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The detachment of particles from coalescing bubble pairs

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ABSTRACT

This paper is concerned with the detachment of particles from coalescing bubble pairs. Two bubbles were generated at adjacent capillaries and coated with hydrophobic glass particles of mean diameter 66 μm. The bubbles were then positioned next to each other until the thin liquid film between them ruptured. The particles that dropped from the bubble surface during the coalescence process were collected and measured. The coalescence process was very vigorous and observations showed that particles detached from the bubble surfaces as a result of the oscillations caused by coalescence. The attached particles themselves and, to some extent the presence of the surfactant had a damping affect on the bubble oscillation, which played a decisive role on the particle detachment phenomena. The behaviour of particles on the surfaces of the bubbles during coalescence was described, and implications of results for the flotation process were discussed.

1. Introduction

Froth flotation is widely used in the separation of mineral particles [1,2]. The process has also been applied successfully in several other areas such as coals cleaning, de-inking of recycling paper fibres, waste water treatment and removal of oils from water [3].

The initial stage in mineral flotation is the grinding of ore in water to release the valuable mineral particles from the waste or gangue. In a suitable cell or column, reagents are added to the slurry of ground ore which render the surfaces of the valuable particles hydrophobic, while leaving the gangue mineral hydrophilic. Frothing agents are also added into the suspension of particles to facilitate the formation of a stable bubble and also froth. The suspension is then aerated and the hydrophobic mineral particles preferentially attach to the rising bubbles, bringing them into the froth phase at the top of the cell where they are collected as concentrate or product.

Not all the particles that attached to the bubbles in the cell are transferred to the concentrate. Some of them detach either in the collection zone [4,5] where the bubble-particle interaction takes place or in the froth layer [6–9]. A particle that has become attached to the surface of a bubble can become detached when the forces that hold it at the surface are exceeded by the detachment forces [10,11]. In the collection zone, the main cause for particle detachment is the presence of turbulence [4,12,13]. Turbulence is necessary to bring bubbles and particles together for collision and attachment and therefore is inherent to most flotation devices. Flows created by turbulence are characterised by the formation of eddies of different length scales. The bubble-particle couplet caught in the centre of eddies experience centrifugal forces which tend to dislodge the particle from the bubble [14–16]. Turbulence within a flotation cell is also known to lead to oscillation and deformation of bubbles which can result in detachment of particles [17,18].

Detachment of particles also occurs in the froth layer although the mechanism may differ from that in the collection zone. It has been conjectured [6–8] that detachment largely occurs at the pulp–froth interface. As the bubble-particle aggregates move towards the pulp–froth interface they essentially come to rest, and momentum is lost due to the difference in the velocity between the two phases. It has been argued [6,7] that the kinetic energy released by deceleration and impact on arriving at the interface result in particle dropback. Evidence to the contrary will be discussed below.

The main source of particle detachment in the froth is reduction in the overall bubble specific surface area. The size of the bubbles in the froth layer increases as they move from the liquid–froth interface to top of the froth for a number of reasons including liquid drainage due to gravity, gas diffusion from smaller bubbles and rupture of films or bubble coalescence [19–21]. A high rate of coalescence will lead to a serious diminution in the recovery of particles from the flotation cell, simply because the interfacial area has been reduced for a given volume of air leaving the cell. The detachment due to insufficient surface area is expected to be effective in a relatively heavily loaded froth or at the top of the froth where the surfaces of the bubbles are fully covered and there

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is a competition between various species with regard to the available surface. In this competition, the particles that are weakly attached or relatively large are more likely to leave the froth [22–24]. Therefore, bubble coalescence is often beneficial in that it promotes the dislodgment of particles that are only weakly hydrophobic, relative to other particles in the system, thus promoting selectivity in the overall process [25]. Particles that are disengaged from the bubbles may be re-collected by the rising bubbles at the lower part of the froth where the bubbles are not completely coated [26].

In the present study an experimental technique is described which allows one to easily collect the particles detaching from coalescing bubble pairs. Two bubbles of similar sizes grown at adjacent capillaries were coated with particles, and coalescence was promoted by forcing them to approach one another. The particles that were ejected from the bubble surface during the coalescence process were collected and measured. Special emphasis was put on the dynamic behaviour of coalescencing bubbles in the presence of particles, and to the effect on the detachment. The results are interpreted in terms of their significance for the flotation process. The observations should not however be limited to flotation. The behaviour of colloid particles on fluid interfaces is a rapidly growing field of interest [27–30], and it is believed that the results could also be useful in understanding the behaviour of such systems.

