Effect of pressure on bubble size in dissolved air flotation

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Abstract Although dissolved air flotation (DAF) has been successfully adopted for water and wastewater treatment, the fundamental characteristics of the process have not been fully investigated. According to recent theoretical work on DAF, bubble size is one of the most important factors that affect the efficiency of the process, with better removal efficiency when the sizes of both bubbles and particles are similar. In this study, a newly developed particle counter method (PCM) was introduced to measure particle sizes. To confirm its usefulness, the results were compared with those from image analysis. Then, using PCM, the size of bubbles in DAF was measured under various pressure conditions which are known to affect the bubble size the most (from 2 to 6 atmospheres). The bubble size decreased as the pressure increased up to a pressure of 3.5 atmospheres. Above this critical pressure, the bubble size did not decrease with further increases in pressure. According to these experimental results, it is not only costly, but also unnecessary, to maintain a pressure above 3.5 atmospheres if the goal is only to generate smaller bubbles.

Keywords Bubble size; dissolved air flotation; image analysis; on-line particle counter; PCM; pressure

Water Science and Technology: Water Supply **Vol 2 No 5–6 pp 41–46** © IWA Publishing 2002

Introduction

Dissolved air flotation (DAF) has been accepted since the 1960s as an alternative to conventional sedimentation processes for removing particles from water and wastewater. The process uses the microbubbles generated when pressurized air-saturated water is released into atmospheric pressure. The main mechanism of particle removal in DAF is creation of a buoyant particle–bubble agglomerate following collision between a particle and a bubble (AWWA, 1999). The agglomerate floats up to the water surface, where it is removed by scrapers. Recently, a collision efficiency model was developed and verified through a series of experiments (Han, 2002; Han *et al.*, 2001a). The model predicts that the electrical charge of the bubbles and particles is important in promoting collision of bubble and particle. The maximum collision efficiency, i.e. approach and agglomeration of bubble and particle to a single unit, is achieved when the bubbles and the particles are a similar size. This points to the importance of bubble size as a parameter in DAF.

The size of bubbles is affected by factors such as the pressure difference across the injection system and the type of nozzle (AWWA, 1999). The bubble size range that is generated under a pressure of 4–6 atmospheres is generally reported to be 10–100 μm, with the average diameter of approximately 40 μm (Edzwald, 1995). The size of the air bubbles produced in DAF is most strongly affected by the pressure difference across the nozzle system. The higher the pressure difference, the smaller the bubbles. However, it was also found that there is a critical point, reported to be 5 atmospheres, above which the size does not decrease further (De Rijk *et al.*, 1994). However, the previous work had few data under confined pressure conditions, mainly because of difficulties in measurement of bubble size.

The size of microbubbles is generally measured by image analysis, which is a visual process involving direct measurement of bubble size. This method is very reliable for measuring individual bubble sizes. However, it is very time consuming and so it is difficult to measure a sufficient number of bubbles to give a reliable size distribution, especially when a number of experiments at different pressures are needed. To overcome this difficulty, the particle counter method (PCM) was recently developed by Han *et al.* (2001b). This new method was developed from the idea that microbubbles behave just like particles (Shulz, 1984); that is, the PCM involves using a particle counter to count and measure bubbles instead of particles.

In this study, the use of the PCM was verified by comparing bubble size measurements with those of image analysis. After use of the PCM was shown to be justified, the size of bubbles generated under various pressure conditions was measured in this way. Recommendations for DAF plant design and operation derived from this work are discussed.

Materials and methods

Bubble size measurement methods

Image analysis. The image analysis system, which is illustrated in Figure 1, includes a measuring cell, a microscope, a CCD camera, and a computer for image processing. This system was previously used for the measurement of the zeta potential of bubbles by the authors (Dockko *et al.*, 1998; Han and Dockko, 1999; Kim *et al.*, 2000). Bubbles were generated inside the measuring cell to prevent the change of bubble size which occurs when bubbles are introduced into the cell through a tube. Images of bubbles were taken using the CCD camera, and their sizes were measured using a micrometer. The upper part of the cell was kept open because the pressure difference inside the cell can affect the bubble size. The microscope was focused at the point directly after the valve to measure the size of bubbles immediately after bubble generation.

