



## Modelling flotation per size liberation class – Part 3 – Modelling recoveries using particle surface area



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### ARTICLE INFO

**Keywords:**  
Flotation  
Particle size  
Liberation  
Mineral surface area

### ABSTRACT

In this work, the flotation recoveries per size liberation class are modelled using the particle surface area. The resulting model presented a very good adjustment for recoveries per size with correlation factors above 0.9. In addition, once it is directly connected to particle characteristics, this model directly indicated the effect of particle size and liberation on flotation.

### 1. Introduction

It is well known since the early days of flotation that coarse and fine particles do not float as well as intermediate-sized particles (Gaudin, 1939, 1957). Data from various operating units show that flotation recovery falls rapidly for particles outside the intermediate size range, the limits of which depend on the type and density of the floated mineral, but are generally between 10  $\mu\text{m}$  and 100  $\mu\text{m}$  (Trahar, 1981).

Predominantly, this result has been explained in terms of the effect of size on the probability of flotation sub-processes: collision, adhesion and detachment, as described by Trahar (1981) and Klassen and Mokrousov (1963).

Due to their lower mass, fine particles present low inertial forces that reduce the probability of collision to bubbles. Detachment is not expressive for fine particles, which tend to form stable bubble particle aggregates after adhesion. However, the negative effect of lower probabilities of collision and adhesion overwhelms the advantage of the lower detachment probability, leading to reduced recovery (Rahman et al, 2012; Feng and Aldrich, 1999).

Coarse particles present large surface areas and higher probability of collision in comparison with fine particles. However, due to their weight, the probability of detachment is also higher in comparison with fine particles, especially in the froth. Detachment is considered the main cause of the lower recovery of coarse particles.

The effect of particle size, however, is conditioned by the degree of hydrophobicity, which mainly depends on the liberation, mineral texture and reagent adsorption. The role of liberation has also been recognized for many years (Klassen and Mokrousov, 1963; Sutherland, 1989; Barbery, 1991), but only in the last two decades, with the advance of automated mineralogical techniques, have detailed studies

been developed to further clarify this aspect (Muganda et al., 2011; Albjanic et al., 2015; Welsby et al., 2010; Farrokhpay and Fornasiero, 2017).

The degree of hydrophobicity is usually evaluated by contact angle or particle-bubble attachment time. Several studies have demonstrated the isolated impact of liberation or hydrophobicity on flotation.

As an example, Muganda et al. (2011) evaluated the kinetics of an enriched sample of chalcopyrite (cpy) in relation to its contact angles and size fractions. A spectrum of contact angles was generated by the pre-oxidation of this predominantly pure chalcopyrite sample followed by conditioning with different collector dosages. The final sample was artificially created based on a pre-defined distribution of size fractions. Tests were performed in a batch bench scale flotation machine, at 2% solids concentration. To be able to float, fine and coarse particles required a higher critical contact angle, implying that the hydrophobicity of fine and coarse materials should be higher than the hydrophobicity of intermediate particles to attain the same kinetic performance.

The work of Albjanic et al (2015), performed with a chalcopyrite ore using batch flotation laboratory tests and the analysis of a single size fraction, showed that attachment time measurements are related to the metal grade: the higher the presence of highly and moderately liberated Cu minerals, the lower the attachment time and the more effective the flotation.

The work of Welsby et al (2010) can be highlighted as one that used a real ore, tested in bench-scale cells on a continuous basis, to evaluate the influence of liberation on flotation. The focus was on estimating the kinetic values of liberation classes and establishing their relationship with flotability components. Results showed that fully-liberated classes had the highest mass fractions and were predominant in the fast-floating component, which also included high grade composites.

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<https://doi.org/10.1016/j.mineng.2018.08.036>

Received 24 December 2017; Received in revised form 26 August 2018; Accepted 27 August 2018

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Liberation data was not stereologically corrected, which may restrict the use of these data in a quantitative analysis.

Other studies were developed using artificial ores (Ross, 1997; Ata et al., 2004; Farrokhpay and Fornasiero, 2017). On the one hand, artificial particles allow the control of liberation textures and proportions, on the other hand, they may not represent real liberation class distributions. Artificial material provides a very good view of isolated effects but may miss the interactions or aspects that can occur in real liberation distributions of a ground ore. Studies have shown that the interaction of particles with different sizes can affect the flotation recovery (Rahman et al, 2012, Lange et al, 1997).

Therefore, it is important to further investigate how liberation, in conjunction with size, affects flotation performance, using a real ore in a continuous circuit, under conditions close to industrial ones and after some sort of stereological correction and reconciliation of liberation data.

This is the main objective of this study and of a series of others based on the same tests. In this work, the behaviour of size liberation classes was evaluated using a chalcocopyrite ore floated in a continuous mini pilot plant circuit, with conditions equivalent to industrial flotation in terms of particle size, solids percentage, and feed mineralogy. The process was accurately sampled, providing measurements of flow rates and grades. To minimize error propagation, hierarchical mass balance and mineralogical correction were performed simultaneously, in which the resulting distribution per liberation classes was consistent with the reconciled process data. The behaviour of size liberation classes was evaluated here in the first rougher cell. The results show how size and liberation distributions are linked to flotation performance in this first rougher, or, in general terms, for the particles that float fast. A mathematical model links flotation performance to the estimated chalcocopyrite mineral surface area for this ore.

