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Critical coalescence concentration of inorganic salt solutions

J.J. Quinn *, J.M. Sovechles, J.A. Finch, K.E. Waters

Department of Mining and Materials Engineering, McGill University, 3610 University Street, Montreal, QC H3A 0C5, Canada

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ABSTRACT

Critical coalescence concentration (CCC) was determined in a laboratory-scale mechanical flotation cell for a series of coalescence inhibiting inorganic salts (KCl, NaCl, Na_2SO_4, $CaCl_2$ and $MgSO_4$) compared to two commercial frothers (methyl isobutyl carbinol, Dowfroth 250C). The salt CCC values ranged from 0.07 M ($MgSO_4$) to 0.31 M (KCl and NaCl) and correlated with ionic strength. The CCC values are compared to transition concentrations in the literature. The effect of salts on gas dispersion in flotation systems is discussed.

1. Introduction

Certain inorganic salts in flotation systems have been shown to inhibit bubble coalescence which helps explain decreased bubble size in the pulp phase (Foulk and Miller, 1931; Marrucci and Nicodemo, 1967; Lessard and Zieminski, 1971; Kim et al., 1990; Craig et al., 1993; Cho and Laskowski, 2002a,b; Quinn et al., 2007). Salts are not added to achieve bubble size reduction as high concentrations (0.02–0.8 M) are required (Craig et al., 1993; Zahradnik et al., 1999) but they may be present naturally due to the water source.

Marrucci and Nicodemo (1967) measured bubble size for various inorganic salt solutions in a laboratory-scale column with bubbles produced at a porous plate. Average bubble diameter decreased with increasing salt concentration until a stable minimum was reached. The concentration at which the minimum was reached was specific to salt type. Salts containing polyvalent ions tended to decrease bubble size at lower molar concentrations.

A common measure of the effect of inorganic salts on bubble coalescence is the transition concentration (TC). There is, however, no consistent definition. Using data from Marrucci and Nicodemo (1967) and Prince and Blanch (1990) determined transition concentration as the concentration at which minimum bubble size was reached (termed for discussion purposes TC100, i.e., 100% coalescence inhibition). Lessard and Zieminski (1971), Zahradnik et al. (1999) and Christenson et al. (2008) contacted bubbles at adjacent capillaries and determined a transition concentration at which 50% of the contacted bubbles coalesced (termed TC50). Craig et al. (1993) determined the TC for a range of inorganic salts using a bubble swarm produced at a glass sinter. A laser beam was passed through the swarm and a detector measured the transmission. Transition concentration was determined when transmission was 50% of the range from water only (assumed 100% coalescence) to the concentration giving minimum transmission (assumed complete coalescence inhibition).

The studies recognized that some inorganic salts inhibit coalescence and others do not and rules were established to predict the behavior (Craig et al., 1993). For coalescence inhibiting salts the TC is lower for multi-valent ions than for mono-valent ions and correlations have been found between solution ionic strength and bubble size (Zieminski and Whittemore, 1971; Keitel and Onken, 1982) and a measure related to bubble size, gas holdup (Quinn et al., 2007; Alexander et al., 2012). It should be noted that certain 1–1 (cation–anion charge) salts (e.g., $NaClO_4$, KI, KNO_3) show extremely weak coalescence inhibition (Marrucci and Nicodemo, 1967; Christenson et al., 2008) and do not follow the ionic strength rule.

The usual method of reducing bubble size in flotation systems is through addition of frother. To characterize frothers the concept of critical coalescence concentration (CCC) proposed by Cho and Laskowski (2002a,b) is becoming the accepted metric. From the measured bubble size distribution the Sauter mean diameter is calculated (D_{32}) and plotted as a function of frother concentration (D_{32}-C). The D_{32}-C curve is characterized by a sharp initial decrease in D_{32} which levels off to reach a minimum which defines the CCC, the concentration at which coalescence is considered fully retarded. The CCC concept is similar to the TC100.

Cho and Laskowski (2002a) used a graphical method to estimate the CCC. Nesset et al. (2007) suggested fitting the D_{32}-C data to the following 3-parameter model:

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* Corresponding author. Tel.: +1 (514) 398 4755x09503; fax: +1 (514) 398 4492.
E-mail address: jarrett.quinn@mail.mcgill.ca (J.J. Quinn).

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$$D_{32} = D_l + A\exp[-B * C] \tag{1}$$

where D_l is the limiting D_{32} as concentration $\rightarrow\infty$, A is the difference between D_l and D_{32} in water (no solute present), B is the decay constant, and C solute concentration. The model allows for calculation of CCCX, the concentration at which D_{32} is reduced by X% from that in water to the D_l:

$$CCCX = -\frac{\ln(1-X)}{B}. \tag{2}$$

As the measure of CCC, Nesset et al. used CCC95. The CCC has been determined for many commercial frothers (Cho and Laskowski, 2002a,b; Grau et al., 2005; Nesset et al., 2007) and surfactants from frother families (Zhang et al., 2012).

The CCC concept can be transferred to inorganic salts as the same general shape of the D_{32}-C curve is observed (Castro et al., 2012b). Using a bubble column, Castro et al. (2012b) determined the CCC for NaCl to be 0.778 M, which appears to be the only salt CCC value in the literature. The purpose of this paper is to determine the CCC for a series of salts commonly encountered in flotation systems, and following previous work on gas holdup (Quinn et al., 2007; Alexander et al., 2012), determine if there is dependence on ionic strength. To verify the technique two frothers for which there is literature CCC data (methyl isobutyl carbinol (MIBC) and Dowfroth 250C (DF250)) were also analyzed.

