

Measurement of bubble bed depth in dissolved air flotation using a particle counter

Mooyoung Han, Tschung-il Kim and Dongheui Kwak

ABSTRACT

In the development of dissolved air flotation (DAF) technology, it is noteworthy that higher hydraulic loading rates are achieved while the reactors become deeper resulting in a smaller footprint. One of the reasons for the increased efficiency is claimed to be the deeper bubble bed depth in the flotation separation zone; however, there has been limited research on the characterization of the bubble bed. In this research, a method for locating the bubble bed interface using a commercially available particle counter is presented. The results compared remarkably well with observations by the naked eye at a pilot plant with a transparent acrylic wall. The method is then applied to locate the bubble bed interface at an operating DAF plant in Wonju, Korea. We can observe that the bubble bed profile changes according to the operational conditions and that higher effluent water quality is obtained with a deeper bubble bed. Based on these results, optimization of DAF process might be possible by monitoring the bubble bed profile in the reactor.

Key words | air bubbles, bubble bed depth, bubble bed interface, dissolved air flotation, particle counter

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INTRODUCTION

Dissolved air flotation (DAF) is a process by which low-density particles are removed from water and wastewater by using micro-bubbles, generated when pressurized air-saturated water is introduced into a reactor. The history of development of the DAF process is well described in a recent report (Han & Edzwald 2007). The design trend is clear that the hydraulic loading rate has increased from $3 \sim 8 \text{ m h}^{-1}$ in the 1960s–1970s to $25 \sim 40 \text{ m h}^{-1}$ after 1996, while the depth of the reactor has increased from 1.5 m to 5.0 m, resulting in a more compact design with a smaller footprint.

The motivation for this study came from the question of why a deeper reactor results in a better particle removal efficiency. Kiuru (2001) suggested that the increased efficiency might be due to the increased bubble bed depth, but the vertical or horizontal distribution of the bubble bed in the separation zone was not measured. Edzwald *et al.* (1999)

reported that, as the loading rate increased, the bubble bed (blanket) went deeper, but the relationship between the bubble depth and removal efficiency was not addressed. Lundh *et al.* (2001) tried to measure the bubble concentration in a pilot plant with a turbidity meter, but the exact bubble bed depth could not be measured.

It is fairly easy to observe the creation of a bubble bed interface in the middle part of the reactor by the naked eye in a pilot scale DAF reactor manufactured with a transparent wall. Although it is not possible to present the interface by a single straight line, a bubble interface zone exists in which above the interface there are clouds of bubbles and below the interface almost no bubbles are observed. The centre of the bubble interface zone is defined as the bubble bed interface. Bubble bed depth is defined by the height from the water surface to the bubble bed interface as presented in Figure 1.

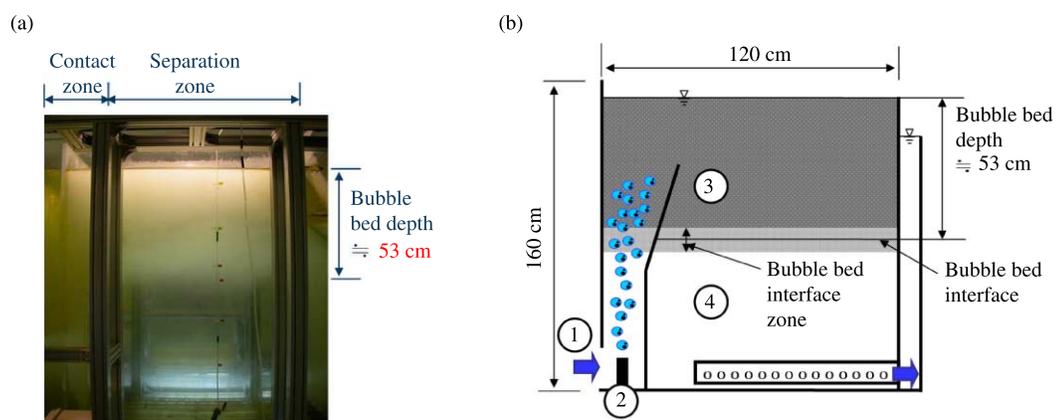


Figure 1 | Pilot plant used to determine the bubble bed depth: (a) pilot plant manufactured from transparent acrylic; (b) cross-section of pilot plant.

However, in a full scale DAF plant, it is not easy to locate the bubble bed interface. The difficulty is that observation by the naked eye is not possible due to structural constraints. Even with a transparent wall, it is not easy to observe the phenomenon occurring within the reactor. Grab sampling from the reactor is not possible because bubbles will soon disappear after sampling. Therefore, the only reliable method is to measure *in situ*.

