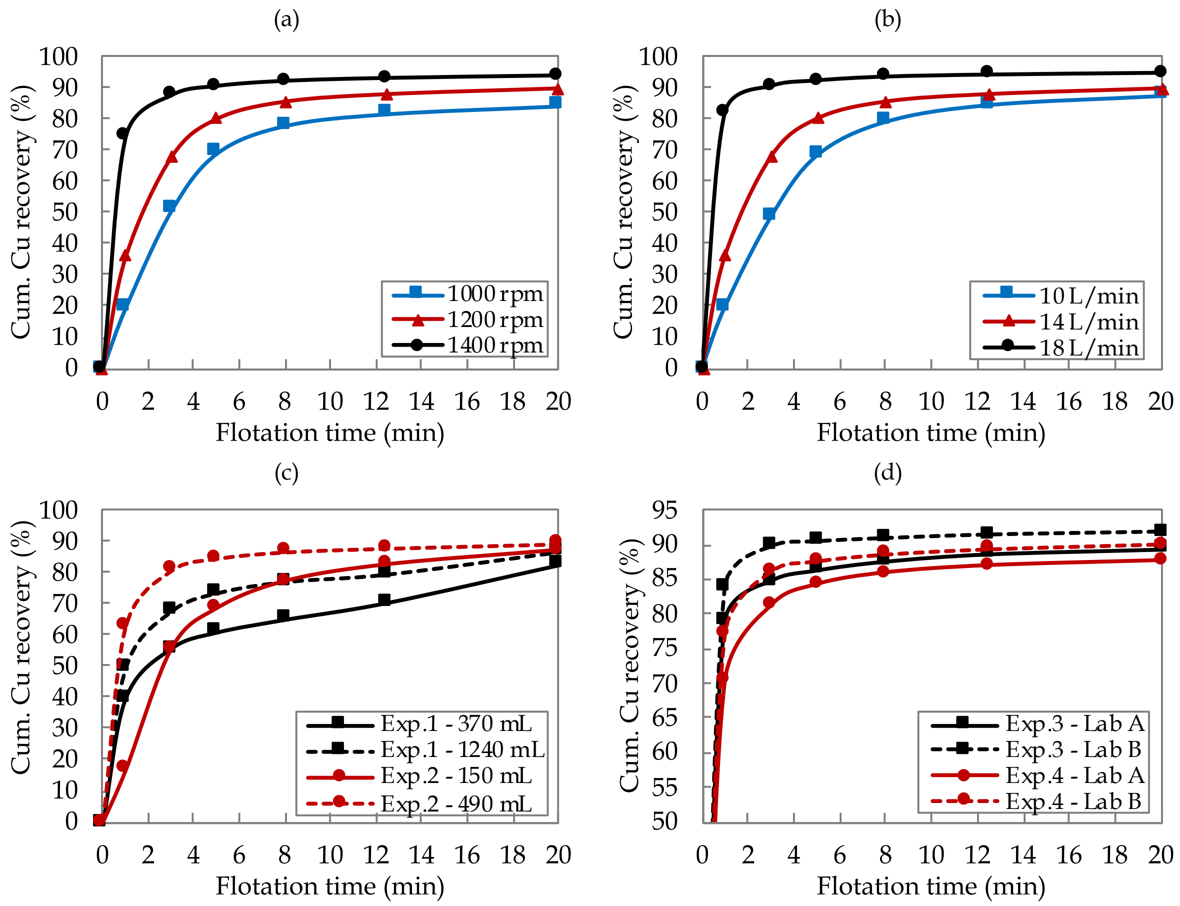

Fig. 3. Batch responses for case A, when changing: (a) impeller speed, (b) gas flowrate, (c) volume of makeup water, and (d) laboratory

Table 5. Characteristics of batch flotation tests to evaluate variable gas flowrate, case A

	Exp. 5, Exp 6 y Exp. 7
Cell type	Agitair
Volume (L)	2.7
Imp. speed (rpm)	1200
Air flowrate (L/min)	Max. 12 (*)
Makeup water vol. (mL)	200 - 600
Laboratory	A

(*) The gas flowrate was differently modified by the operator throughout Exp. 5, Exp. 6 and Exp. 7, with a maximum of 12 L/min.