Particle counter method (PCM). On-line particle counters (Chemtrac Model PC2400 D, USA) were used to measure the size of bubbles. This model provides seven adjustable channels to measure size ranges. In this research, two identical particle counters were used to increase the number of channels, in order to increase the precision of the measurements (Figure 2).

In this method, a laser light is projected through the sensor (holding the sample) onto the detector. When the sample passes through the sensor, the light is scattered and obscured by the bubbles. This scattering and obscuring of the light causes a decrease in the intensity of the light reaching the detector which is proportional to the bubble size. According to the decrease of the laser light, a voltage pulse is generated. Here, the number of pulses

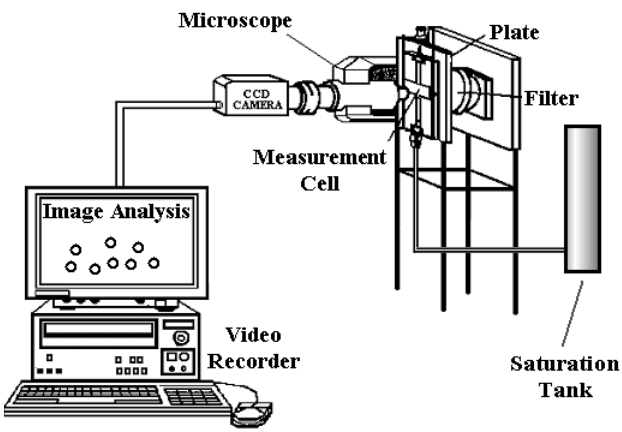

Figure 1 Image analysis system

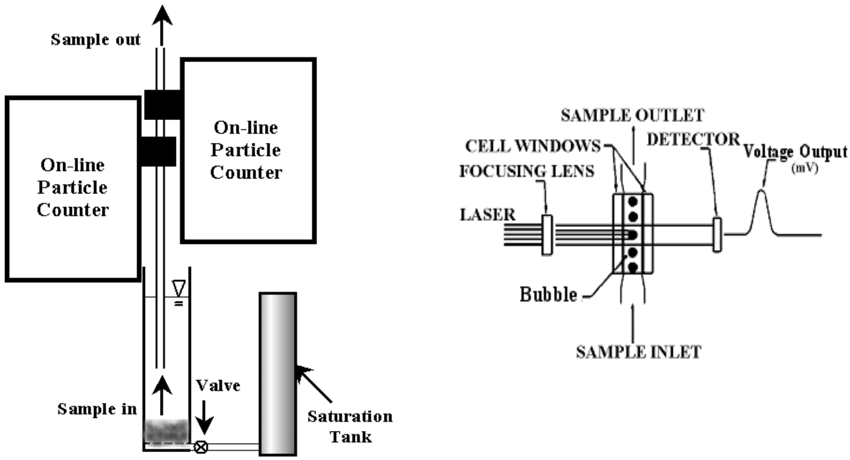

Figure 2 Schematic of on-line particle counter and details of the sensor

represents the number of bubbles, and the height of each pulse represents the size of the particular bubble.

To minimize possible bubble coalescence before reaching the sensor, a straight tube, which was kept as short as possible, was used. The sampling flow rate was 100 mL/min., as set by the manufacturer. Because this method cannot discriminate bubbles from particles, and to reduce interference from solid particles, distilled and deionized water was used. Blanks showed that nearly all remaining particles had a size $< 10\ \mu m$. Very few bubbles are in this size range. Therefore, although the measurement size range of the particle counter was set as from 2–100 μm at increments of 10 μm, the results from the first channel (2–10 μm) were ignored. At each pressure condition, three distribution datasets were acquired, and the average was used for analysis.

