Communication

Role of Sparger Configuration in Determining Flotation Performance under Oscillatory Air Supply

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Abstract: Bubble size is crucial for determining flotation efficiency. Fine bubbles can be cost-effectively generated using a multi-orifice sparger with oscillatory air supply. Sparger configuration is defined by the orifice size, the plate thickness and the chamber volume. To date, the effect of sparger configuration on bubble size with oscillatory air supply is not clear yet. To facilitate the control of bubble size formed with oscillatory air supply, the present work investigated the dependence of bubble size on sparger configuration. It was found that bubble size was positively correlated with the chamber volume and the orifice size, while a nonlinear relationship was observed with the plate thickness. Besides, it was found that flotation recovery decreased over increasing bubble size when changing the sparger configuration. The results indicated that sparger configuration exhibited a significant effect on flotation performance via influencing bubble size when oscillatory air supply was applied.

Keywords: flotation; bubble size; sparger; oscillatory air supply

1. Introduction

Froth flotation is a process for the separation and concentration of minerals and other particulate materials by exploiting the difference in their affinity to air bubbles in aqueous medium. Bubble size is of great importance for determining the flotation efficiency. Small bubbles are beneficial for recovering both fine and coarse particles in froth flotation [1,2]. Recent studies have shown that microbubbles can be cost-effectively generated using a multi-orifice sparger by replacing steady air supply with oscillatory air supply [3,4]. A bubble usually breaks off at an order of magnitude larger size than the orifice size under steady air supply, while it would detach from the orifice plate at a much earlier stage under an oscillatory air supply which provides an additional lifting force for bubble detachment. Li and Wang (2018) investigated the role of the features of oscillatory air supply in influencing bubble size, and found that oscillatory frequency, on/off time ratio within one circle and air flow rate were the dominating variables which should be taken into account. Microbubble generation with oscillatory air supply has been used in algae harvesting [5], coal flotation [6,7] and fine particle mineral flotation [8,9].

Bubble size generated with a multi-orifice sparger is also determined by the sparger configuration. It has been well known that, under steady air supply, bubble size is closely related to plate thickness [10], orifice size [11] and the chamber volume [12]. However, the role of sparger configuration in determining bubble size under oscillatory air supply is not clear yet, which hinders the optimization of bubble size in practice to some extent. Thus, for the first time, the present work studied the effects of sparger features on bubble size and corresponding flotation recovery with oscillatory air supply, the underlying mechanisms for which were also discussed.
2. Materials and Methods

2.1. Materials

Fine quartz (>99% pure) purchased from Yijing China was used as a flotation material. Its particle size was measured using a Malven Mastersizer 3000E. The particle size distribution of the quartz is shown in Table 1. An ether amine, 3-(2-Ethylhexyloxy) propylamine (>99% pure, Aladdin, Shanghai, China) was used as both collector and frother for silica flotation, and acetic acid (>99.5% pure, Yong Da, Suqian China) was used to neutralize the ether amine (at 20% \( w/w \)) to enhance its solubility [13]. Deionized water was used throughout the work.

Table 1. The particle size distribution of quartz used in this study.

| Passing (%) | 10 | 30 | 50 | 70 | 90 |
|-------------|----|----|----|----|----|
| Size (\(\mu m\)) | 3.1 | 9.8 | 16.7 | 27.4 | 45.4 |

2.2. Experimental Set-Up

Figure 1 schematically depicts the experimental set-up, which comprises a flotation column (50 mm in diameter and 1120 mm in height) with a sparger of porous plate placed at the vicinity of the column bottom. The sparger were made of stainless steel plates with different thicknesses and orifice sizes as needed. The chamber volume of the sparger could be justified between 5 cm and 200 mL.

