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Effect of gas rate and impeller speed on bubble size in frother-electrolyte solutions

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ABSTRACT

In a flotation cell, bubble size is a function of both coalescence and breakup phenomena. Two phase tests, conducted in a conventional 5.5 L Denver mechanical flotation cell, studied the effect of impeller speed, gas flow rate and frother concentration on bubble size in various electrolyte-frother solutions. The addition of frother to a synthetic sea salt did reduce the measured bubble size (at certain mechanical conditions); whereas the effect of frother addition to NaCl was too small (when compared to measurement errors) to make significant conclusions. This led to more detailed CCC curves (0–50 ppm MIBC) for NaCl, NaCl + $MgCl_2$, NaCl + $CaSO_4$, and NaCl + KCl solutions, at constant electrolyte concentrations, to be conducted. They showed an increase in bubble size with the addition of MIBC. This was attributed to the saturation of frother at the air-water interface, reducing local surface tension gradients that help produce smaller bubbles. This occurrence is typically masked in traditional CCC curves due to the dominance of coalescence effects at low frother concentrations.

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1. Introduction

In the extraction of a mineral from an ore body, froth flotation is one of the most common separation processes, utilising air bubbles inside of a column or mechanically agitated cell to selectively recover mineral particles. The size of the bubbles created, and the associated surface area, is paramount to efficient mineral separation. The bubble size is a function of a number of factors, including (but not limited to): frother concentration and type; air flow rate; impeller/stator design; impeller speed (power intensity); pulp temperature; and gas density (Nesset et al., 2007). Bubble size is also largely dependent on the quality of the process water and the chemicals added. With the increasing size and demands of mining operations, the availability and cost of fresh water sources has become more of a concern. This occurrence has led to an increase in the number of mineral processing plants that utilise water high in electrolyte concentrations, such as saline bore or sea water (Wang and Peng, 2014).

Typically frothers will be added to facilitate the creation and preservation of fine bubbles (0.5–1.0 mm in diameter) *via* coalescence inhibition and break-up phenomena. The presence of certain soluble inorganic ions, however, has also been shown to decrease bubble size and increase gas holdup in flotation systems (Laskowski et al., 2003; Quinn et al., 2007). Quinn et al. (2014) showed that inorganic solutions with an ionic strength of approximately 0.4 had an average bubble size similar to 8–10 ppm of methyl isobutyl carbinol (MIBC) in water. One flotation concentrator, Glencore's Raglan operation in northern Quebec (Canada), operates without frother due to the high salt content of the process water, which provides adequate bubble size reduction and frothing characteristics (Quinn et al., 2007). However, the interactions between surface active compounds (frothers) and surface-inactive compounds (inorganic salts) are very complex, and not well understood, many flotation circuits operating with saline solutions still employ the use of frothers.

The majority of the research performed on bubble coalescence and breakage has been carried out in independent frother (Cho and Laskowski, 2002a; Chu et al., 2016; Grau et al., 2005; Nesset et al., 2006) or inorganic electrolyte solutions (Craig et al., 1993; Lessard and Zieminski, 1971; Marrucci and Nicodemo, 1967; Quinn et al., 2014). The mechanism of bubble coalescence in strictly frother solutions has been extensively studied and discussed (Cho and Laskowski, 2002b; Finch et al., 2008), although a comprehensive understanding has still not been reached. It is well accepted that coalescence of bubbles can be fully inhibited at frother concentration exceeding a particular concentration, referred to as the critical coalescence concentration (CCC) (Cho and Laskowski, 2002a; Grau et al., 2005). Sovechles and Waters (2015) extended the concept of the CCC point to cover the effect of different inorganic electrolytes on the size of bubbles in a lab-scale mechanical flotation cell. It was concluded that, over a range

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of coalescence inhibiting salts (commonly found in flotation circuits), the ionic strength of the solution determines its effect on the average bubble size. This was shown to hold true for single electrolyte solutions and mixtures.

Castro et al. (2013) studied the effects of various frother and inorganic electrolyte mixtures on the size of bubbles. They concluded that the addition of frothers (MIBC and DF-250) to NaCl solutions had no further reducing effect on bubble size. Instead, bubble size increased with a small addition of frother (~10 ppm), and then decreased back to the original value with further frother addition. However, when the frothers were added to a seawater solution the bubble generation/coalescence mechanisms produced finer bubbles. This demonstrates the complex interactions between electrolytes and frothers in solution, and validates the need for further research in this field.

The purpose of this work was to study the effects of air flow rate and impeller speed, being the two main operating variables in mechanical flotation cells, on bubble size in frother-electrolyte solutions. For these tests, two industrial frothers (MIBC and Dowfroth 250) were used at various concentrations in the presence of either a sodium chloride or synthetic sea salt solution. Following this, the effect of salt type on bubble size in various frother concentrations was investigated through the development of CCC curves for a range of salt combinations (NaCl, NaCl + $MgSO_4$, NaCl + $MgCl_2$, NaCl + $CaSO_4$, NaCl + KCl and sea salt).