2. Experimental

2.1. Materials

Two different size of soda-lime glass beads were purchased from Potters Industries Pty. Ltd. (Melbourne, Australia). The first sample (designated Size 0) was used as received while the second sample was divided into various size fractions using a Warman cylosizer with five hydrocyclones (Warman International Ltd., Sydney, Australia). Only the first two of the cyclosizer products (designated Size 1 and Size 2, respectively) were used in the experiments. The density of samples was 2.5 g/cm^3 as given by the manufacturer. The d_{90} and the Sauter-mean diameter (d_{32}) as determined from Malvern (Mastersizer 2000) are given Table 1 while the volume distribution of the samples is shown in Fig. 1. Analytical grade cetyltrimethylammoniumbromide (CTAB) was used to make the particles hydrophobic, facilitating the attachment of particles to the bubbles. The glass particles were cleaned in acid solution before use. More information regarding the preparation of samples can be found in Ata [31].

2.2. Method

In the experiments, particles that had detached from coalescing bubbles were collected and analysed. Bubbles were formed at the tips of adjacent capillaries, by admitting air at a constant rate through separate syringe pumps. The description of the experimental set-up and the methodology were given in detail elsewhere [31]. All the steps until the coating of the bubble pairs were the same as described previously [31]. Once the bubbles are coated, they were moved sufficiently close so that a thin film could be formed between them. The bubbles were then left until the film ruptured and they coalesced. The particles that detached from the surface of the bubbles were collected in a conical stainless steel catcher that was located directly beneath the bubbles. The catcher was 10 mm in diameter and 15 mm deep. The catcher was put in the cell after the bubbles were coated and all the particles in the suspension had settled down. Once the particles were collected, the collection cone was removed from the cell and the process was repeated. The collected particles were dried and weighed to calculate the total mass. Between 20 and 25 coalesced pairs were performed under each condition and the average mass detached per event was taken. In all cases, there was one coated bubble and one uncoated. With this system there was a reasonable probability that coalescence would occur, and was preferred to the alternative where both bubbles were coated, when coalescence could not always be seen as reported in our earlier work [31].

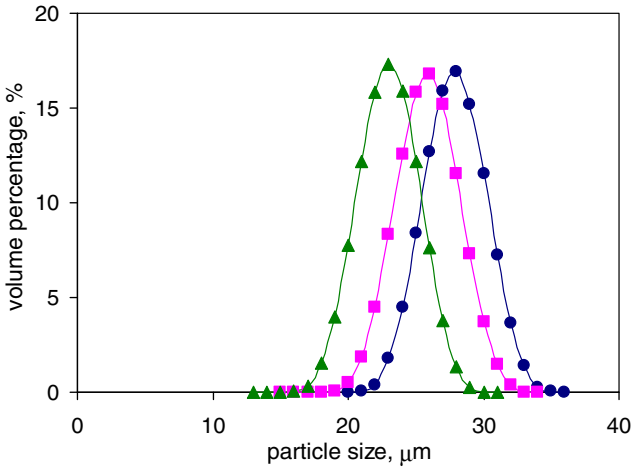

Fig. 1. Particle size distribution of the test samples used in the study: ● 92 μm; ■ 74 μm and ▲ 52 μm.

For benchmarking, it was necessary to know the mass of particles on each bubble prior to coalescence and detachment. To this end, a single bubble was coated following the standard procedure. The catcher, filled with solution from the quiescent cell, was placed under the loaded bubble. The bubble was carefully detached from the capillary with a small wire and was transferred in a beaker where it was burst. By repeating the procedure, particles from a total of 20 bubbles were accumulated, from which it was possible to determine the average bubble load. The average bubble surface coverage was 92 ± 3%. For each run, the surface area of the bare bubble (determined before the bubble was coated) and also the area of the bubble that was coated by particles, were determined by digital image analysis of photographs, using the software Optimas 6.5® (Media Cyberbetics Inc., Silver Spring, MD). The images of coated bubbles were analysed for dimensional measurements first. The measurements for glass particles covered bubbles included the diameters of the uncovered bubbles and the heights of the coverage (denoted as c′1 and c′2) as well as the length of the uncovered area (denoted as α′1 and α′2) as shown in Fig. 2. In order to calculate the surfaces of the bubbles covered by particles, a surface integral was solved to obtain a general expression where measurements were then substituted. The surface integral was solved using spherical coordinates to simplify the calculations. Important assumptions were that the lower part of the bubble was spherical whereas the upper part was ellipsoidal because of the deformation of the bubble caused by buoyancy of the bubble restrained by the capillary. It was also assumed that the half-ellipsoid was oblate and the uncoated surface was symmetrical.

Table 1
The Sauter-mean diameter and d_{90} for the samples used in the experiments.

Sample	d_{32} (μm)	d_{90} (μm)
Size 0	64	92
Size 1	51	74
Size 2	36	52