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Passive acoustic emission monitoring to detect bubble coalescence in the presence of solid particles

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ABSTRACT

Passive acoustic emission monitoring was used to study the role of solid particles on bubble coalescence. The effect of 1–10% w/w talc (hydrophobic) or silica (hydrophilic) particles on air bubble formation and coalescence at a capillary in the presence of MIBC or sodium chloride was determined. Both solids slightly inhibited bubble coalescence while silica created a larger region of partial coalescence compared to talc. At 10% w/w the silica particles appeared to promote coalescence at high MIBC concentration.

1. Introduction

Optical techniques are typically used to investigate the action of solutes in retarding bubble coalescence in air/water systems (Hofmeier et al., 1995; Zahradnik et al., 1999; Cho and Laskowski, 2002a,b; Tse et al., 2003). To be closer to flotation conditions solid particles should be present. Slurries render systems opaque which means direct visual techniques cannot be used. This introduces the idea of acoustic monitoring.

Passive acoustic emission monitoring (PAEM) has been used on a variety of unit operations and processes in the minerals industry: crushing and grinding (Zeng and Forssberg, 1993), hydrocycloning (Hou et al., 1998), bubble formation (Kracht and Finch, 2009), flotation machines (Spencer et al., 2010), and frothing (Vanegas and Holtham, 2008). The reliability, non-intrusive nature, low cost and the capability of real-time continuous measurement make acoustics an attractive tool for monitoring and control (Boyd and Varley, 2001; Vanegas and Holtham, 2010).

In his classic book ‘The Flotation Process’, Rickard (1916) noted “the noise made by the bursting bubble suggests the fact that it is a receptacle of energy.” The first systematic study of sound production upon bubble formation was undertaken by Minnaert (1933) and was entitled “On musical air-bubbles and the sounds of running water”. He introduced an energy balance which related the sound frequency produced (commonly termed the Minnaert frequency), ν, and the equilibrium bubble diameter, d_b:

$$\nu = \frac{1}{\pi d_b}\left[\frac{3\kappa p^{\circ}}{\rho}\right] \quad (1)$$

where κ is the ratio of specific heats of the gas phase, ρ the liquid density and p° the hydrostatic pressure. A range of bubble sizes and gas types were fit by the equation.

Strasberg (1956) noted that when bubbles split or coalesce, a decaying sinusoidal pulse of sound is emitted, just as in bubble formation. Deane and Czerski (2008) demonstrated that sound was excited by the rapid decrease in volume accompanying the collapse of the bubble neck upon detachment. Manasseh et al. (2008) studied initial bubble deformation upon release from a nozzle using high-speed photography to understand the physical mechanisms generating sound. After bubble release (bubble neck breaking) a liquid jet was shown to enter the bubble corresponding to increased pressure within the bubble.

Leighton et al. (1991) used high-speed photography to observe air bubble behaviour in water at a 0.5 mm internal diameter nozzle. An individual bubble released from the orifice produced a single decaying sinusoidal acoustic signal. At higher gas rates (0.1–5 ml s^{-1}) coalescence occurred in proximity to the nozzle resulting in a characteristic acoustic signal: initial bubble detachment resulted in a decaying sinusoid with subsequent peaks in the acoustic signal relating to each coalescence event (which created a larger bubble which emitted a lower frequency signal). The

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authors noted that bubble shape oscillations could promote coalescence.

Using a stroboscope and digital video camera Hofmeier et al. (1995) observed bubble formation at a capillary and frit in various solutions (including sodium chloride). Similar to Leighton et al. (1991), Hofmeier et al. noted bubble regimes which were flow rate dependent: (1) At low gas flow rates bubbles were released individually and anti-coalescence agents (some surfactants and inorganic salts) had little effect on bubble generation; and (2) At intermediate gas rate bubbles interacted close to the orifice with the initial bubble either bouncing off or coalescing with the subsequently produced bubble(s). In pure liquids, bubbles were more likely to coalesce and create larger bubbles. In systems containing certain surfactants or inorganic salts, bubbles were more likely to bounce.

The presence of flotation frother surfactants or certain inorganic salts have been shown to inhibit bubble coalescence (Lessard and Zieminski, 1971; Zahradnik et al., 1999; Cho and Laskowski, 2002a,b). The mechanism in the case of surfactants has been attributed to surface tension gradients stabilizing thin liquid surface films against drainage through the Gibbs elasticity and the Marangoni effects (Dukhin et al., 1998; Finch et al., 2008). Inorganic salts (at relatively high concentrations) may act in a similar manner as surface tension gradients can be generated (Quinn et al., 2013, 2014).

The effect of solid particles on bubble coalescence has attracted attention but mainly related to properties of the froth phase (Pugh, 1996; Ata et al., 2004; Pugh, 2005; Ata, 2012). While potentially of some relevance to bubble formation, the role of solids in the froth phase is likely different to that in the pulp phase (Ata, 2012). Hydrophobic particles have been shown to stabilize or destabilize the froth depending on concentration, size and shape (Dippenaar, 1982; Garrett, 1993; Pugh, 1996; Ata, 2012). Pugh (2007) noted that increasing water contact angle (increasing hydrophobicity) initially tended to increase froth stability (decrease bubble calescence) but highly hydrophobic particles could destabilize the froth by promoting coalescence probably due to bubble bridging by the hydrophobic particle. With hydrophilic particles any bridging could have the opposite effect and cause liquid retention in the film thus delaying coalescence (Ip et al., 1999; Pugh, 2007; Ata, 2008).

