Minerals Engineering 74 (2015) 207–215

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

On the relationship between hydrodynamic characteristics and the kinetics of column flotation. Part I: Modeling the gas dispersion

Ali Vazirizadeh *, Jocelyn Bouchard, René del Villar

Department of Mining, Metallurgical and Materials Engineering, LOOP (Laboratoire d'observation et d'optimisation des procédés), Université Laval, Pavillon Pouliot, Quebec City G1V0A6, Canada

ARTICLE INFO

Article history:
Received 19 July 2014
Revised 22 September 2014
Accepted 26 September 2014
Available online 27 November 2014

Keywords:
Interfacial area of bubbles
Flotation
Gas hold-up
Bubble surface area flux
Distribution function

ABSTRACT

Modeling of flotation has been the subject of many investigations aiming at better understanding the process behavior per se, and as well for process design, control and optimization purposes. With this regard, the importance of hydrodynamic characteristics, either as manipulated or measured variables, are paramount. The interfacial area of bubbles (I_b) is introduced in Part 1 of this paper as a hydrodynamic variable providing more information about the size distribution than the commonly used bubble surface area flux (S_b). Experimental evidence shows that the bubble size distribution can exhibit normal, lognormal, and even multi-modal shape. Unlike the Sauter mean diameter (d_{32}) and S_b, the interfacial area of bubbles is derived from the complete bubble size distribution, and takes into account these specific characteristics. Fundamental expressions are proposed to allow characterising I_b using the population mean and standard deviation. Experimental results indicate that for lognormal bubble size distributions, I_b correlates well with the gas hold-up and d_{32}. Part 2 of the paper analyzes the correlation of gas dispersion characteristics with flotation rate constant.

1. Introduction

Hydrophobic particles present in a mineral pulp are collected in a flotation column by injecting fine air bubbles through a sparger located at the bottom of the reactor. The resulting bubble-particle aggregates rise through the collection zone of the column, i.e. the collection zone, allowing separation from the hydrophilic particles, which flow through the tailings valve. The bubble particle agglomerates rise into the froth zone, where typically a counter current water wash helps to remove entrained fine, hydrophyllic gangue particles. Bubble coalescence occurs in the froth zone leading to the loss of some hydrophyllic particles but providing improved mineral selectivity. The overall flotation process can then be considered composed of a reaction process (collection) followed by a separation process (froth selectivity).

1.1. Hydrodynamic variables and particle size

Hydrodynamic variables have a significant role on the performance of flotation cells since they affect the reaction rate and the mass transport (water and particles) by increasing the specific area of the dispersed phase. For instance, it has been experimentally proven that the rate constant decreases for coarse particles at high superficial gas rates and that fine particles require much higher superficial gas rates for effective flotation (Heiskanen, 2000). However, Newell and Grano (2006) reported that increasing the superficial gas velocity leads to a linearly increased overall flotation rate constant, whereas Yoon (1993) stated that decreasing bubble size is more effective than increasing gas rate to reach higher recoveries.

Many studies have been conducted to determine the effect of the bubble surface area flux (S_b) on the collection recovery. For instance, Gorain et al. (1997) obtained a linear relationship between the flotation rate constant and the bubble surface area flux, the slope increasing with decreasing particle sizes. This investigation characterized the performance of mechanical cells using this model. Later on, the same authors reported that the $k - S_b$ relationship was a function of the froth depth. Only for shallow froths was a linear relationship found (Gorain et al., 1998). It can then be concluded that froth depth plays an important role on the overall kinetics.

The existence of a linear relationship between the flotation rate constant and the froth depth was also confirmed by Vera and coworkers (1999), The authors also claimed that the collection zone rate constant of the two evaluated minerals (chalcopyrite and pyrite) increases with the air flow rate, observing though a reduction in froth-zone recovery. This was associated to a detachment of

* Corresponding author. Tel.: +1 581 9986866; fax: +1 418 6565343.
E-mail address: a.vazirizadeh@gmail.com (A. Vazirizadeh).

http://dx.doi.org/10.1016/j.mineng.2014.09.026
0892-6875/

Nomenclature

BSD	bubble size distribution	$f(d_b)$	size distribution function
d_b	bubble size	I_b	interfacial area of bubbles
$d_{b\ max}$	maximum bubble size	I_{bc}	calculated I_b
$d_{b\ min}$	minimum bubble size	I_{bm}	predicted I_b from d_{32} and ε_g
d_0	bubble size at $J_g = 0$	J_g	superficial gas rate
d_{10}	mean diameter of the BSD	k	flotation rate constant
d_{32}	Sauter mean diameter of the *BSD*	μ	mean of the *BSD*
erf (x)	error function	S_b	bubble surface area flux
ε_g	gas hold-up	σ^2	variance of the *BSD*

particles from the bubbles in the froth-zone, thus justifying the use of a shallow froth in the present work to exclude this effect.

