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Tracking velocity of multiple bubbles in a swarm

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ABSTRACT

This communication describes a new technique to identify and track individual bubbles moving in a bubble swarm covering bubble diameters from 0.2 to 5 mm and gas hold-up from 2% to 30%, conditions relevant to mineral flotation systems. The technique employs a 2D column, slot-type spargers, a digital high-speed camera and image analysis software developed for tracking multiple moving objects. The camera collects sequences of images recorded at 2 ms intervals at 1280 × 1024 pixel size. The software allows bubble geometric properties to be measured in the image sequence and compiled into a data structure. To track each bubble, a shape and proximity criterion is applied on consecutive pictures to identify each bubble. The bubble trajectory is reconstructed from the data structure; up to 60,000 matching bubbles can be tracked per test. The bubble tracking measurements revealed a velocity–size relationship with some of the following features: faster moving bubbles speed up slower moving ones whether larger or smaller; a large population of slow moving fine bubbles slows all bubbles; surfactant type affects velocity, equivalent size bubbles in Polyglycol moving slower than in n-Pentanol. Practical implications in flotation are discussed.

1. Introduction

Bubble behaviour plays an important role in heterogeneous reactors and adsorptive bubble separation processes, such as flotation. Most studies focus on aspects of single bubble behaviour (Sam et al., 1996; Tao, 2004; Clift et al.; 2005) or bubble swarm hydrodynamics (Lammers, 1994; Hibiki and Ishii, 2002; Mudde, 2005). In the latter, individual bubble motion is not considered and average properties of the swarm are measured, for example gas hold-up (Mena et al., 2005) or average swarm velocity (Nicklin, 1962; Shen and Finch, 1996; Krishna et al., 1999).

Nicklin (1962) proposed a measurement technique to determine bubble swarm velocity in bubble columns, based on a sudden interruption of the gas injection and tracking the bubble front thus formed. The velocity of the front corresponded to the bubble swarm "buoyancy" velocity. Shen and Finch (1996) developed a measurement technique using a fast-response conductivity meter to track the front. They demonstrated the reduction in bubble swarm velocity when the gas hold-up was increased, interpreted as a consequence of bubble interactions, in analogy to the hindered effect on settling particles (Masliyah, 1979). However, the bubble front tracking technique does not provide information on bubble interaction to support the interpretation.

The rise of a bubble front can involve bubbles rising at different velocities creating segregation along the column. This characteristic helped Siram and Mann (1977) interpret that the dynamic change in gas hold-up was dependent on bubble size distribution. With high-speed cinematography and Particle Image Velocimetry (PIV), Lee et al. (1999) observed bubble interactions in bimodal bubble size distributions. They showed that bubble–bubble and bubble–fluid interactions resulted in both small bubbles being pulled along by faster rising bubbles and small bubbles hindered by other small bubbles. These experiments were conducted without surfactant and coalescence was occurring, meaning the bubble size distribution was not constant.

A variety of techniques have been applied to characterize bubble swarm motion in columns operated with continuous gas injection. Becker et al. (1999) studied the dynamics of circulation flows by employing Laser Doppler Anemometry (LDA) on bubble plumes. Continuing this work, Pfleger et al. (1999) incorporated PIV and PTV (Particle Tracking Velocimetry). The techniques helped determine bubble plume behaviour; however, no particular attention was given to bubble interactions. PIV and LDA techniques are useful to track fluid motion (Deen et al., 2000; Buwa and Ranade, 2002) and to describe mixing characteristics in bubble columns (Lin et al., 1996; Mudde, 2005), but shadows generated by bubbles make it difficult to track fluid motion accurately, and the technique is limited to 1–4% volume fraction of the dispersed phase (Deen et al., 2002).

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Prasser et al. (2002) used a wire mesh sensor to measure individual bubble velocity in bimodal bubble size distributions. The bubble distributions were generated using two arrays of orifices in a perforated plate. The method detected individual bubbles (small and large) and helped "visualize the air-water flow". However the technique did not provide information on bubble velocity. A similar technique based on four conductivity needle probes helped measure the velocity of individual 15 mm (diameter) bubbles (Munholand and Soucy, 2005); smaller bubble sizes require smaller probes, which become progressively less sensitive (low signal-to-noise ratio). Risso and Ellingsen (2002) did develop a small sensor (50 μm diameter) based on a double optical fibre probe. The instrument provided measurement of velocity for 2.4 mm bubbles at gas hold-up 0.5 to 1.05%, but the level of dispersion on the velocity measurement was high. To reduce dispersion, a four-point optical fibre was proposed by Guet et al. (2003). The technique gave velocity measurements on individual bubbles in a column with gas hold-up up to 30%. Both techniques (conductivity and optic fibre sensors) can be used to measure individual bubble velocity and size, but bubble trajectory and bubble interaction cannot be measured. For these tasks, high-speed cinematography and image analysis seem to be the most appropriate techniques.

