

Effects of surface charge, micro-bubble size and particle size on removal efficiency of electro-flotation

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Abstract Flotation is a water treatment alternative to sedimentation, and uses small bubbles to remove low-density particles from potable water and wastewater. The effect of zeta potential, bubble size and particle size on removal efficiency of the electro-flotation process was investigated because previous model-simulations indicated that these attributes are critical for high collision efficiency between micro-bubbles and particles. Solutions containing Al^{3+} as the metal ion were subjected to various conditions. The zeta potentials of bubbles and particles were similar under identical conditions, and their charges were influenced by metal ion concentration and pH. Maximum removal efficiency was 98 and 12% in the presence and absence of flocculation, respectively. Removal efficiency was higher when particle size was similar to bubble size. These results agree with modelling simulations and indicate that collision efficiency is greater when the zeta potential of one is negative and that of the other is positive and when their sizes are similar.

Keywords Charge reversal; electro-flotation; flocculation; microbubble; particle size; zeta potential

Introduction

Flotation processes are very effective for separating particles, such as algae and oil, from water. These particles are not easily settled because of their low densities. The efficiency of flotation processes depends on effective collision between micro-bubbles and particles, which is influenced by their size and zeta potential (Han *et al.*, 2001; Han, 2001). The collision efficiency diagram of Han *et al.* (2001) was constructed using trajectory analysis and shows that efficiency is highest when bubbles and particles have opposite surface charges and are of similar sizes. Bubble size has been measured using image analysis, but this is difficult to analyse. Consequently, a new technique that uses a particle counter was developed (Han *et al.*, 2002). A few studies have measured particle and bubble zeta potential (Dockko *et al.*, 1998; Kim *et al.*, 2000; Shin, 2003).

Electro-flotation (EF) uses micro-bubbles generated by electrolysis of H_2O to remove low-density particles from water. It is considered effective because it is easy to operate and removal efficiency is high. Two advantages of EF are that bubbles are smaller than those generated by the dissolved air flotation process (Burn *et al.*, 1997; Han *et al.*, 2002) and the charge of the bubbles can be controlled (Kim *et al.*, 2000). The surfaces of bubbles are negatively charged under normal conditions. A previous report suggested that bubbles could be selectively targeted at specific particles by taking their zeta potential into account (Shin, 2003). Han *et al.* (2004) reported that it was possible to induce a positive charge on the surface of bubbles using divalent ions. However, information on the effect of the type of ion on the bubble zeta potential is scarce. Moreover, the effect of bubble zeta potential on removal efficiency has not been studied. Therefore, we studied the effect of the trivalent aluminium ion on zeta potential. Our results, which agree with those of previous modelling simulations, demonstrate that collision efficiency between

bubbles and particles is higher when the zeta potential of one is negative and that of the other is positive and when their sizes are similar.

Methods

We used the method of Shin (2003) to measure the zeta potentials and sizes of bubbles generated by electrolysis. The zeta potentials of particles were measured using a zeta-phoremeter (Sephy Zetaphoremeter II). A laser diffraction size analyzer (LS13320) was used to determine the sizes of particles.

We used the trivalent aluminium ion to make an AlCl_3 solution and adjusted pH using NaOH and HCl. In order to preclude an effect of NaOH per se, a 0.001 M NaCl solution was used as the electrolyte.

We examined bubble zeta potential response to ion concentration and pH using 10^{-3} M and 10^{-4} M AlCl_3 solutions of pH 3–12. A distribution diagram of aluminium species was conducted and zeta potential of hydrated precipitation was measured in order to investigate the effect of aluminium and aluminium hydrolytic substances on the zeta potential of bubbles.

To change the particle size, mixing times of 300, 600 or 900 s were applied at a G value of 115 s^{-1} using a jar test. In order to measure floc size, samples were inserted into a cell (2 mm (height) \times 100 mm (length) \times 100 mm (width)) made of polyvinyl chloride. We analysed floc size using image analysis (Kim, 2004) after photographing the sample with a digital camera (Nikon Coolpix 4500) attached to a microscope (Meiji Techno C.).