1.2. Bubble surface area flux models

The bubble surface area flux is defined as the surface of a given number of rising bubbles per unit time and unit of cell cross-sectional area. Assuming same-size spherical bubbles, a relation for S_b can be derived as a function of the superficial gas velocity J_g and the bubble diameter d_b.

$$S_b = \frac{6J_g}{d_b} \tag{1}$$

Since bubbles do not have the same size, it is customary to replace d_b by the Sauter mean diameter d_{32}

$$S_b = \frac{6J_g}{d_{32}} \tag{2}$$

The d_{32} is a scalar value obtained from a bubble size density function or directly calculated from observed data. However, important information related to the shape of the bubble size distribution (BSD), such as multi-modal and tails behavior, is lost in this compression exercise (Maldonado et al., 2008b). The general S_b definition suggests that bubble size distribution play an important role in the metallurgical performance of any flotation process.

For uniform bubbles, an empirical relationship was presented by Finch and Dobby (1990) to predict bubble size from the superficial gas velocity. Finch and Dobby's model was further developed by Nesset et al. (2006), who proposed an empirical model for estimating the d_{32} based on d_o (bubble size at $J_g = 0$) and two parameters depending on the bubble generation system, the used chemical reagents, and eventually, the slurry properties. Base on the collected data from commercial flotation cells, they also reported that the d_{32} values are sensitive to the relative percentage of large bubbles (larger than 1.5 mm), whereas d_{10} values are more sensitive to the amount of small bubbles (smaller than 1 mm). Instead of using direct values of d_{32} from histograms describing the size distribution, other authors have used the bubble size density function to evaluate the d_{32} (Grau and Heiskanen, 2005; Vinnett et al., 2012).

Gorain et al. (1999) presented a model to predict the S_b in mechanical cells as a function of the impeller peripheral speed, the air flow rate per unit cell cross-sectional, the impeller aspect ratio and the 80% passing size of the feed. This model seems adequate for cells with forced air feed mechanisms. However, it is known to predict inaccurate values for self aspirating cells (Gorain et al., 1999).

Heiskanen (2000) criticized Gorain's model, claiming that "*the measurement and computation of superficial gas velocity, as well as the bubble size in some cases, could be biased under some conditions*". Moreover, the model validation would not address the real behavior of various particle sizes, as larger bubble sizes show a higher flotation rate constant, and poor dispersion conditions give a good flotation response, both results contradicting earlier research findings and industrial experience. Heiskanen concluded that the bubble surface area flux needed a broader validation using different types of ore, and that the linear $k - S_b$ relationship required being further investigated.

1.3. Bubble size measurement

Cape Town University (CTU) presented the first attempts to measure bubble size using an optical system. The experimental set-up sampled bubbles using a belled tube, wherefrom they were driven to an inclined viewing chamber. The system combined high intensity lighting and a camera placed at either sides of the viewing chamber to allow taking pictures (O'Connor et al., 1990; Tucker et al., 1994).

The HUT bubble size sampler developed at Helsinki University of Technology has also been applied by Grau and Heiskanen (2005) to measure the bubble size distribution in mechanical cells. They had previously compared the HUT and CTU systems to measure the bubble size and they found some limitations with the CTU method, "*when the gas was not efficiently dispersed*" (Grau and Heiskanen, 2002). The bubble sampling system in the CTU method also caused bubbles larger than 1 mm to breakup, hence leading to finer bubble size distribution than the actual ones (Grau and Heiskanen, 2002).

The McGill bubble size analyzer is another visual technique which was introduced by McGill University researchers (Vinnett et al., 2012). Its operational principle is based on conveying a sample of bubbles (with some pulp) into a viewing chamber where they are exposed to an appropriate light source and are photographed with a digital camera. An automated image analysis procedure allows the size of the collected bubbles to be measured. The bubble viewer system consists of a sampling tube attached to the bottom of a sealed viewing chamber (Hernandez-Aguilar et al., 2004). It is worth mentioning that the viewing chamber must be periodically purged of accumulated air, and periodically cleaned/refilled with fresh water because of progressive slurry buildup, thus making online measurement challenging.

Until now, the use of the bubble viewer has been reported basically in offline process audits (gas dispersion conditions in cells or columns). The only known application for bubble size control (i.e. continuous d_b measurement) is the two-phase research work at Université Laval (Maldonado et al., 2008b).

For process control purposes, Maldonado et al. (2008b) used the commercial software program Image-J to analyze the bubble images. Based on circular shape detection, the method however fails at recognizing clustered, large or elliptical bubbles. Vinnett et al. (2012) proposed a semi-automatic methodology using the