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Indirect estimation of bubble size using visual techniques and superficial gas rate

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ABSTRACT

In this paper, an indirect method for determining the Sauter mean diameter of a bubble population is presented. The technique relies on the estimation of the percent area occupied by bubbles in a 2D image as well as on the superficial gas rate. The percent area was defined as the quotient between the black pixels (bubble representation) divided by the total pixels in a binary image. A linear model to describe the Sauter diameter as a function of the percent area and the superficial gas rate was proposed. The regressions showed a fairly good predictive capacity in laboratory and industrial flotation machines under bubbly regime, which makes the proposed methodology a promising tool for monitoring and controlling gas dispersion in real time.

1. Introduction

Gas dispersion describes the non-continuous phase distribution within the flotation machines and it is, therefore, one of the most important parameters in flotation due to its direct relation with the process efficiency. The role of gas dispersion in flotation has been extensively discussed in literature for process modelling, flotation rate prediction and technology comparisons (Schwarz and Alexander, 2006; Deglon et al., 2000; Finch and Dobby, 1990; Gorain et al., 1995; Clift et al., 1978). Gas dispersion is typically characterized in terms of bubble size distribution (usually represented by Sauter mean diameter, $D_{32} = \sum d^3/\sum d^2$), gas concentration or holdup (ε_G) and superficial gas rate (J_G).

Bubble size distribution (BSD) is perhaps the most important indicator of gas dispersion in flotation machines since it defines the available surface area over which particles will attach. BSD can be used to predict flotation performance, and it is commonly used for process control (Gorain et al., 1995). Between the techniques and approaches for bubble size determination, the following are highlighted: (i) conductivity probes (Barigou and Greaves, 1992); (ii) drift flux analysis using gas rate and gas holdup measurements (Banisi and Finch, 1994; Yianatos and Levy, 1989); (iii) optical sensors (Randall et al., 1989); and (iv) image analysis of recorded bubbles (Grau and Heinskanen, 2002; Hernandez-Aguilar et al., 2002).

The conductivity devices have shown reproducible and appropriate results for on-line measurements in two-phase systems, but hardly applicable to multi-phase industrial conditions (Chen et al., 2001). The method of drift flux has allowed bubble diameter ranging from 0.5 to 2 mm to be obtained with superficial gas rates lower than 3 cm/s (Yianatos and Levy, 1989). However, the bubble size estimates require of parameters such as superficial liquid rate, pulp density and pulp viscosity, with are usually difficult to obtain at industrial scale. The UCT bubble size analyser introduced by Randall et al. (1989) is one of the most popular optical devices, consisting of a capillary tube that is submerged in the collection zone to capture the rising bubbles. Bubbles pass through a bubble detector that sizes the length, and thus, the volume of the bubbles. Some limitations of this device are the size of the capillary, which produces bias towards small bubbles (bubbles with diameter smaller than the capillary diameter cannot be reliable measured). Also, big bubbles can break in the capillary distorting the BSD measurements (Grau and Heiskanen, 2002).

Currently, the simplest and most accepted devices are those based on visual techniques. One of the most used devices is the McGill bubble viewer, which consist of a sampling tube to capture the rising bubbles from the collection zone and direct them into a chamber. Bubbles are recorded with a video camera and automated image analysis software determines the BSD based on border detection. However, this is not straightforward: the

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background of images varies depending upon the image sensing device and the lighting quality (Hernandez-Aguilar et al., 2002). Other potential sources of bias are bubbles overlapping, blurring, poor contrast, misunderstanding the formation of shadow zones and, in three-phase systems, difficulties in sizing particle-bubble aggregates. This makes the automated image analysis challenging. Vinnett et al. (2009) have used the McGill bubble viewer along with semi-automated software to reduce biased BSD results. However, semi-automated software requires a suitable selection of the number of processed bubbles to obtain an adequate trade-off between non-biased BSD results and time of processing.

In this paper, an empirical linear model for determining the Sauter mean diameter of a BSD is presented. The model structure is based on the estimation of the percent area occupied by bubbles in 2D images and on superficial gas rate measurements. Both parameters can be obtained in real time; therefore, the proposed method is a suitable tool for on-line D_{32} estimations. The proposed model was evaluated at laboratory and industrial scales.

2. Image analysis: percent area

Several correlations for the bubble diameter estimation have been reported in literature. For instance, Finch and Dobby (1990) proposed a potential correlation between the bubble diameter and the superficial gas rate. Also, Nesset (2011) developed an expression for D_{32} dependant on key factors affecting bubble size such as frother type and concentration, superficial gas rate, impeller tip speed, pulp viscosity and altitude of a geographic location. More recently, Vinnett et al. (2014) reported an exponential relationship between D_{32} and superficial gas rate in mechanical flotation cells at industrial scale. The aforementioned correlations allow for indirect estimations of bubble size considering operating variables. However, an estimate based only on the J_G value is sensitive to changes in the frother type and concentration or impeller speed. On the other hand, correlations based on multiple variables might be difficult to implement in real-time applications.