In order to examine effects of bubble and particle zeta potential and size on removal efficiency, we made a cylindrical electro-flotation reactor with a volume of 1 L (6 cm (diameter) \times 45 cm (height)), and used platinum for a pole plate (Figure 1). We fixed the electric current at 300 mA in order to produce a fixed amount of bubbles. The test solution, to which kaolin particles were added, had an initial turbidity of 100 NTU. We measured the turbidity of disposal water after the reactor had been operated for 10 min.

Results and discussion

Effect of aluminium ions on bubble and particle zeta potential

We observed the response of bubble and particle zeta potential to pH in solutions of 10^{-3} M and 10^{-4} M AlCl_3 (Figure 2). In the 10^{-4} M solution, bubble and particle zeta potentials were positive at pH 3–7 and 3–9, respectively. When the concentration was increased to 10^{-3} M, the positive charges of bubbles and particles were reversed at pH

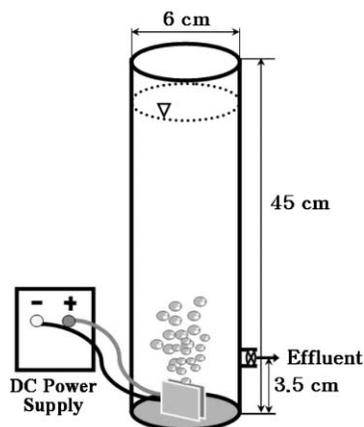


Figure 1 Electro-flotation reactor

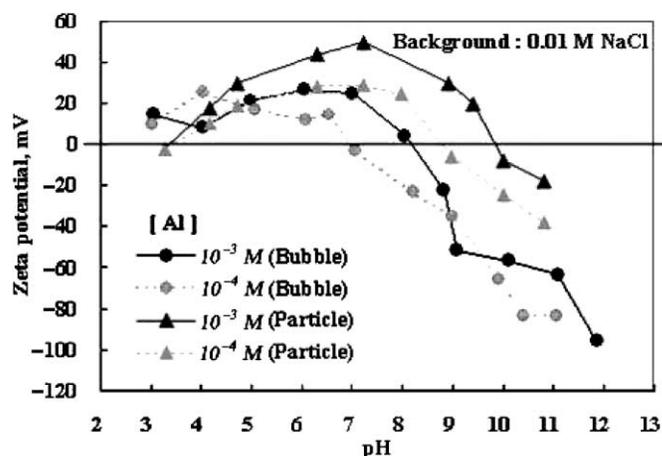


Figure 2 Zeta potentials of bubbles and particles in AlCl_3 solution

8.2 and 9.8, respectively. The maximum bubble and particle zeta potentials were +30 and +48 mV, respectively.

The distribution diagram of aluminium metal ion species (Figure 3) shows that Al^{3+} , $\text{Al}(\text{OH})_{3(s)}$ and $\text{Al}(\text{OH})_4^-$ were the predominant species and that pH differed between the two concentrations used. Under acidic conditions when Al^{3+} was the predominant species, charge reversals of bubbles and particles were observed under all conditions shown in Figure 2. Charge reversal at this pH seems to be influenced by the mechanism by which the ionized hydroxide, such as Al^{3+} , is absorbed at the surface (Li and Somasundaran, 1991).

Figure 4 shows zeta potentials in AlCl_3 solutions of 10^{-2} and 10^{-3} M for pH 5–9. We assumed that the surface charge of $\text{Al}(\text{OH})_{3(s)}$ was positive in this pH range. The hydrated precipitation of Al species decreased as pH increased, and was negative above pH 9. The zeta potential of hydrated precipitation of Al species varied according to pH, but bore no relation to the concentration of AlCl_3 .

