Colloids and Surfaces A: Physicochem. Eng. Aspects 330 (2008) 112–115

Contents lists available at ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

journal homepage: www.elsevier.com/locate/colsurfa

Measurement of flow visualized on surface of bubble blown in air

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ARTICLE INFO

Article history:
Received 2 April 2008
Received in revised form 15 July 2008
Accepted 17 July 2008
Available online 31 July 2008

Keywords:
Flotation
Frother
Surfactant
Bubble
Marangoni Effect

ABSTRACT

Bubbles blown in surfactant (frother) solution reveal surface flows attributed to gravity drainage and opposing Marangoni Effect. A technique is introduced to visualize the flows and estimate trajectory velocity. The flow pattern and velocity depend on frother type (pentanol vs. a polyglycol) and concentration but no correlation with surface tension was found. The relevance of the observations to the action of frother in flotation is briefly discussed.

1. Introduction

Mineral flotation systems are characterized by the nearly universal addition of surfactants called frothers. These reagents have two principal functions, namely to reduce bubble size and to promote froth stability. Frothers are non-ionic heteropolar (amphipathic) reagents and two classes used commercially are alcohols (e.g. MIBC, methyl isobutyl carbinol, a branched C-6 alcohol) and polyglycols (e.g. Dowfroth 250, $CH_3(PO)_4OH$, where PO is propylene oxide). Due to their amphipathic nature, frother molecules adsorb at the air–water interface oriented with the polar (hydrophilic) group to the water side and the non-polar (hydrophobic) group (hydrocarbon chain) to the air side. As surfactants, frothers reduce surface tension, although the magnitude at industrial doses is small [1]. In the case of froth stabilization frothers act by retarding coalescence, apparently through a combination of surface viscosity [2,3] and surface elasticity effects [4,5]. Their action in the case of bubble size reduction is less clear. Prevention of coalescence is the common explanation [6,7] and a mechanism based on this hypothesis has been suggested [8]. Recent literature has entertained that frothers may act to promote bubble break-up [9,10].

Basic studies continue to try to resolve mechanisms. One investigation was into the properties of thin films on air bubbles blown in frother solutions [11]. The study calculated film thickness as a function of frother type which later was shown to vary in the same manner as the volume of water transported by bubbles, a key factor in modeling flotation systems, and formed the basis of the hypothesis on coalescence prevention in bubble size control [8]. The work revealed a surface in constant motion and displaying varying colours. Sarma and Chattopadhyay [12] consider the motion is induced by variations in surface tension: as the film drains by gravity surfactant is re-distributed which creates surface tension gradients and an associated force and fluid flow, i.e., the Marangoni Effect. These surface tension gradient-driven flows oppose the drainage (even drawing in liquid from the pool below as Sarma and Chattopadhyay demonstrated using dye as tracer) and thus extend bubble (film) lifetime. This Marangoni Effect is understood to promote froth stability [5,13]; however, analysis is usually theoretical rather than based on measurements.

These surface features on a bubble blown in air suggest a novel way to access the Marangoni Effect. As a first approach we consider visualizing the motion and measuring the velocity of the flows. Sarma and Chattopadhyay described using a laser beam to project an image of the flows. We tried this and flows were evident but proved difficult to follow. In this communication we introduce a technique based on direct imaging of the bubble surface.

2. Experimental

2.1. Materials

Two frothers were used, an alcohol *n*-pentanol ($C_5H_{11}OH$), and a polyglycol ($H(PO)_7OH$, where PO is propylene oxide, commercial

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doi:10.1016/j.colsurfa.2008.07.042

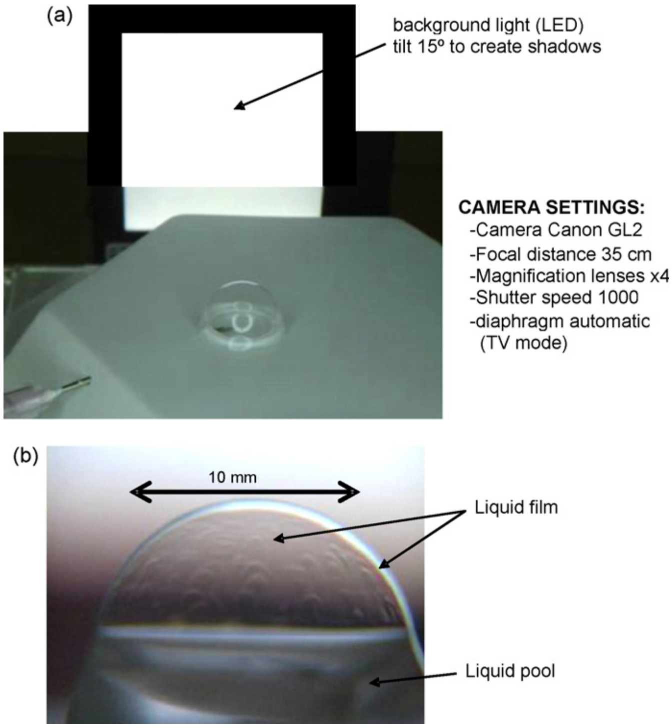

Fig. 1. (a) General set-up showing a bubble blown in frother solution. (b) Close up of bubble blown in a liquid film (detail).

name F150) giving a range of action from 'weak' to 'strong', respectively, based on the concentration required to reduce bubble size and generate foam[1] [14]. The *n*-pentanol was from Fisher Scientific (99.7% purity) and F150 from Flottec (99%). Solutions were prepared in Montréal tap water.