A solenoid valve (Festo, Shanghai, China) was used to change the flow pattern of air supply from steady to oscillatory. The features that can be adjusted included the switching frequency and the on/off time ratio within every switching cycle. The pressure and gas flow rate passing through the solenoid valve were controlled using an air pressure regulator and air flow meter, respectively. A laser probe (A2 Photonic Sensors, Grenoble, France) was used to measure bubble size in situ. The probe is made of an optical fiber with a micromachined tip. It operates by contact and measures all bubbles that get pierced by the probe.
2.3. Experimental Procedure

The flotation tests were carried out at a continuous mode. The sparger with required orifice size and plate thickness was mounted to the column bottom before flotation, and the chamber volume was adjusted as needed. For each test, 0.76 kg of quartz with 14.5 kg of water was pre-conditioned in a 30 L conditioning sump and the neutralized collector was added to the feed at a dosage of 500 g/t for 10 min prior to the flotation tests. Several other preparation stages were undertaken before starting the flotation: firstly, the flotation column was prefilled with water to avoid sparger blocking during feeding; then, the solenoid valve was turned on and run at the switching frequency of 40 Hz and the ratio of on/off time of 0.2. Air was introduced to the column at a superficial gas velocity of 1.70 cm/s and air pressure was set at 200 KPa. Feed was pumped into the column at 0.8 L/min and the tailing volumetric flowrate was regulated at the same time to maintained froth depth at 100 mm for each test. After the flotation system achieved a steady status which was about twice particle residence time according to preliminary tests, the laser probe was placed 50 mm above the sparger to measure bubble size, after which the froth and tailings streams were collected for 2 min. The collected samples were dried and weighted to calculate flotation recovery. Some conditions were repeated three times and the error bars represent one standard error obtained from the three independent experimental runs.

3. Results and Discussion

3.1. Chamber Volume

Figure 2 shows the effects of the chamber volume on bubble size (solid lines) and flotation recovery (dash lines). In these tests, the orifice size was 63 µm and the plate thickness was 0.1 mm. The chamber volume was varied at 5 mL, 25 mL, 50 mL, 100 mL, 150 mL and 200 mL, respectively.

![Figure 2](image_url)

Figure 2. Effects of chamber volume on bubble size and flotation recovery.

Figure 2 reveals that the chamber volume exhibited significant effects on bubble size and flotation recovery. Under oscillatory air supply, bubble size was dramatically increased from 1087 µm to 1695 µm (a 55.9% increase) and consequently quartz recovery
was decreased from 85.1% to 49.8% (a 41.5% decrease) as the chamber volume was enlarged from 5 mL to 200 mL. Differently, under steady air supply, bubble size experienced a much less increase from 1506 μm to 1641 μm (only 8.96% increase) and quartz recovery was only decreased from 63.3% to 56.8% (a 10.3% decrease). Note that the difference in bubble size and corresponding silica recovery between oscillatory and steady air supply progressively decreased when the chamber volume was increased to 150 mL, above which no significant difference can be observed. The results show that the chamber volume exhibited a more significant effect on silica recovery for oscillatory air supply than for steady air supply via influencing bubble size.

The effect of chamber volume on bubble formation can be evaluated using the dimensionless capacitance number $N_c$. The flow condition in the chamber can be classified into constant flow condition ($N_c < 1$), intermediate condition ($1 < N_c < 10$) and constant pressure condition ($N_c > 10$) [14,15].

$$N_c = \frac{4g_\rho V_C}{\pi d_o^2 P_C}$$

where $\rho$ is gas density (kg/m$^3$), $V_C$ is chamber volume (mL), $d_o$ is orifice size (mm), $g$ is gravity acceleration (m/s$^2$) and $P_C$ is the pressure of air supplied to the chamber.