The zeta potential of $\text{Al}(\text{OH})_{3(s)}$ in the 10^{-3} M AlCl_3 solution was small because the extent of hydrated precipitation was reduced by the decreased aluminium ion concentration (Figure 4). Thus, the charge reversal of bubbles and particles in an AlCl_3

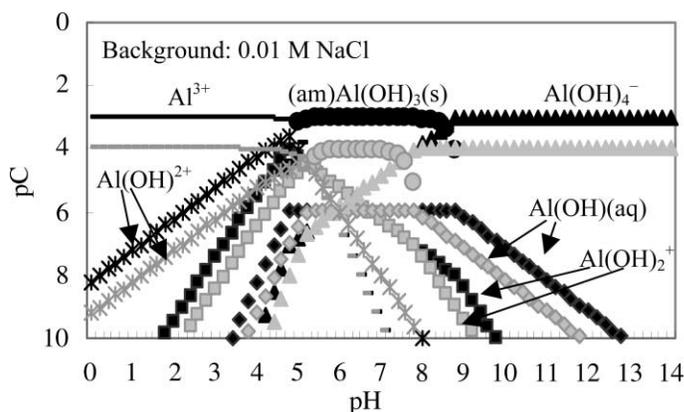


Figure 3 Aluminium species distribution as a function of pH (Black line: 10^{-3} M AlCl_3 , Grey line: 10^{-4} M AlCl_3)

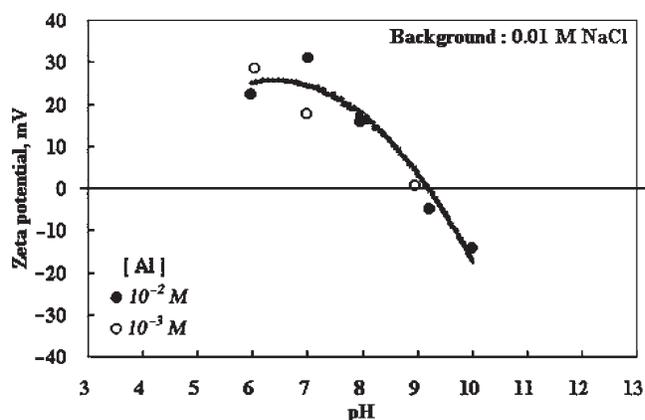


Figure 4 Zeta potential of $\text{Al(OH)}_{3(s)}$ as a function of pH

solution appears to be influenced by hydrated precipitation of positively charged Al species.

The removal efficiency was very low when bubble and particle zeta potentials were both either positive or negative, and was high when one was positive and the other negative (Figure 5). When bubble and particle zeta potentials were both either negative or positive, removal efficiency increased in the region of 0 mV. In this experiment, the average sizes of kaolin particles and bubbles were 0.1 and 27 μm , respectively.

Effect of bubble and particle size and zeta potential on removal efficiency

Figure 6 shows the floc removal efficiency in the electro-flotation reactor for various flocculation times. G-value was 115 s^{-1} , and kaolin particles were used in an AlCl_3 solution of 10^{-3} M . The response pattern of flocculated solutions to pH was similar to that of the unflocculated solution but the absolute values differed. This effect is possibly because of differences in the bubble and particle zeta potential. Removal efficiency was 98% after

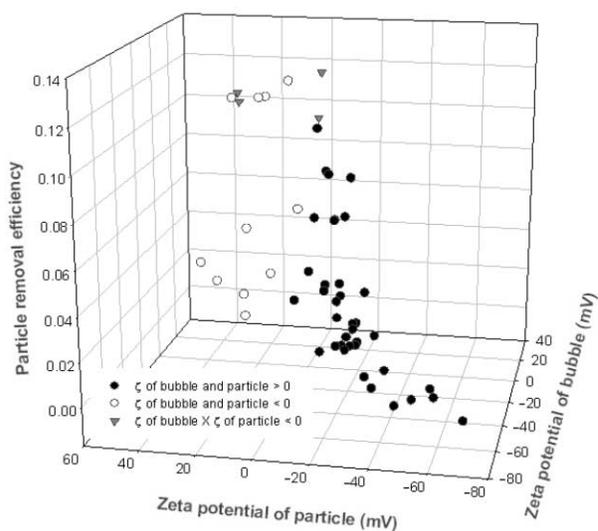


Figure 5 Effect of zeta potential of bubbles and particles on removal efficiency in the absence of flocculation (average size of unflocculated kaolin: 0.1 μm)

