Effect of surface electrical charge on microbubbles' terminal velocity and gas holdup

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ABSTRACT

The objective of this research was to study the effect of the electrical charge of microbubbles on their terminal velocity when they are conditioned with typical flotation reagents. Some of the contrasting collectors studied were potassium ethyl xanthate (anionic) and dodecylamine (cationic), and the studied frothers were terpinol, methyl-isobutyl-carbinol (MIBC), and 2-ethylhexanol. It was found that the microbubbles' terminal velocity is mainly affected by their diameter, but the electrical charge has a significant effect, as it can change the boundary layer thickness of water surrounding each bubble. This behaviour is explained by considering that the attraction between the potential-determining ions and the counterions [e.g., hydrated proton ($+$) and xanthate ($-$)] shrinks and compacts the boundary layer thickness, which can reach high density, decreasing the microbubble terminal velocity. The opposite occurs when the bubble charge has the same sign as the counterions [e.g., hydroxyls ($-$) and xanthate ($-$)]; in this case, the diffuse layer and the boundary layer do not grow and the bubble terminal velocity increases.

1. Introduction

It is known that in the froth flotation process, the bubble size has a significant effect on particle recovery, as it is recognized that for each particle size distribution, there exists a bubble size distribution that increases its collection efficiency (Han et al., 2007; Pease et al., 2005). For example, fine particles require small bubble sizes with low terminal velocity, not only because they need a long induction time to traverse the boundary layer thickness of water surrounding the bubbles in order to make contact with the air surface but also because they provide a high specific bubble surface area to carry a sufficient mass of fines particles. In this case, the bubble terminal velocity, bubble charge, and boundary layer thickness should be interesting variables for the optimization of the fine particles' froth-flotation, as demonstrated in this paper.

As mentioned by other researchers (Parkinson et al., 2008), so far there are few studies about microbubbles' terminal velocity (diameter $<$ 100 μm; Re $<$ 1), and this lack of information is caused by the lack of sophisticated technology to visualize each individual floating microbubble. Fortunately, in recent years this technology has

become available, which has permitted the realization of this study.

This paper explains that in bubbling reactors, the gas holdup is not only a function of the bubble diameter and gas flow rate; in fact, other phenomena such as the effect of the double layer charge, the boundary layer thickness, and the friction between the adsorbed surfactant and the liquid side can be the origin of these gas holdup changes. This is a novel contribution to the knowledge of gas–liquid dispersion that can be used to explain the reasons why bubbles of the same diameter conditioned with different collectors can have different flotation velocities, affecting the gas holdup in the bubbling reactor.

This paper is original and contributes new information to the fundamental knowledge of surfactant adsorption on bubble surfaces, the electrical charge of microbubbles, and microbubbles' terminal velocity.

2. Background

2.1. Effect of surfactants and electrolytes on bubbles' terminal velocity

This section discusses why some physicochemical phenomena can affect the hydrodynamics of microbubbles and conventional bubble

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sizes similarly. For example, the forces that define the bubbles' rise velocity are the gravity, drag, and buoyancy, and once these forces are present for bubbles of both sizes (microbubbles and conventional bubbles), their rise velocities can be affected by the force balance. Independently of the bubble size, one of the variables of the bubbling reactors which is directly associated with changes in rise velocity is the gas holdup. In this context, the rise velocity can also be modified at both bubble sizes, because the double electrical layer is equally present in both cases, which affects the boundary layer volume and the drag force, as proposed in this paper. However, the hydrodynamics of microbubbles will be more affected than those of conventional bubbles.

Kracht and Finch (2010) studied the effect of F150 frother and NaCl on the sphericity and velocity of bubbles. They observed that initially the bubbles accelerated up to a maximal velocity, after which there was a period with frequent velocity oscillations, and finally the bubbles reached their terminal velocity. They also found that when the bubbles are spherical, which is due to increased frother adsorption, they float slowly. Several authors (Dukhin et al., 1998; Krzan et al., 2007; Maldonado et al., 2013) discuss this phenomenon, explaining that surfactants reduce the terminal velocity of floating bubbles for two reasons: because they reduce the bubble diameter and because they increase the friction between the bubble surface and the liquid side. As evidence of this phenomenon, Fig. 1(a) shows the effect of frother concentration on bubble diameter, where it can be seen that the frother concentration decreases the bubble size, but this effect is different for each frother (Tan et al., 2013). A detailed description of the mechanism related to the effect of the frother type and concentration on the bubble diameter is outside of the scope of this paper, but it involves some factors such as molecular sizes, molecular orientation and packing at the bubble surface, surface mobility, surface tension gradients, and so on. The frothers can also affect the bubble rise velocity because they increase the bubble–liquid friction, as shown by the same authors in Fig. 1(b). Similar results were obtained by Kracht and Finch (2010), and Maldonado et al. (2013).they

Krzan et al. (2004) also studied the bubble terminal velocity, the effect of the distance travelled, and the bubble sphericity. They found that the bubble terminal velocity decreased with the increment of reagent additions, and reported changes from 35 to 15 cm/s, even when the bubble diameter changed by only 10%. Analysing the literature, in general it is observed that the authors consider that a bubble reaches this velocity after travelling a distance of 100 times its diameter (Navarra et al., 2009; Rafiei et al., 2011; Tan et al., 2013).