For the constant flow condition in a small chamber, the status of the gas exiting the chamber (i.e., entering the bubble) is the same to that of the gas entering the chamber. Thus the lifting force resulting from oscillatory air flow drives bubbles detaching at an early stage; for the intermediate condition, the flow pattern of air exiting the chamber becomes not necessarily synchronous to that of air entering the chamber; further enlarging the chamber to reach the constant pressure flow, the chamber impose a cushioning effect on the air flow pattern and thus the air pressure at the orifice is transitioned to be constant. Hence, the lifting force provided by the oscillatory flow recedes in the chamber and consequently bubbles detach at a much later stage. It is calculated that, in this study, the critical chamber volume for constant flow condition is 46.46 mL. This explains why the bubble size for oscillatory air supply was much smaller than that for steady air supply in small chamber volumes, while the difference decreased as increasing the chamber volume, especially in the intermedia condition region.

### 3.2. Plate Thickness

Figure 3 shows the effects of the plate thickness on bubble size and consequent silica recovery. In these tests, the orifice size was 500 μm and the chamber volume was maintained at 5 mL. The plate thickness was varied at 0.05 mm, 0.1 mm and 0.5 mm, respectively.

![Figure 3](image-url)
Figure 3 shows that a nonlinear correlation exists between bubble size and plate thickness. More specifically, the bubble size for the plate thickness of 0.1 mm was 2147 µm; it was 2559 µm and 2858 µm for the plate thickness of 0.05 mm and 0.5 mm, respectively. Oppositely, quartz recovery increases firstly and then decreases with the increase of orifice thickness. It is expected that capillary resistance is the factor which determines bubble size when varying the plate thickness, especially in a channel like the micro-orifice in this study. Capillary resistance is directly related to the channel length. When the 0.05 mm plate was used, the orifice channel length is far smaller than its diameter, which results in a low channel resistance. Given that air was supplied in an oscillatory pattern, air supply was closed for a certain period of time within every cycle. Thus the weeping phenomenon could appear when air was shut down as the low channel resistance could not hold water flowing downward in the channel. The weeping phenomenon would hinder the bubble formation and cause bubble detachment at a late stage [12]. The capillary resistance increases as increasing the thickness of the orifice plate, which will retard the downward flow of the liquid inside the orifice channel and avoid the weeping phenomenon [10]. Note that with an over thick plate the capillary resistance could also weaken the lifting force originated from the oscillatory air flow pattern and result in bubble detachment at a late stage. Therefore, an appropriate plate thickness should be selected to avoid the weeping and meanwhile minimize the energy dissipation of oscillatory air supply imposed by the channel resistance. This explains why the medium plate thickness generated the finest bubbles in this study.

3.3. Orifice Size

Figure 4 shows the effects of the orifice size on bubble size and flotation recovery of quartz. In these tests, the plate thickness was 0.05 mm and the chamber volume was 5 mL. The orifice size was varied at 20 µm, 50 µm, 80 µm, 110 µm and 140 µm, respectively.

![Figure 4](image_url)

**Figure 4.** Effects of orifice size on bubble size (a) and flotation recovery (b) under oscillatory air supply.

As can be seen from Figure 4a, bubble size increased with increasing the orifice size, which is consistent with literature [16,17]. It is interesting to note that the ratio of bubble size to orifice size decreased with the orifice size since the capillary resistance decreases over the orifice size [10]. Figure 4b shows that increasing the orifice size decreased the flotation recovery owing to increased bubble size, which falls the same trend compared to chamber volume and plate thickness.
4. Conclusions

This present work investigated the effect of sparger configuration on bubble size and consequent flotation recovery under oscillatory air supply. The results showed that bubble size was positively related to the chamber volume and orifice size. A thin plate could cause weeping while increasing the plate thickness would also result in the energy dissipation in the orifice channel owing to capillary resistance, implying that an appropriate thickness should be selected for bubble generation with oscillatory air supply. In addition, it was observed that in this study the flotation recovery of fine quartz significantly decreased over increasing bubble size. It was concluded that the sparger configuration exhibited significant effects on flotation recovery via influencing bubble size. Care should be taken in the design of sparger configuration under the use of oscillatory air supply. More specifically, the chamber volume and aperture size should be as small as possible when microbubbles are needed. In addition, the plate should maintain a certain thickness to avoid weeping although it might compromise the effectiveness of oscillatory air supply to some extent.

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