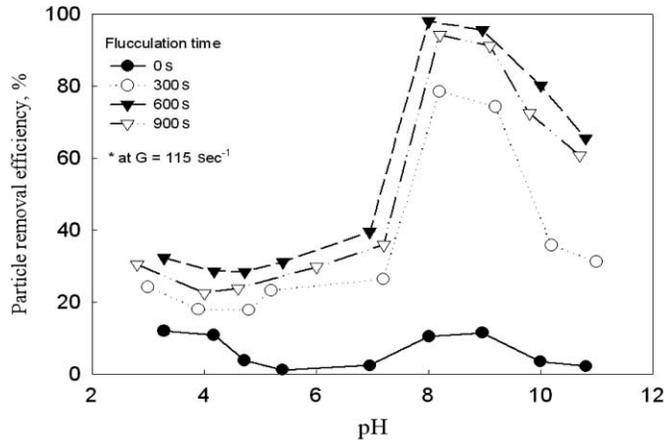


Figure 6 Effect of flocculation time on removal efficiency (10^{-3} M AlCl_3 solution)

flocculation, which was considerably higher than before flocculation. Floc sizes were 18.2, 27.8 and 42.8 μm at flocculation times of 300, 600 and 900 s at a G value of 115 s^{-1} (Table 1). The removal efficiency was highest at a flocculation time of 600 s. The bubble size at this point was also 27 μm , indicating that the highest removal efficiency occurs when bubble sizes are similar to particle size.

When the kaolin particles were removed without flocculation, efficiency was less than 12% (Figure 7). Efficiency increased with floc size until 27.8 μm . This result is similar to that predicted by a simulation model (Han, 2002), and indicates that collision efficiency

Table 1 Bubble and particle size during flocculation

Flocculation time (s)	Size (μm)	
	Particle	Bubble
0	0.1	
300	18.2	27
600	27.8	
900	42.8	

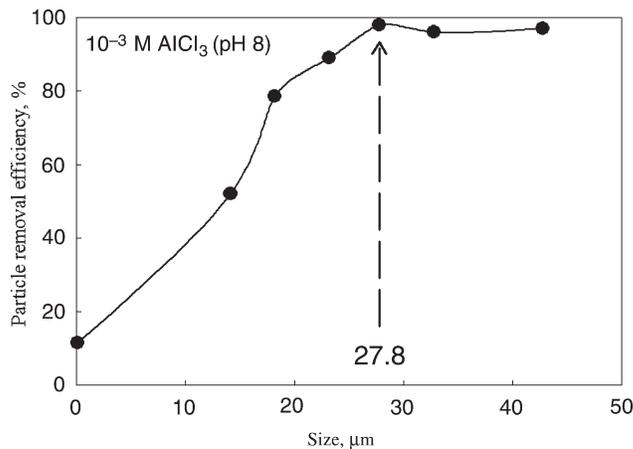


Figure 7 Effect of floc size on particle removal efficiency (10^{-3} M AlCl_3 solution)

is higher when bubble size and particle size correspond. Thus, the efficiency of electro-flotation will increase when bubble and particle zeta potentials are of opposite charge (or are both near zero mV) and when their sizes are similar.

Conclusions

In summary, we investigated the effects of bubble and particle zeta potential and size on the removal efficiency of the electro-flotation process. The results from this study show that bubble and particle zeta potentials are similar under identical conditions. The removal efficiency was very low when bubble and particle zeta potentials were both either positive or negative, and was high when one was positive and the other negative or when both potentials were close to 0 mV. Maximum particle removal efficiency was only 12% in the absence of flocculation, but was increased to 98% by flocculation. This indicates that the highest removal efficiency occurs when particle size is similar to bubble size. We produced positively charged bubbles by manipulating aluminium concentration and pH. A better understanding of the characteristics of particles and bubbles and their applications will optimise removal efficiency.

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