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Experimental study on the shape–velocity relationship of an ellipsoidal bubble in inorganic salt solutions

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ABSTRACT

Individual bubbles ca. 2.3 mm in diameter were produced at a capillary in water containing an inorganic salt ($NaClO_4$, KCl, NaCl, Na_2SO_4, or $CaCl_2$). Using high speed photography and image analysis techniques, bubble aspect ratio and rise velocity were measured at 1 ms time intervals over a distance ca. 1.15–1.20 m above the capillary. All conditions showed oscillations in bubble aspect ratio and velocity that were related. Increasing concentration, on average, created more spherical bubbles that rose at lower velocities. The same observations were made in the presence of MIBC frother. Results suggest a unique relationship between bubble shape and rise velocity independent of solute type. The effect of inorganic salts on bubble behavior and gas dispersion in flotation systems is discussed.

1. Introduction

Froth flotation and gas dispersion in saline solutions has garnered increased attention in recent years (Craig, 2011; Alexander et al., 2012; Castro, 2012; Wang and Peng, 2013). The scarcity of fresh water especially in remote mining locales has forced several plants to recycle process water (which typically concentrates contaminants) or to use saline bore or sea water. The presence of certain soluble inorganic ions has been shown to decrease bubble size and increase gas holdup in flotation systems (Laskowski et al., 2003; Nesset et al., 2006). Quinn et al. (2007) showed that inorganic solutions with ionic strength ca. 0.4 gave similar gas holdup to 8–10 ppm MIBC frother in water. One flotation concentrator, Xstrata's Raglan operation in northern Quebec, operates without frother due to the high salt content of the process water which provides adequate bubble size reduction and frothing characteristics. Several authors have investigated the effect of saline process water on flotation performance (Yoon and Sabey, 1989; Pugh et al., 1997; Castro, 2012).

Frother is typically added to flotation circuits with one function being the reduction of bubble rise velocity (Klimpel and Isherwood, 1991). The ability of surfactants (frothers) to lower single bubble rise velocity is well documented (Fuerstenau and Wayman, 1958; Sam et al., 1996; Bozzano and Dente, 2001; Krzan and Malysa, 2002a,b; Finch et al., 2008). The stagnant cap model describes how surfactant molecules on the bubble surface are swept to the rear of a rising bubble creating surface tension gradients which increase drag and thus retard bubble rise (Savic, 1953; Dukhin et al., 1998). A similar mechanism seems to control bubble shape, surface tension gradients resisting deformation (Dukhin et al., 1998; Finch et al., 2008). In comparison, the mechanism(s) by which inorganic salts act to modify shape and velocity of rising bubbles is not clear although surface tension gradients may be at play as most inorganic salts slightly increase surface tension.

Much of the literature concerning bubble dispersions in inorganic salt solutions discusses their ability to inhibit bubble coalescence (Lessard and Zieminski, 1971; Craig et al., 1993; Craig, 2011). All inorganic salts tested here retard coalescence and encompass a range of coalescence inhibiting strength, ranking as follows: $NaClO_4 < KCl < NaCl < Na_2SO_4 < CaCl_2$ (Lessard and Zieminski, 1971; Zieminski and Whittemore, 1971; Craig et al., 1993; Zahradnik et al., 1999; Christenson et al., 2008).

Much of the data on bubble rise velocity in inorganic salt solutions comes from oceanography and typically focuses on bubble diameters below 1 mm in sea water or sodium chloride solutions (Detsch and Harris, 1989; Detsch, 1991; Henry et al., 2008). Bubble sizes below roughly 1 mm diameter are spherical and show little effect of contaminants on shape or velocity (Clift et al., 2005). The present work uses bubbles ca. 2.3 mm sphere-volume equivalent diameter which lie in the ellipsoidal shape regime where surface tension forces are dominant (Bhaga and Weber, 1981; Clift et al., 2005). This size was chosen as bubble shape and velocity are sensitive to the presence of contaminants (Clift et al., 2005).

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The bubble size is within the range encountered in flotation systems (Nesset et al., 2006). Tomiyama et al. (2002) noted that bubble behavior in the ellipsoidal regime was not well understood and that no theoretical models for terminal velocity existed.

Researchers have found that bubble shape and velocity strongly interact in surfactant, polymer and inorganic salt solutions both close to and far from bubble generation (Bozzano and Dente, 2001; Tomiyama et al., 2002; Kracht and Finch, 2010). Gomez et al. (2010) reported a unique relationship between bubble shape and velocity for a given bubble volume independent of surfactant (frother) type or polymer. Maldonado et al. (2013) tested bubbles in polymer, frother and two inorganic salt solutions and also showed a unique dependence between bubble shape and velocity independent of solute type. The researchers found that for ca. 2.5 mm bubbles in water, aspect ratio was ca. 0.57 and rise velocity was ca. 28 cm/s while in concentrated solutions (frother, polymer or salt), aspect ratio increased to ca. 0.95 and rise velocity decreased to ca. 17 cm/s.

It has been demonstrated that the nature of bubble formation (release) affects bubble shape, velocity and motion (Wu and Gharib, 2002; Tomiyama et al., 2002; Peters and Els, 2012). Tomiyama et al. (2002) observed that bubbles released with small initial shape deformation resulted in more spherical bubbles (high aspect ratio) with low terminal velocities compared with bubbles with large initial shape deformation which resulted in oblate bubbles (low aspect ratio) with high terminal velocities. Tomiyama et al. (2002) noted the presence of surfactant acted to damp initial shape deformation.