Results showed that the batch recovery profile can significantly change when gas flowrate is arbitrarily manipulated throughout the flotation test. This also has an important effect on the concentrate grade. Therefore, establishing a maximum gas flowrate in batch flotation protocols is not a suitable condition to reach a standard operation. A fixed value should be defined instead. This allows for obtaining a standardised operation, avoiding the operator manipulation and its effect on the metallurgical performance.

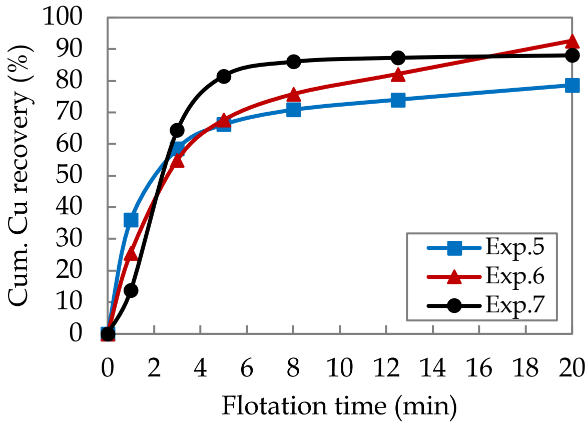

Fig. 4. Batch responses for case A, when using variable gas flowrate

3.1.2. Effect of flotation operator

Fig. 5 shows the effect of the operator on the batch flotation response for the case B, considering a primary and secondary Cu ore (Fig. 5a and Fig. 5b, respectively), following the same flotation protocol. The primary and secondary ores used in the tests correspond to two different composites of drilling samples from the industrial operation (case B) and showed Cu grades of 0.6%Cu and 0.7%Cu, respectively. Results showed that the batch recovery profile can notably vary when the operator changes, for both ore samples.

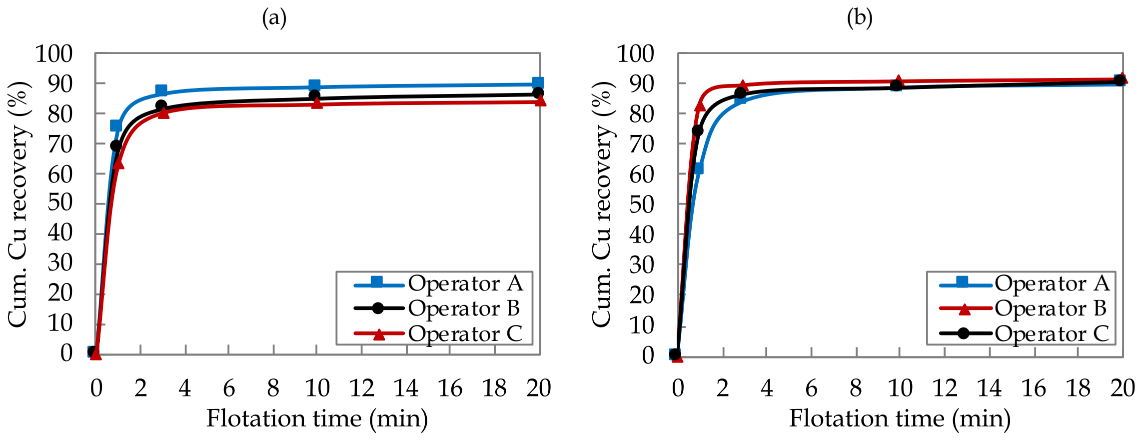

Fig. 5. Batch responses for case B, when changing the operator, using (a) primary and (b) secondary ore

3.1.3. Effect of ore type and water quality

Fig. 6 shows the effect of the ore type and water quality on the batch flotation response for the case A. The selected ores have fast, intermediate, and slow floatability (Ores 1, 3 and 2, respectively), while the selected water types correspond to less and more salty water (Water 1 and 2, respectively). Although these characteristics do not directly modify the flotation batch protocol, they can affect the scale-up factors estimation, because the effect of these variables can lead to operating problems at batch and industrial scale, promoting changes in the batch and/or industrial operation.

