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Break-up in formation of small bubbles: Comparison between low and high frother concentrations

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ABSTRACT

Frothers are widely used in flotation to help generate small bubbles, with coalescence prevention generally considered the predominant mechanism. However, recent studies have demonstrated that the presence of frothers also reduces the size of bubbles at the initial formation stage. One possible explanation is that frothers introduce a surface tension gradient-driven stress, which increases instabilities along the air/water interface: increasing the number of instabilities along the surface of a finite-volume air mass means that more small bubbles will break away. The magnitude of surface tension gradient, and thus number of instabilities, is related to frother concentration. This paper investigates the effect of increasing frother concentration on the size of bubble formed. The hypothesis tested is that while low concentration may sustain gradients, at high concentration mass transfer may be sufficient to damp them. The finding is that with an increase in frother concentration the bubble size initially decreased to a minimum then increased supporting the hypothesis.

1. Introduction

Frothers in flotation help reduce bubble size. The concentrations required are remarkably small, just are a few ppm, that is, a few grams per tonne of water (Wills and Finch, 2016). However, the controlling mechanism is not well understood (Finch et al., 2008). The action of frother is often ascribed to surface tension reduction (Gupta and Yan, 2006), but experiments do not support such a connection, at least with the equilibrium (or static) surface tension (Aldrich and Feng, 2000; Grau and Laskowski, 2006; Machon et al., 1997; Sweet et al., 1997).

Generation of bubbles in a flotation machine is the result of two complementary mechanisms, namely, break-up and coalescence. Most literature on the role of frother is based on coalescence inhibition (Harris, 1976; Laskowski, 2003). Cho and Laskowski (2002) introduced the term "critical coalescence concentration" (CCC) to describe the concentration when minimum bubble size in a swarm is reached. Table 1 lists the CCC95 (*i.e.*, the concentration giving 95% reduction in bubble size relative to water alone) of some frothers under typical flotation conditions, confirming the low concentration required.

Experiments, such as bringing two bubbles together, have confirmed the role of frother in coalescence prevention (*e.g.*, Bournival et al., 2014). There are occasional references that the frother also acts to promote break-up (Acuña et al., 2007; Finch et al., 2006; Grau and Laskowski, 2006). Kracht and Finch (2009) investigated the effect of frother on break-up by exposing mono-sized bubbles to a turbulent field generated by an impeller. They observed that frother not only reduced coalescence but also promoted break-up, noting that the fraction of bubbles within 90% of the original volume increased. Javor et al. (2013) adopted the same technique and tested the effect of frother with different chain lengths. Their conclusion was that with the long chain frothers the minimum bubble size on break-up is smaller than with the short chain frothers.

Coalescence and break-up generally take place simultaneously. To eliminate the impact of the former, Chu and Finch (2013, 2014) developed an experimental setup and procedure to mimic single bubble formation at the break-up stage. The results revealed that the presence of frother produces smaller bubble sizes compared to water alone. They proposed an explanation based on the Marangoni effect, that frothers introduce a surface tension gradient-driven stress, which increases instabilities along the air/water interface: increasing the number of instabilities along the surface of a finite volume of air means that more small bubbles will break off. The development of surface tension gradients assumes that the bulk frother concentration is not sufficient to restore concentration uniformity at the air/water interface over the time involved in the break-up process. The corollary is that sufficient frother concentration may damp surface tension gradients, and their contribution to bubble formation be lost.

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Table 1
CCC95 of typical frothers adapted from Nesset et al. (2007).

Frother	Formula	CCC95 (ppm)	CCC95 (mM)
MIBC	$(CH_3)_2CHCH_2CH(OH)CH_3$	10.4	0.102
DF250[a]	$CH_3(PO)_4OH$	8.4	0.032
F150[a]	$H(PO)_7OH$	3.7	0.0087

[a] PO is propylene oxide (propoxy) [$—O—CH_2—CH_2—CH_2—$].

Table 2
Frothers tested.

Name	Formula	Molecular weight (g/mol)	Supplier
MIBC	$(CH_3)_2CHCH_2CH(OH)CH_3$	102.18	Sigma-Aldrich
Dowfroth 250[a]	$CH_3(PO)_4OH$	264.35	Sigma-Aldrich
F150	$H(PO)_7OH$	425	Flottec
F160-13	Polyethylene and polypropylene ethers	250	Flottec

[a] PO is propylene oxide (propoxy) [$—O—CH_2—CH_2—CH_2—$].