The present work aims to build upon the work of Gomez et al. (2010) and Maldonado et al. (2013) and test the bubble shape – rise velocity relationship in a series of inorganic salt solutions ($NaClO_4$, KCl, NaCl, Na_2SO_4, $CaCl_2$). The results are compared to MIBC, a typical flotation frother. The inorganic salts tested were chosen based on ions which are typically present in flotation concentrator process water (Alexander et al., 2012) and to encompass a range of bubble coalescence inhibiting behavior. For the bubble size used (ca. 2.3 mm) the Reynolds numbers range from ca. 280–670 and Eötvös numbers range from ca. 0.65–0.85, showing bubbles to be in the ellipsoidal shape regime (Bhaga and Weber, 1981; Clift et al., 2005).

2. Experimental

2.1. Setup and image collection

The experimental setup is shown in Fig. 1. Individual air bubbles were created at a glass capillary orifice (406 ± 25 μm inner diameter) in the various test solutions (Table 1). All inorganic salts were supplied by Fisher Scientific and were ACS grade. The MIBC sample was supplied by Sigma Aldrich and was GC grade. Bubble generation frequency was controlled at 5 s using a high-precision pressure regulator (Fairchild, model M4100A, 0–5 psi). The aim was to form bubbles under constant release conditions to restrict effects of release on initial shape. Bubble formation time was 71 ms ± 2 ms (95% confidence interval, CI). The pressure regulator was connected to the capillary via coiled tubing with inner diameter 200 μm. After detachment, the bubble rose through a 1 m vertical clear PVC pipe (0.025 m diameter) to a rectangular viewing chamber (height 0.60 m, width 0.22 m, depth 0.14 m). Liquid level was maintained at 1.35 m above the capillary. The viewing chamber was back-lit using an arrangement of light emitting diodes (Phlox, model LLUB-QIR-24V) covering an area of 0.10 × 0.10 m. Images were collected of bubbles rising between a height of ca. 1.15 m to 1.20 m above the capillary.

A Fastec Imaging (model No. HiSpec5 8G Mono) high-speed camera equipped with a Nikon–AF Micro Nikkor 60 mm 1:2.8 D lens was used to capture images at 1000 frames per second (fps). Typical images were 800 × 1710 pixels. The magnification was chosen to ensure horizontal bubble diameters comprised a minimum of 80 pixels with a typical image resolution 35 pixels/mm. The viewing area was ca. 0.023 m (horizontal) × 0.049 mm (vertical). Image sequences of ten bubbles were collected and analyzed for each condition. Image sequences consisted of 180–300 images depending on the bubble rise velocity.

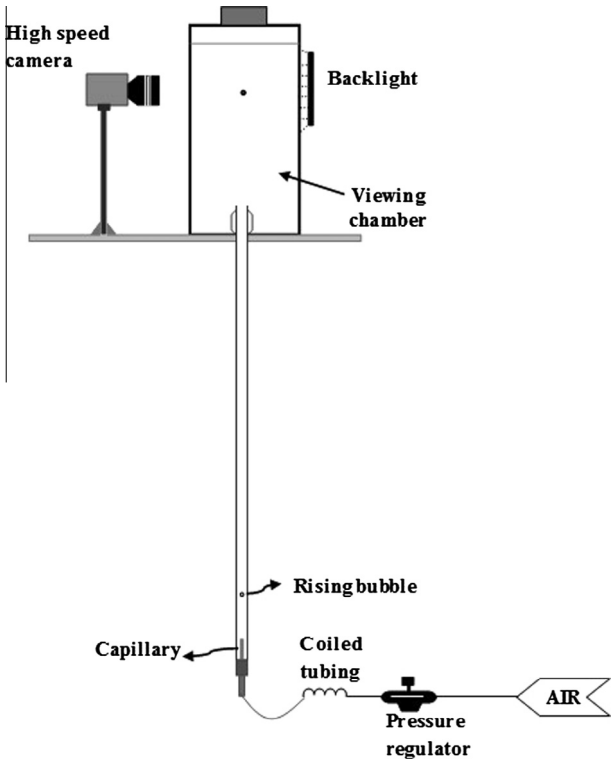

Fig. 1. Experimental Setup.

Table 1
Reagents and concentration range.

Inorganic salt	Concentration (M)
$NaClO_4 \cdot H_2O$	0.01–2.0
KCl	0.0125–1.0
NaCl	0.01–1.0
Na_2SO_4 (anhydrous)	0.01–1.0
$CaCl_2 \cdot 2H_2O$	0.005–1.0
Frother	**Concentration, ppm (mg/l)**
MIBC (4-methyl-2-pentanol)	1–100

2.2. Image analysis

Image sequences were analyzed off-line using ImageJ software and a macro which automatically calculated and tabulated: (1) bubble size, (2) bubble aspect ratio and (3) bubble velocity. These parameters were tracked at intervals of 1 ms.

(1) *Bubble size*

The sphere-volume equivalent diameter (d_e) was calculated using the major (a) and minor (b) semi-axes of an ellipse fitted to the projected bubble area (Eq. (1)), assuming the bubble to be an oblate spheroid (i.e., symmetric about the minor axis):