The characteristics of Ores 1, 2 and 3 are shown in Table 6, while the qualities of Water 1 and 2 are detailed in Table 7.

Results showed that the batch recovery changes when modifying ore type and water quality. It must be noticed that the effect of water quality was higher for the ore with slow floatability (Ore 2). On the other hand, mass pull was notably higher for minerals with slow floatability (25%, compared with 8-12% for faster ores), which can require changes to be implemented in batch and/or industrial operation.

Table 6. Characteristics of Ores 1, 2 and 3 to evaluate ore type, case A

	Ore 1	Ore 2	Ore 3
Cu feed grade (%)	0.95	0.87	1.17
Pyrite content (%)	0.4	14.1	4.5
Clays content (%)	16.0	30.0	20.9
Main Cu Sulfides (%)	Chalcopyrite (82%) Bornite (15%)	Chalcocite (65%) Chalcopyrite (15%)	Chalcopyrite (63%) Bornite (20%)
Free Cu sulfides (% mass)	73%	26%	66%

Table 7. Characteristics of Water 1 and 2 to evaluate water quality, case A

	Water 1	Water 2
Conductivity (µS/cm)	494	32,384
pH	8.3	7.6
Main ion content (mg/L)	Chloride (125 mg/L) Sodium (61 mg/L)	Chloride (13,521 mg/L) Sodium (6,606 mg/L)
Total dissolved solids (mg/L)	310	23726

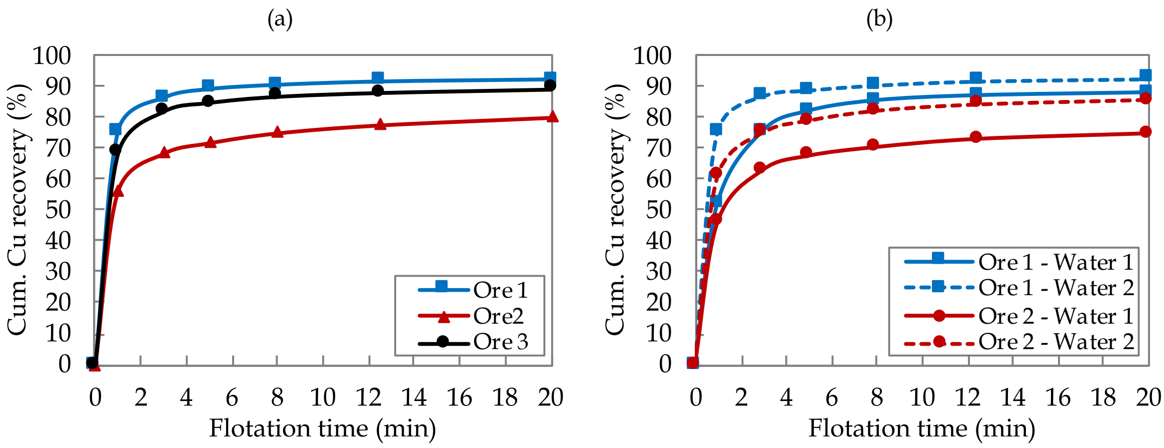

Fig. 6. Batch responses for case A, when changing: (a) ore type, and (b) water quality

3.2. Estimation of industrial flotation response from batch flotation tests

Fig. 7 shows the batch and industrial rougher responses for cases A, C, and D (Fig. 7a, Fig. 7b and Fig. 7c, respectively). It was observed that the batch flotation results, for case A, suitably represent the industrial operation. On the contrary, for cases C and D, the batch responses did not represent the industrial bank, being too fast or reaching the plateau at low recovery, respectively.

The differences between batch and industrial responses depend on the batch protocol and industrial conditions used in each case. According to Table 1, batch flotation tests for cases A, C and D follow different protocols to represent the respective industrial rougher responses. However, Figs. 7b and 7c show that the protocols used in cases C and D are not suitable to describe the industrial response and should be modified, changing operating conditions until a new operating point is found. Thus, although it is difficult to identify the effect of each condition (from Table 1) on the batch responses, those for Case C and Case D should turn into a slower and faster responses, respectively. Regarding Case A, the agreement between the batch and industrial responses is because the batch protocol was well established to suitably represent the industrial operation.