Miyahara et al. (1986) introduced imaging techniques to characterize bubble motion in a column. However no techniques were developed to track individual bubbles (or transparent objects) until Nishino et al. (2000). They introduced a technique based on stroboscopic background illumination and stereo imaging to track and size spherical glass beads dispersed in water. The result showed that stereo imaging helped reduce the depth of field distortion, but uneven light distribution reduced the tracking capability. For bubbles in swarms Kluytmans et al. (2002) presented image analysis techniques coupled with high-speed cinematography to measure bubble size, velocity, interfacial area and coalescence behaviour in a 2D bubble column. The bubble sizes generated (10 to 25 mm) and the absence of surfactants, resulted in high variability on bubble size measurement and bubble velocity. Cheng and Burkhardt (2003) used a similar technique to track vapour bubbles in image sequences. The background illumination, bubble reflections and bubble wobbling, however, made it difficult to construct bubble trajectories. Zaruba et al. (2005) improved the illumination using an LED array and reduced the number of superimposed bubbles using a 2D column. In this case bubble clusters (touching bubbles) were difficult to distinguish from ellipsoidal bubbles. To tackle that problem, Honkanen et al. (2005) proposed algorithms to recognize overlapping ellipse-like bubble images. Cheng and Burkhardt (2006) proposed a technique based on high-speed cinematography and matching patterns ("templates" selected manually) but the problem of uneven illumination, overlapped bubbles and bubble clusters remained.

The motivation for our work is investigation of flotation systems. There is no previous research characterizing individual bubble motion in bubble swarms under flotation-related conditions, typified by the presence of surfactants (frothers), bubble sizes (diameter) ca. 0.1 to 4 mm and gas hold-up approaching 15–20%. From the work of Zhou et al. (1991) and Azgomi et al. (2007) there appears to be an effect of frother type on bubble velocity in swarms. Comparing the gas hold-up vs. concentration relationship for two reagents, Azgomi et al. inferred that the same size bubbles in the presence of F150 (a commercial frother, Polyglycol, $H(C_2H_4O)_4OH$) rose more slowly than with n-Pentanol. Examining this claim forms part of the current work. One problem is decoupling the effect of frother on bubble production from bubble motion which is addressed here using slot-type spargers. Another problem is that the image analysis techniques require complex pattern recognition algorithms to identify and isolate ellipsoid bubbles from bubble clusters or bubbles with flexing surfaces (Nguyen and Schulze, 2004). A contribution to solving this is made here. Ultimately, the development of techniques to measure and characterize bubble motion in swarms requires integrating surface chemistry, fluid dynamics, instrumentation and image analysis programming.

2. Bubble tracking technique

2.1. General features

The technique is based on high-speed cinematography and tracking of multiple moving objects in a sequence of images. Images are generated from approximately 2D bubble swarms and recorded at intervals of 2 ms. Image processing algorithms are implemented to isolate and measure geometric properties of the bubbles. Images are converted into a data structure (The MathWorks, Inc., 2003) containing geometric parameters for each bubble. The geometric parameters and a matching criterion are applied on consecutive data structures to identify and track matching bubbles using an incidence matrix (Corman et al. 2001). The individual bubble trajectory velocity is reconstructed from the data structure vector and the matched objects in the sequence of images. As a result, individual bubbles can be tracked from 5 to 30 consecutive pictures, and up to 60,000 matching bubbles can be detected.

2.2. Generation of a 2D bubble swarm

The experiments are conducted in a narrow rectangular transparent column with an inclined top section (15°) (Fig. 1). Bubble swarms are generated using a double chamber sparger, assembled with a slot sparger (Harris et al., 2005) and porous slot sparger (Southern and Wraith, 1990) with independent gas injection. The gas velocity is quoted per unit area of slot, U_s (m/s). This combination generated bubble size distributions similar to those found in industrial flotation machines, 0.1 to 4 mm (Nesset et al., 2006). Bubble images are collected at selected distances: 3 cm, 6 cm, 50 cm (near top of vertical section) and 90 cm (near top of the inclined section), in order to include the effect of surfactant accumulation on the bubble. The bubble-generating device produces an approximately 2D (or "flat") bubble swarm, which facilitates tracking bubbles in the first 50 cm of the column. After this distance, bubble interactions and liquid re-circulation initiate formation of a bubble plume (i.e., 3D swarm), which makes it difficult to track trajectories. To limit this condition, the inclined section forces the plume to spread into a 2D array once more.

The surfactants tested were the commercial frother, Polyglycol ($H(C_2H_4O)_4OH$, trade name F150) supplied by Flottec, and n-Pentanol (Fisher reagent grade). Solutions were made with Montreal tap water at room temperature (16–18 °C). Slot spargers have the advantage that the bubble size is nearly independent of system chemistry (Harris et al., 2005) meaning the impact of surfactant type on bubble motion can be tested on a similar bubble size distribution.

2.3. High-speed cinematography and bubble imaging

A digital high-speed camera (Troubleshooter HR) with macro lens (Nikon, AF Micro Nikkor) is used to collect sequences of images in AVI file format (Audio Video Interleave), in 256 grey scale levels on a CMOS sensor (15.4 × 12.8 mm). Once movies are recorded in a circular RAM memory (1 GB), the AVI files are transferred to a computer where they are deployed into TIFF pictures (Tagged Image File Format). The Troubleshooter HR allows different combinations of image size (1280 × 1024 down to 320 × 240 pixels), frame rate (125 up to 16,000 pictures/s), and exposure time or shutter speed as a factor of the frame rate (1 to 20). These combinations restrict transfer rate to 625 MB/s.

In order to meet the compromise of picture size (7 pixels defines smallest detectable bubble), frame rate (to track the same bubble over at least 30 frames) and magnification and viewing area (to track the largest bubble over at least five consecutive frames), the camera is set to 500 pictures/s, image size to 1280 × 1024 pixels, shutter speed to 2000 s^{-1} and image resolution to 60 pixels/mm. A macro lens and focal distance of 20 cm provides a depth of field of 5 mm, which helps reduce superimposition of bubbles.