Several techniques have been used to quantify the effect of solutes on bubble coalescence with no solid particles present. The contacting of bubble pairs at adjacent capillaries has been widely used (Lessard and Zieminski, 1971; Zahradnik et al., 1999; Christenson et al., 2008). Contacting mineralized bubbles (bubbles covered by hydrophobic particles) showed increased resistance to coalescence (Ata, 2008; Gallegos-Acevedo et al., 2010). One study measuring bubble size as a function of frother concentration with and without solid particles, talc and silica, found no effect (Zhang et al., 2012), and the close comparison between bubble size data from two-phase tests and from flotation systems suggests little effect of solid particles (Finch et al., 2008). Others have noted increased bubble size in flotation systems (i.e., in presence of frother) at increasing solids concentration (O'Connor et al., 1990; Tucker et al., 1994; Grau and Heiskanen, 2005). The effect may be related to slurry viscosity allowing bubbles to linger in proximity to the gas dispersing device which could promote bubble coalescence. The presence of solid particles may adsorb some frothers (Kulkarni et al., 1977; Kuan and Finch, 2010) and cause bubbles to coalesce, but this is an indirect effect of solids. Ojima et al. (2014) attributed a decrease in gas holdup observed in a bubble column in the presence of 100 μm silica (hydrophilic) particles to increased bubble coalescence creating larger, faster rising bubbles. They suggested that high concentrations of hydrophilic particles in the thin liquid film could destabilize it due to particle motion and result in rupture.

Kracht and Finch (2009) used high speed photography and acoustic emission monitoring to determine the transition gas flow rate at which the bubble regime changed from non-coalescing to coalescing (termed coalescence plots) at a 200 μm diameter capillary. The characteristic acoustic signal upon coalescence (as described by Leighton et al., 1991) was used to determine the onset of coalescence as air flow rate was increased. Example coalescence plots are given in Fig. 1 for MIBC and sodium chloride which show the transition gas flow rate between non-coalescence and coalescence. For NaCl the presence of a partial coalescence region is seen (i.e., not all bubble-bubble interactions resulted in coalescence). Comparison of the plots (not shown) gave a ranking of frother 'strength' in terms of coalescence prevention, the stronger frother requiring a higher transition gas rate for the onset of coalescence.

Recently, Kracht and Rebolledo (2013) used the acoustic technique to test 1-alcohols, commercial frothers, and inorganic salts. The concept of a local critical coalescence concentration (*l*-CCC) curve was developed to compare the coalescence prevention strength of the solutes. Similar to the work of Kracht and Finch (2009) (for NaCl), the authors found that certain inorganic salts (NaCl, KCl, and $CaCl_2$) showed the partial coalescence regime.

The present paper extends the work of Kracht and Finch (2009) to determine the effect of hydrophobic and hydrophilic solid particles on the transition between bubble regimes at a capillary using passive acoustic emission monitoring.

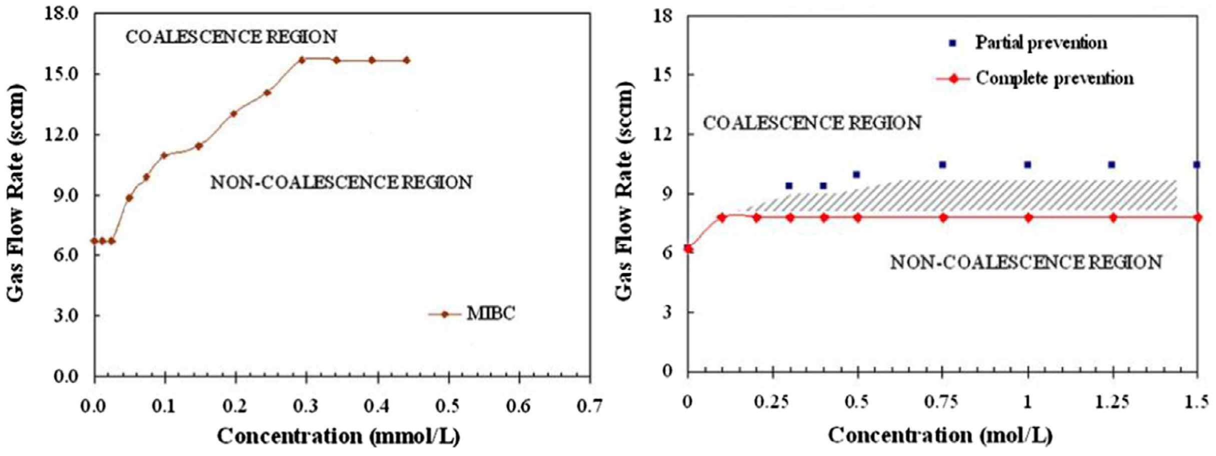

Fig. 1. Coalescence plots for MIBC (left) and sodium chloride (right) (adapted from Kracht and Finch, 2009).