A new parameter named percent area, σ_B, was defined for the black and white representation of recorded images. This parameter has shown correlation with the bubble size. The σ_B value is defined as the number of black pixels divided by the total pixels in the processed image, Eq. (1).

$$\sigma_B = 100 \times \frac{\sum(\text{Black Pixels})}{\sum(\text{Total Pixels})} \quad (1)$$

Fig. 1 shows two examples of industrial images, in which $D_{32} = 1.1$ mm and $\sigma_B = 35\%$ (Fig. 1a) and $D_{32} = 4.6$ mm and $\sigma_B = 11\%$ (Fig. 1b) were obtained. The percent area has the potential to be obtained in real-time because of its low computational cost and its low sensitivity to the presence of clusters.

Fig. 2 shows the D_{32} values as a function of σ_B for mechanical cells of 15–130 m^3 operating in rougher, cleaner and scavenger circuits of an industrial concentrator. The experimental procedure to obtain the D_{32} values is detailed in Vinnett et al. (2014). A decrease in bubble size is related to an increase in σ_B, which was represented by an exponential trend. Results from Fig. 2 were obtained for superficial gas rates ranging from 0.8 to 1.8 cm/s. The D_{32} correlation with σ_B was evaluated at laboratory scale for a wide range of J_G values.

3. Experimental procedure and data processing

The D_{32} dependence as a function of σ_B was studied at laboratory scale using the experimental settings shown in Fig. 3. This cell represents a slice of the upper radial section of an industrial flotation cell. Forced-air was fed from the bottom to 24 porous spargers. The froth discharge at the top of the cell is kept constant by a pump, which recirculates the froth to the feed tank.

Experiments were structured in order to evaluate the effects of superficial air rate and frother concentration on the bubble size. The frothcrowder angle was set in 45°. Methyl isobutyl carbinol (MIBC) was used as a frother. The MIBC concentration in the cell was evaluated for 2, 4, 8 and 16 ppm. Also, for each frother concentration the following superficial gas rates were set by means of a needle valve: 0.5, 1.0, 1.5, 2.0 and 2.5 cm/s. These experimental conditions allowed a wide range of bubble size distributions to be obtained. Experiments included one replicate for each operating condition.

Bubble size distributions were measured using the McGill bubble viewer for image acquisition (installation in Fig. 3). The MBSA was adapted to determine the local superficial gas rate, which was obtained by water volume displacement over time. For the air flowrate conditions, the estimated local superficial gas rates were in good agreement with the values set with the available instrumentation.

The image processing software USM-IMA (Vinnett et al., 2009) was used to obtain the bubble size distribution (BSD) and the statistical parameters from the bubble population (e.g. Sauter mean diameter D_{32}). The USM-IMA is a semi-automated software developed in MATLAB 2009 (The MathWorks Inc., 2009), which allows single bubble diameters to be estimated as the equivalent ellipsoid diameter. Also, simple clusters of bubbles can be automatically segmented and processed using either the Watershed or the

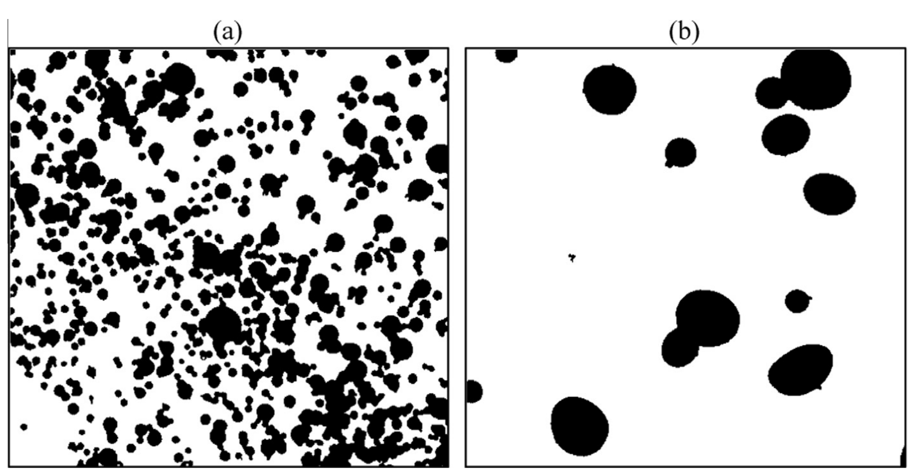

Fig. 1. Industrial images in black and white representation, (a) $D_{32} = 1.1$ and $\sigma_B = 35\%$ (b) $D_{32} = 4.6$ and $\sigma_B = 11\%$.