Comparison of each method. Two methods of measuring bubble sizes (image analysis and PCM) were tested, and the characteristics of each method are compared in Table 1.

Even though continuous size measurement is not possible using the image analysis, the results are more accurate than those from the PCM, owing to the measurement principles. However, the most useful feature of the PCM is the very rapid rate at which data can be acquired. The time needed to measure 2,000 bubbles by each method was approximately 3,000 and 10 minutes, respectively. Even though the size measurement of individual bubble is more accurate in image analysis than PCM, a more reliable size distribution can be obtained using the faster method because of the large number of bubbles that can be measured. Furthermore, setup and operation of the equipment is much simpler than for image analysis.

Results and discussion

Development of a new method

To verify the PCM, microbubbles were generated under the same conditions, and air was pressurized and dissolved into water under 6 atmospheres. Only a small volume of bubbles

Table 1 Comparison of characteristics of bubble size measurement methods

	On-line measurement	Size accuracy	Equipment setup	Measuring time (min)*
Image analysis	X	Excellent	Complicated	3,000
PCM	O	Good	Simple	10

* For measurement of approximately 2,000 bubbles

was generated to avoid the possibility that a high concentration might decrease the accuracy of the particle counters and increase the possibility of bubble coalescence. During the experiments, the injected volume was so small that the water surface difference in the reactor could not be visually discriminated before and after bubble generation. The size and size distribution of bubbles were measured by image analysis and PCM, respectively. The results from each method are similar, as illustrated in Figure 3 and listed in Table 2.

The modal size was the same for both sets of measurements. The average of the measurements by image analysis was larger than by the PCM. This seems to be mainly due to the number of bubbles measured in each case. That is, approximately 2,000 bubbles were measured in PCM, whereas only about 200 bubbles were measured in image analysis. However, the result is expected to become similar to that of the PCM if the number of bubbles measured in image analysis were to be increased. Besides, while it is possible for microbubbles to coalesce to become larger, it is almost impossible for them to become smaller. Therefore, the authors consider that the result from the PCM is more accurate than that from image analysis. The size range of bubbles from PCM is wider than from image analysis, which means that a small number of larger bubbles were detected in the PCM. One possible reason for this might be the coalescence of bubbles during transport to the sensor. Another reason, applicable to the PCM, is possible overlapping of bubbles inside the sensor, which would result in counting fewer but larger bubbles. This is an inherent shortcoming of the particle counter. Nevertheless, the fraction of bubbles smaller than 55 μm (d_{55}) in all measurements is more than 97%, so that the difference in size range is of little importance. From this comparison, the accuracy of measuring bubbles by PCM is considered good enough to be used for process monitoring. Most important, the fast response of the PCM is an especially good feature.

Effect of pressure on bubble size

To find the effect of pressure on bubble size, the PCM was used. The experimental setup is the same as in Figure 2. Distilled and deionized water was used as the liquid in the reactor and the saturation tank. The pressure differential for bubble generation was increased from 2 to 6 atmospheres in increments of 0.5 atmospheres, and the results are shown in Figure 4.

The right-hand plot clearly shows that bubble size decreases as the pressure increases until a critical pressure is reached, after which the size is constant. This has been reported in

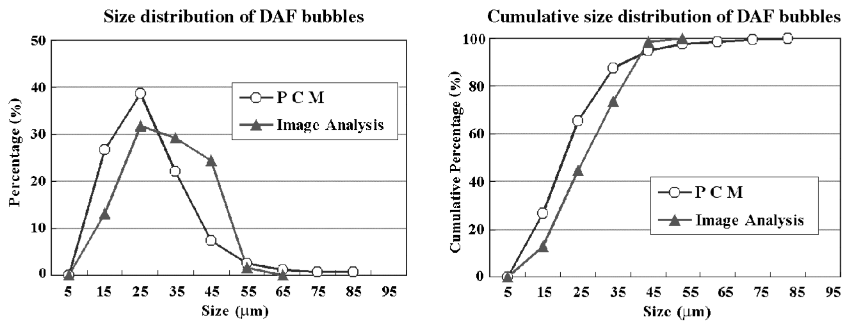

Figure 3 Comparison of bubble size distribution from each method

Table 2 Size characteristics of bubbles measured by each method

	Size range (μm)	Average size (μm)	Modal size (μm)	d_{55}* (%)
Image analysis	14–56	32	25	99.0
PCM	15–85	28	25	97.6