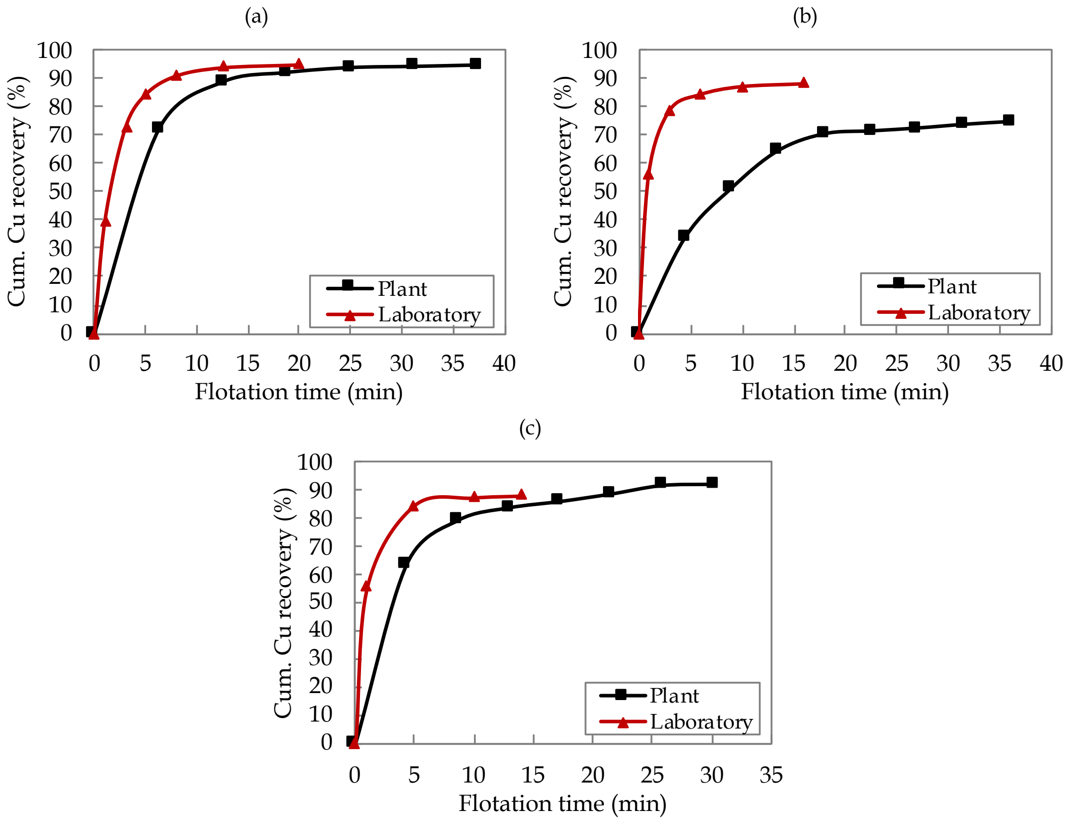

Fig. 7. Batch and rougher responses for (a) case A, (b) case C, and (c) case D

3.3. Estimation of scale-up factors

Table 8 shows the scale-up factors obtained from the batch and rougher responses (Fig. 7), using the time ratio approach. Results showed a scale-up factor of 2.5 for case A, which is within the range commonly used. On the other hand, factors for cases C and D were abnormal, considering the responses observed in Figs. 7b and 7c.

Table 8. Scale-up factor estimated from batch and rougher responses, cases A, C, and D

	Plant recovery (%)	Plant time (min)	Batch time (min)	Scale-up factor
Case A	94.4	37.4	15.2	2.5
Case C	74.4	36.1	2.3	15.7
Case D	92.0	30.2	40.2	0.8

Considering the scale-up factor for case A was within the normal range, a sensitivity analysis allowed for evaluating how much this factor can change when modifying variables of the batch flotation protocol.

Fig. 8 shows the effect of changing the impeller speed and gas flowrate, on the recovery profiles and scale-up factors, for the case A at batch scale, based on trends of cumulative recovery (Fig. 3a and 3b). Results showed that the scale-up factor of 2.5 (Table 4) decreases to 0.4 if the impeller speed decreases from 1300 to 1000 rpm. On the other hand, the scale-up factor increases to 6.2 if the gas flowrate increases from 12 to 18 L/min.