2. Experimental part

2.1. Apparatus

The experimental set-up is shown in Fig. 1. Two-phase (solution-air) tests were undertaken using a Denver laboratory-scale mechanical flotation machine (Denver, SN: TCS-1101-3, Size: D-1 FLOT) equipped with a 5.5 L (active volume) cell (Fig. 2). All tests were performed at room temperature (18–22 °C) using de-ionized (DI) water. The solution level was maintained at the overflow throughout the experiment. The impeller was operated at 1200 rpm and the air flow rate was maintained at 4.32 L/min (equivalent to a superficial gas velocity of 0.3 cm/s at X, Fig. 2) using a Matheson Gas Products 604 flow meter. The McGill bubble viewer (Fig. 1) was used to sample bubbles from the solution phase at X. Bubbles rose through a 1.6 cm inner diameter by ca. 90 cm long sampling tube into the viewing chamber (24 cm (diameter) × 14 cm (depth)) filled with test solution. The viewing chamber was back-lit using an arrangement of light emitting diodes (Phlox, model LLUB-QIR-24 V) covering an area of 10 cm × 10 cm. In the viewing chamber, bubbles contact the inclined (15°) window and spread into a near monolayer (Gomez and Finch, 2002, 2007). Images of the bubbles sliding up the inclined window were taken using a Canon EOS 60D camera (equipped with a Canon EF 100 mm 1:1.28 USM macrolens) at a rate of 1 frames per second. Typical image resolution was 150 pixels/mm. Image size was ca. 35 mm (l) × 23 mm (h). A minimum of 2500 bubbles (typically 10,000 bubbles) were measured for each condition tested.

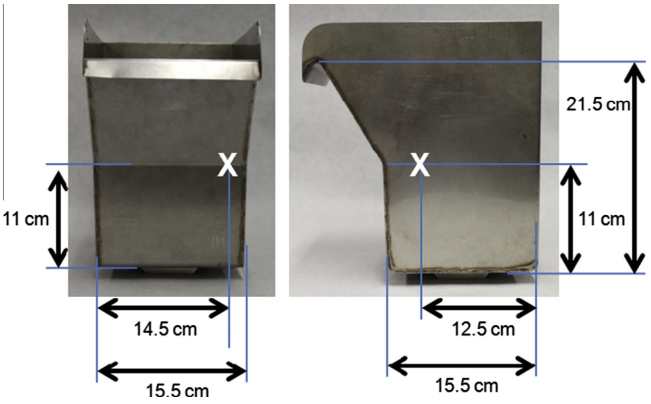

Fig. 2. Dimensions of flotation cell (X indicates bubble sample location).

2.2. Reagents

Table 1 summarizes the chemicals used and Table 2 gives some TC and CCC data. A minimum of ten concentrations were tested for each solute sufficient to define the D_{32}-C curve to fit the 3-parameter model (Eq. (1)). Concentrations were chosen based on literature data to straddle the CCC and TC values. Three replicate tests were performed for NaCl and MIBC to determine reproducibility.

2.3. Bubble sizing – image analysis

An automated image analysis procedure using ImageJ software was utilized to determine the bubble size distribution. The software tabulated projected bubble area, A_p, which was used to

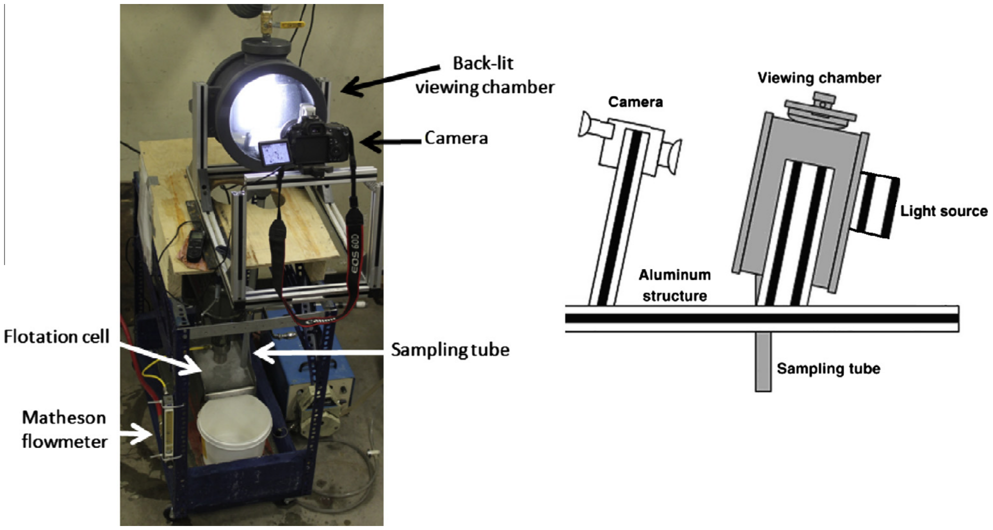

Fig. 1. Bubble viewer in operation (left) and a schematic of the bubble viewer (right).