## 2. Method

### 2.1. Tests

The basis of this work is the same as described in Santos et al. (2014). Three continuous pilot tests had been conducted in a flotation mini pilot plant (MPP) using a chalcocopyrite ore from the north of Brazil, and each test had a specific froth height in the first rougher cell, to allow an evaluation of froth recovery. Tests were called Cal 01, Cal 02, and Cal 03 and were performed with low, intermediate, and high froth height, respectively.

The circuit included rougher, scavenger and cleaner stages at a feed rate of 110 g/min–118 g/min (~7 kg/h), at 30% solids and with a particle size approximately 85 percent < 210  $\mu\text{m}$ . As this circuit aimed to evaluate the characteristics of flotation size-liberation class, there was no regrinding of intermediate concentrates, which would involve a change in the particle size distribution and, therefore, a resetting of the model in the middle of the circuit. Tests were conducted in an open circuit to obtain a high accuracy in the parameters. It is important to clarify that it would not be difficult to achieve circuit stabilization with recirculation loads. However, flow rates are small in the MPP, only some grams per minute in intermediate flows. If circuit was closed, sampling of recirculating flows should be performed in small aliquots of 20 s taken every 10–15 min. Then, to obtain the appropriate amount of material to perform all the analyses, at least 200 g, the duration of each test and ore feed consumption would be multiplied several times, what would not be feasible due to the limited amount of ore available for these tests. With an open circuit, it is possible to collect the intermediate concentrates over the required time, around two hours, what reduces sampling bias and promotes accuracy.

Fig. 1 shows the flowsheet. Each square corresponds to a 1.7-L cell with a froth crowder.

Due to the small flow rates, the whole flows of products were collected. Therefore, the obtained material was not a “sample” as a

“portion” of the flow, but was the whole flow accumulated during a certain time. Tailings were taken in aliquots of 1 min. In particular, concentrate flows were accumulated for two and half hours. Considering that the residence time of the circuit was around 45 min (~15 min in Rg + Sc and ~30 min in Cl), concentrate flows were taken during 3 residence times without interruption. Due to this time-span, this was a very accurate product from a circuit, once it was able to absorb any process fluctuation. Flows of solids and water were determined with this whole amount. From this product, samples were split for chemical and physical analysis. Details can be referred to in Santos and Galery (2011).

These products were screened at 210  $\mu\text{m}$ , 150  $\mu\text{m}$ , 74  $\mu\text{m}$ , and 44  $\mu\text{m}$  and the fraction below 44  $\mu\text{m}$  was analysed in a cyclosizer. Chemical analyses of Cu, Fe, Si, and S were performed for the overall sample and the size fractions.

The mineralogical analysis was conducted in QEMScan for size fractions of –210  $\mu\text{m}$  + 150  $\mu\text{m}$ , –150  $\mu\text{m}$  + 74  $\mu\text{m}$ , –74  $\mu\text{m}$  + 44  $\mu\text{m}$  and –44  $\mu\text{m}$  + 20  $\mu\text{m}$ , for the feed and the rougher 1 concentrate, rougher 2 tailings, scavenger concentrate, cleaner concentrate and cleaner tailings. The liberation distribution in other size fractions and streams was obtained through the QEMScan estimate and mass balance.

### 2.2. Mass balance

Data were balanced using the revised Savassi method (Santos and Galery, 2018a,b; Savassi, 2006). This method uses a hierarchical procedure for mass balance reconciliation, in which the first level restricts and conditions the reconciliation in the following sublevel. Sampling and analysis must be made with as much redundancy and precision as possible to minimize errors in the global mass balance. Reconciliation in the size fractions is carried out to be consistent with this global balance. As a sort of stereological correction, the beta distribution function is used to estimate the 3D liberation distribution from the 2D image analysis while reconciling each measured distribution with the balanced grade and density of the corresponding size fraction.

Using this approach, global flow rates as well as mass proportions by size and liberation class with their mineral grades were reconciled for all flows.

An overview of the results of the first rougher comparing the different froth heights is presented in Santos and Galery (2017a,b).

This work details and models the effect of liberation on flotation for the first rougher considering the mineral surface area, showing how size and liberation are related to flotation performance. The whole circuit as well as the more detailed results on the kinetics of liberation classes will be the subject of future studies.

## 3. Results

### 3.1. Feed characterization

In the ore, chalcocopyrite is the main copper mineral and contributes to approximately 6.2% of the mass. Other copper minerals such as covellite, digenite and malachite are rare. Gangue is composed of quartz, feldspar, actinolite, iron oxides, mica and chlorite. This ore was considered a binary system formed by chalcocopyrite and gangue.

Figs. 2 and 3 present the size distribution and chalcocopyrite content per size fraction of the ground feed ore. The size distribution is compatible with industrial data.

Most chalcocopyrite, approximately 80%, is distributed as intermediate-sized particles, ranging from 20  $\mu\text{m}$  to 150  $\mu\text{m}$ .

#### 3.1.1. Distribution of size liberation classes in feed and definition of variables

The set of results comprises global mass flow rates and grades, size distribution and mineralogical distribution for each flow, as well as the respective grades per size and class. Once there are two levels of

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