* Fraction of bubbles smaller than 55 μm

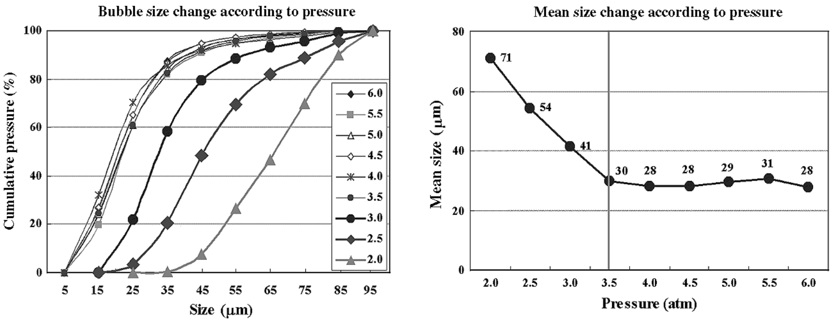

Figure 4 Bubble size distribution and average bubble size according to pressure change

other studies (De Rijk *et al.*, 1994). However, the critical pressure in this study is 3.5 atmospheres, which is lower than the value of five atmospheres that was reported by De Rijk *et al.*

The average size of the bubbles produced in this work is smaller than those reported in the literature. The reason is that in this study, bubbles sizes were measured immediately after release from the pressure vessel. Literature values are measured from a contact zone in an operating DAF plant in which the pressures are reduced by passage through piping, valves, and orifices. Lower pressures tend to increase the size of the bubbles. In addition, the opportunity for bubble coalescence increases with increasing time between generation and measurement and literature values reflect this fact.

During practical operation of DAF processes, the pressure generally ranges from 4–6 atmospheres, or higher, in an attempt to generate bubbles that are as small as possible. However, according to these experimental results, bubble size is not a function of pressure above 3.5 atmospheres. Therefore, it is not only costly but also unnecessary to maintain a pressure above 3.5 atmospheres if the goal is only to generate smaller bubbles. Nevertheless, good treatment efficiency might be expected under higher pressure conditions due to higher bubble volume concentration, rather than smaller bubble size. Another factor that should be considered in this study is that the pressure conditions measured in this work were the pressure around the nozzle system. In real plants, this is greater than the pressure in the saturation tank, because pressure is lost while saturated water passes through a pipeline from the saturation tank to the nozzle system. Therefore, it is important in DAF plant design to make the pipeline as short as possible and keep the pressure constant at all nozzles in operation.

Conclusions

In this study, a new method for bubble size measurement using on-line particle counters (PCM) was developed and the method was verified by comparing the method with image analysis. Using the new method, bubble sizes were measured under various pressure conditions and the following conclusions drawn.

- In spite of a few trivial shortcomings of PCM, the new method is valid and easy to apply to laboratory experiments and/or real flotation plants for bubble size measurement.
- A critical pressure exists (3.5 atmospheres), above which the bubble size does not become smaller. For efficient and economical operation, increasing the bubble volume concentration is recommended as likely to be more effective than increasing the pressure.
- Because pressure in DAF has a direct effect on bubble size, it is necessary to design the pipeline from saturation tank to nozzle to be short as possible.

Acknowledgement

This work is funded by MOCT under the project 2001-JAYU A08 and the Research Institute of Engineering Science of SNU and is also appreciated.

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