Another phenomenon resulting from the effect of surfactant adsorption is that bubbles of the same diameter conditioned with different surfactants have different flotation velocities, affecting the gas holdup in bubbling reactors. Azgomi et al. (2007) attempted to explain this observation, postulating that this effect is due to the changes of the

bubble terminal velocity, as was also observed by Rafiei et al. (2011), who noted that bubbles with the same diameter conditioned with NaCl ascended more rapidly than those conditioned with methyl-isobutyl-carbinol (MIBC), producing gas holdup increments.

2.2. Effect of the microbubble electrical charge on the boundary layer thickness and the bubble terminal velocity

It is known that the electric force of aqueous solutions has a strong effect on the electric double layer, as explained by Derjaguin, Landau, Verwey and Overbeek (DLVO) theory. This signifies that when the microbubbles are present in an aqueous solution with a strong concentration of counterions they produce a compact double layer, which may be related to their increased rise velocity, whereas a low concentration of counterions produces low compaction and possibly more friction during movement. It should be mentioned that a dense and heavy double layer also decreases the speed of the bubble.

It is interesting that in the case of one microbubble, the volume of its boundary layer may be significant, in contrast to the gas volume, which is the reason why its rice velocity can be considerably affected by the surfactant adsorption. Gélinas et al. (2005), using the ultraviolet-visible spectrophotometric technique, estimated the boundary layer thickness of the bubbles and found that this thickness increases with surfactant adsorption.

Depending on the charge of the surface immersed in the electrolytic solution, it will attract a layer of ions with the opposite sign. When the Stern layer is covered (positive or negative), it will attract other approaching ions of opposite charge, forming a diffuse layer of counterions and eventually reaching a dynamic equilibrium and neutrality. This physical phenomenon is related to the boundary layer thickness of the microbubbles and may be the origin of the change of the microbubbles' terminal velocity.

Because this work deals with the relationship between the terminal velocity and the electrical charge of the microbubbles, some references and results regarding the characterization of the zeta potential of microbubbles conditioned with typical froth flotation reagents are presented. Kubota and Jameson (1993) estimated the zeta potential of fine bubbles in the presence of surfactants in aqueous solution and observed that the surfactant adsorption density changes with different chemical reagents. In another work, Nguyen and Schulze (2003) studied the effect of the electrolytes NaCl and KCl; they found that at pH > 3, the hydroxyl ions are adsorbed on the bubble surface, acquiring a negative charge, and suggested that the Na^+, K^+, and Cl^- ions remain as indifferent electrolytes.

Fig. 2(a) shows the zeta potential values measured by Bueno-Tokunaga et al. (2015) for air bubbles as a function of pH in the presence of typical froth flotation collectors at 25 ppm. Based on this
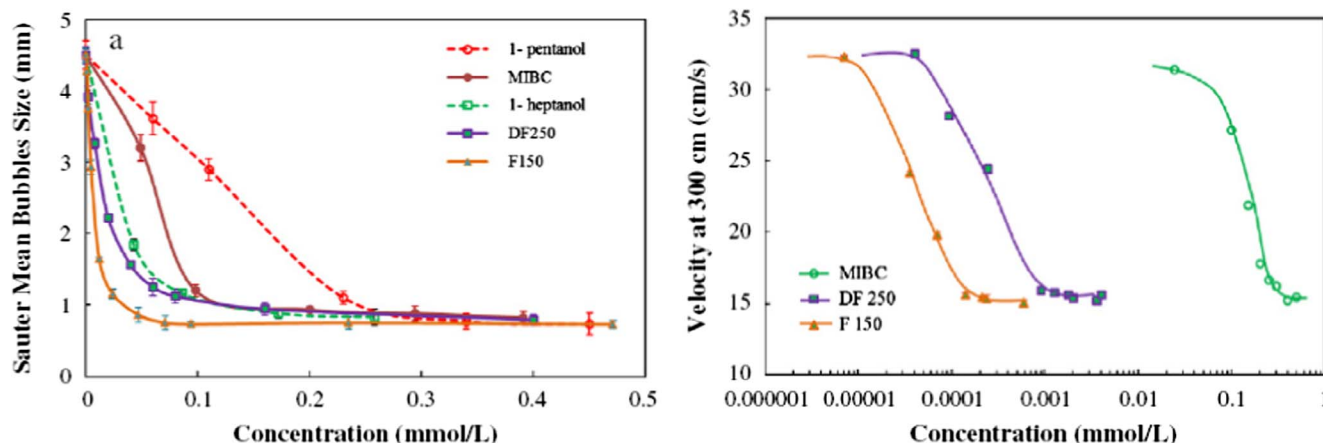

Fig. 1. Effect of frother concentration on bubble diameter (a) and bubble rise velocity (b) (Tan et al., 2013).