2. Experimental

2.1. Materials and test conditions

Throughout the test work, two frothers (MIBC and DF-250), five salt types (NaCl, KCl, $MgSO_4$, $CaSO_4$, $MgCl_2$) and a synthetic sea salt solution were tested. The MIBC was sourced from Sigma Aldrich (USA), as 4-Methyl-2-pentanol, at a purity of 98%; industrial grade Dowfroth 250 (DF-250) was sourced directly from the manufacturer: Nasaco International LLC (USA). The sodium chloride (ACS grade), potassium chloride (>99%), and magnesium chloride hexahydrate (>98%) were all sourced from Fisher Scientific (USA). Both the magnesium sulphate (>99.5%) and calcium sulphate dehydrate (>99%) were sourced from Sigma-Aldrich (USA). The choice of synthetic sea salt was based upon a study conducted by Atkinson and Bingman (1998). They found, after an analysis of eight commercially available synthetic sea salt mixtures, that the Instant Ocean Aquarium Sea Salt Mixture (Instant Ocean, USA) was a suitable replacement for seawater. Inductively coupled plasma mass spectrometry was also conducted on three samples of the Instant Ocean sea salt, with the coefficient of variation for the major cations tested varying between 1.0% and 6.8%. The sea salt solution (equivalent ion composition to natural seawater) was produced following the manufactures guidelines: 35.9 g of sea salt per kilogram of deionised water.

Table 2
Salt combinations tested.

Salt type and concentration
0.5 M NaCl
0.5 M NaCl + 0.053 M $MgSO_4$
0.5 M NaCl + 0.053 M $MgCl_2$
0.5 M NaCl + 0.013 M $CaSO_4$
0.5 M NaCl + 0.05 M KCl
Sea salt solution

The conditions tested for the varying impeller speed and gas flow rate experiments are outlined in Table 1. Both frothers were added at five and ten parts per million (ppm) to the base electrolyte solutions. Impeller speeds were tested at an interval of 200 RPM, from 800 to 1600 RPM at a constant superficial gas velocity (J_g) of 0.25 cm s^{-1}. The air flow rates were controlled to give a constant increase in J_g of 0.25 cm s^{-1} over the range tested (0.25–1.50 cm s^{-1}), at a constant impeller speed of 1600 RPM. These conditions were chosen after a preliminary study was performed to determine under which conditions boiling occurred in the cell, due to its relatively small volume.

Following this an impeller speed of 1200 RPM and a J_g of 1.00 cm s^{-1} was chosen for the development of the CCC curves, completed over a range of 0–50 ppm MIBC, for the salt combinations listed in Table 2.

2.2. Apparatus

The two phase (solution-air) experiments were conducted using a Denver D-12 laboratory-scale mechanical flotation machine (Serial: TCS-1101-3, Size: D-1 FLOT) equipped with a 5.5 L (active volume) cell (Fig. 1). The entire experimental set-up is shown in Fig. 2. De-ionised (DI) water, which had been allowed sufficient time to reach room temperature (18–22 °C), was used to make

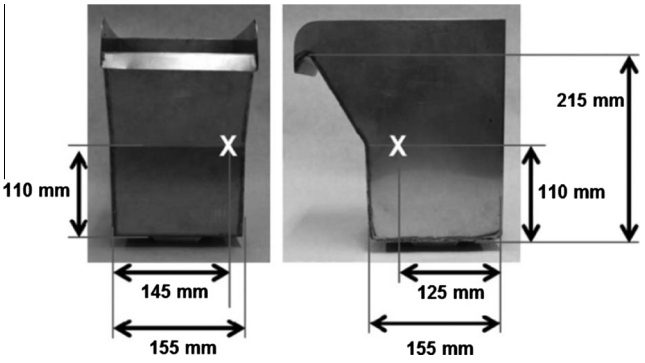

Fig. 1. Dimensions of 5.5 L flotation cell and sample location, indicated by X. Reproduced with permission from Sovechles and Waters (2015).

Table 1
Summary of test conditions.

Test number	Electrolyte solution	Frother addition	Impeller speed range (RPM)	Superficial gas velocity range (cm/s)
1	0.54 M NaCl	None	800–1600	0.25–1.50
2	0.54 M NaCl	5 ppm MIBC	800–1600	0.25–1.50
3	0.54 M NaCl	10 ppm MIBC	800–1600	0.25–1.50
4	0.54 M NaCl	5 ppm DF-250	800–1600	0.25–1.50
5	0.54 M NaCl	10 ppm DF-250	800–1600	0.25–1.50
6	Sea salt	None	800–1600	0.25–1.50
7	Sea salt	5 ppm MIBC	800–1600	0.25–1.50
8	Sea salt	10 ppm MIBC	800–1600	0.25–1.50
9	Sea salt	5 ppm DF-250	800–1600	0.25–1.50
10	Sea salt	10 ppm DF-250	800–1600	0.25–1.50

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