Then, the effect of changes in the industrial operating condition on the scale-up factor was evaluated. Fig. 9 shows the effect of upgrading the recovery of the rougher industrial bank on the scale-up factors, for the case A. Increases in 1% and 2% of recovery were considered, as an example, to evaluate the sensitivity in the estimation of scale-up factors. Results showed that the scale-up factor of 2.5 (Table 4) decreases to 2.0 and 1.6, if the rougher final recovery increases 1% and 2%, respectively.

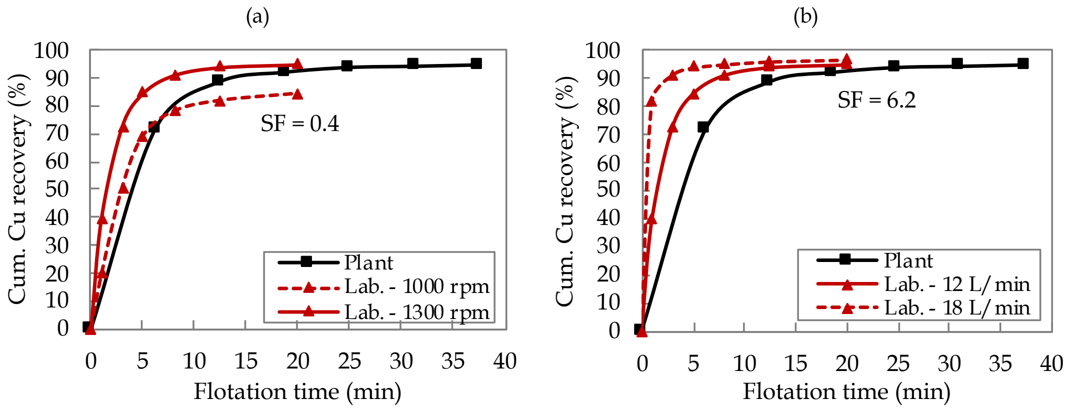

Fig. 8. Rougher vs. batch response for changes in (a) impeller speed, and (b) gas flowrate

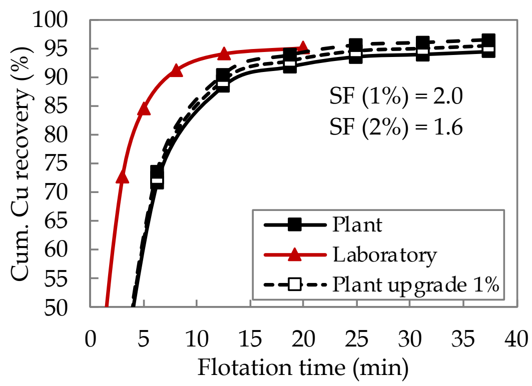

Fig. 9. Rougher vs. batch response for increases in industrial recovery (upgrade)

4. Conclusions

Batch and industrial metallurgical responses were analysed for four different cases, each representing an industrial operation.

Results showed that, for the same ore, the batch response can significantly change when modifying operating conditions, such as impeller speed, gas flowrate, volume of makeup water, flotation machine (in different laboratories), and operator.

Additionally, the batch recovery significantly changes when modifying the ore type and water quality. Although these characteristics do not have a direct impact on the flotation batch protocol, they can require changes to be implemented in the batch and/or industrial operation, affecting the scale-up factors.

When comparing the batch and industrial (rougher) flotation results, case A showed a suitable agreement between both responses. On the contrary, for cases C and D, the batch responses did not represent the industrial bank, being too fast or reaching the plateau at low recovery, respectively. This generated a normal scale-up factor of 2.5 for case A, but abnormal factors of 15.7 and 0.8 for cases C and D, respectively.

In summary, the scale-up factors are quite sensitive to changes in batch and industrial conditions. Therefore, each plant should implement a batch flotation protocol, according to their own conditions, being aware of variables that can significantly affect the scale-up procedure, such as gas flowrate, water quality, makeup water, rpm, among others, as well as changes in the industrial plant. There is not a standard batch protocol to represent all industrial operations.

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