The purpose of this paper is to test the effect of increasing frother concentration on the bubble size formed at break-up. The hypothesis is that there may exist a critical bulk concentration above which surface tension gradients are lost such that the effect of frother on bubble size at break-up diminishes.

2. Experimental

2.1. Setup

The experimental setup adopted is that of Chu and Finch (2013, 2014). Fig. 1a shows the main components: an 800 mL beaker with a custom-made glass spoon to accommodate a known volume of air (the ‘air pocket’); a magnetic stirrer (Corning, PC-420D); and a syringe pump (Fisher Scientific, 78-0100I). The spoon, with an inner diameter of 20 mm, is connected to the syringe pump through a hollow handle and plastic tubing. Fig. 1b shows the initial state of a 2 mL-air pocket.

2.2. Frothers

Table 2 gives the frothers tested. Reverse osmosis (RO) water was used to prepare 4L of frother solution at room temperature (*ca.* 20 °C). At least three separate sets of experiments were conducted on each solution, each consisting of six bubble formation experiments. The apparatus was thoroughly rinsed with hot tap water followed by RO water between each set of the experiments.

2.3. Procedures

The volume of each tested solution was kept constant as 750 mL, and a 1.5 in. magnetic stirrer rotating at 900 RPM provided the agitation. Rotation of the liquid causes a vortex that draws down air from the pocket forming a bulge. With sufficient energy input the bulge breaks away to form a bubble. The bulging and break-away events were recorded with a digital high-speed camera (Fastec Imaging HiSpec5 8G Mono/Color). The image of the newly formed bubble is processed (software ImageJ) to acquire the sphere-volume equivalent diameter (Fig. 2). Using the major (b) and minor (a) semi-axes of an ellipse fitted to the projected bubble area and assuming the bubble is symmetric about the minor axis, the diameter, *d*, is given by:

$$\boldsymbol{d} = \sqrt[3]{(2\boldsymbol{a})^2 \times (2\boldsymbol{b})} \quad (1)$$

3. Results

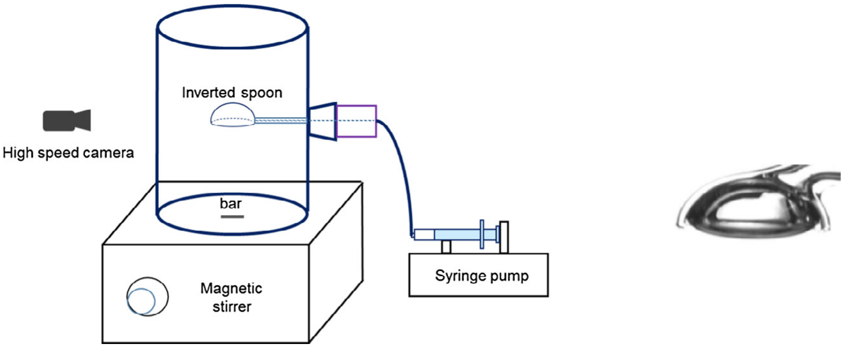
3.1. Visual

A typical bubble formation sequence in RO water is shown in Fig. 3a. It was observed that the induced mechanical energy deforms the air pocket with bubble production following the sequence: formation of bulge, elongation of bulge, and bubble break-away.

Fig. 3b shows an example of bubble formation in the presence of frother. A dosage of only 0.6 ppm (0.006 mM) MIBC noticeably alters the shape of the bulge compared to RO water and produces a finer bubble size. In the presence of frother, bubble formation also seems to occur faster, the bubble appearing by image 4 (Fig. 3b) compared with image 6 (Fig. 3a). (Fig. 3b also shows a second bubble forming but only the first is considered in such cases to avoid possible effects due to subsequent coalescence.)

Fig. 3c shows a sequence of bubble formation with MIBC at increased frother concentration, 2.88 ppm (0.028 mM). At this concentration (*ca.* 380% increase) the bulge formation process becomes similar to that in RO water, and consequently produces a larger size bubble compared with 0.6 ppm MIBC.

Bubble formation generally followed the described three-stage sequence. However, there are occasions where a bubble forms in a different manner. Fig. 4 shows such an example for MIBC solution at 0.006 mM. In this case, the air/water interface is perturbed at a point location, generating a smaller bulge than typical and subsequently a smaller bubble. This phenomenon was only observed



a – Setup b – Initiate state of 2 mL-air pocket

Fig. 1. Apparatus.

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