2.2. Generating bubbles

At concentrations applicable to flotation practice (<0.2 mmol/L) the task of blowing a bubble is quite delicate and the following procedure was devised. A needle was inserted into an upturned Teflon (weighing) tray to make a small hole over which a pool of frother solution was placed. The needle was connected to 20 mL syringe to blow the bubble using flexible (vinyl) tubing to reduce vibrations (Fig. 1a). Once the desired bubble size was reached, ca. 10 mm diameter, air injection was stopped (Fig. 1b). The hydrophobic Teflon surface helped keep the bubble stable and it was found that by leaving the syringe in place to maintain the static pressure bubbles could be preserved to the lowest concentrations, with care even in tap water alone.

The assembly was placed on a firm surface (to reduce vibrations) under a box to shield both from air currents (which affect bubble lifetime) and ambient light (which reduces contrast).

2.3. Imaging bubble surface

Fig. 1a includes the lighting set-up and the camera settings. The monochromatic back-lighting LED array at an angle 15° forward to vertical created shadows which revealed the surface features (texture) which can be just seen in Fig. 1b. The camera was set to a fixed shutter speed (TV mode) of $1/1000\,s^{-1}$, and connected to a computer with images stored as tiff files (8 bit spectral resolution). Using Matlab Image Acquisition Toolbox, images were acquired at ten frames per second. To calibrate, a ruler was imaged at the same time.

2.4. Tracking the flows

The tiff files were transferred into PowerPoint, and using the scribble function each feature to be tracked was marked with a particular colour (RGB colour map). The same feature was identified on consecutive frames. Up to 10 frames were used to track a feature and up to 20 features were followed simultaneously. The distance moved by the feature centroid over the sequence of images was determined and the average trajectory velocity was estimated using an object tracking routine developed in Matlab Image Processing Toolbox. While tedious, it was the only method suited to the available software.

3. Results and discussion

Fig. 2 shows a close up of the surface of the bubble blown in polyglycol (left) and *n*-pentanol (right). Using contrast enhancement and shadow direction transform [15] an image intensity plot (below) was developed to embolden the features. There is a clear difference in the surface texture, the *n*-pentanol showing broader features than the F150.

Fig. 3 shows example sequences of images tracking a feature in F150 (a) and *n*-pentanol (b). The broader feature in *n*-pentanol moves down, then up. The impression from the image sequence for F150 is that movement is upwards but in general motion appears chaotic.

Fig. 4 examines the trajectory velocity as function of concentration (a) and equilibrium surface tension (b, Wilhelmy Plate method, Krauss Tensiometer). Fig. 4a shows the velocity increases with concentration, more sharply with *n*-pentanol over this concentration range, but there is significant scatter (error bar is 1 standard deviation). Fig. 4b shows there is no unique dependence on surface tension. It is generally understood that surface tension (at least equilibrium surface tension) is not the common factor in frother related properties (e.g., [1]).

The velocity results do not capture the visual differences between the frothers noted in Fig. 2. In future work we plan to include the 'size' of the feature using stereoscopic imaging in order to estimate the volume and thus volumetric flow rate using the tracking procedure, and to resolve the trajectory velocity into components to derive an estimate of upward, i.e., restoring Marangoni Effect, flow.

The study has shown that bubble surface texture can be revealed and the associated flows tracked by the imaging procedure described. While the Marangoni Effect is often considered in analyses, quantification remains difficult [17]. The method introduced here may provide one route. Regardless, the measurement does introduce a possible new way to study frothers. The F150, for example, tends to generate more foam than *n*-pentanol and the difference may lie in the strength of the Marangoni Effect revealed by the magnitude of surface flows.

The discussion has referred mainly to froth formation. The Marangoni Effect also plays a role in determining bubble rise velocity in the presence of surfactants [16]; and Acuna et al. [10] have speculated on the possible role of the Marangoni Effect in creating surface perturbations that may contribute to bubble break-up, i.e., promote small bubble production. Difficult to observe on bubbles in water, the phenomenon is readily observed on a bubble blown in air and such investigations may throw light on processes relevant to flotation.

[1] The term foam is used rather than froth to indicate it is two-phase, i.e., no solids are present.