Therefore, the aim of this study is to develop a simple method to measure the bubble bed depth *in situ*. Specific parts of the study include: first, to find a method to locate the bubble bed interface by a particle counter. The results are compared easily by the naked eye in a pilot plant manufactured from transparent acrylic. Second, bubble bed profiles are measured at an operating DAF plant under different operating conditions. Finally, some problems that might occur during measurement and sampling are discussed.

EXPERIMENTAL METHODS

Bubble size measurement using a particle counter

Since bubbles coalesce or sometimes disappear during sampling, bubble size measurement should be made *in situ* or by image analysis. Although image analysis is straightforward for the measurement of the size distribution of bubbles, it takes too much time to produce any results for operational use (Han *et al.* 2007).

In order to overcome this shortcoming, a method of measuring micro-bubble size using a particle counter

(Chemtrac Model PC2400D, USA) has been developed (Han *et al.* 2001, 2002b). This arose from the idea that micro-bubbles behave like particles (Schulze 1983), and therefore a particle counter can be used to measure bubbles. Han *et al.* (2002a) have previously used this method to determine the size of bubbles in DAF.

In this study, we used the same particle counting method and measured combined counts of bubbles and particles at different locations in the DAF system as shown in Figure 1 (b); sample 1: the flocculated particle (without bubbles), sample 2: bubbles from saturator (without floc particles), sample 3: bubble and particle mixture in the contact zone, and sample 4: effluent (without bubbles). In this research only one particle counter is used measuring at seven channels (1 ~ 5 μm , 5 ~ 10 μm , 10 ~ 20 μm , 20 ~ 30 μm , 30 ~ 50 μm , 50 ~ 70 μm , 70 ~ 100 μm). The flow rate was 100 ml min⁻¹, and the number of particles of each size range shows the number of bubbles and particles per 100 ml.

Determination of bubble bed depth at a pilot plant

In order to compare the results of bubble bed depth obtained by using the naked eye and by using a particle counter, a set of experiments was carried out at a pilot plant manufactured from transparent acrylic as illustrated in Figure 1. The size of the pilot plant is 1.0 m (width) \times 1.2 m (length) \times 1.6 m (height). Bubbles are introduced from the bottom of the contact zone. Then, bubbles and flocculated particles undergo collisions in the contact zone, and removal of

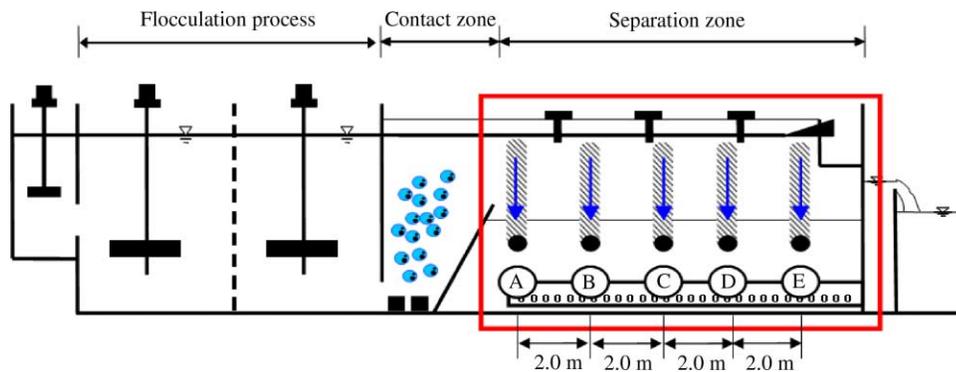


Figure 2 | Schematic diagram and sampling points at Wonju DAF plant.

bubbles and flocs attached to bubbles occurs in the separation zone. The effluent is drawn from the bottom of the separation zone. The operating conditions such as pressure and recycle ratio are easily adjustable. The samples are taken by a tube using a pump from any positions of interest. The on-line particle counter is located at the suction side of the pump to avoid possible breakup by the impeller.

Bubble bed depth measurement at an operating DAF plant

Using the method developed at the pilot plant, bubble bed depth was measured at Wonju water treatment plant located in Gangwon province, Korea. The capacity is about 200,000 m³/day and the details of the plant are reported elsewhere (Kwon *et al.* 2004).

The schematic diagram and sampling points are shown in Figure 2. The size of each separation zone is 9.1 m (width) × 9.6 m (length) × 2.6 m (height). In order to determine the horizontal profile, samples are collected at several heights in five positions (A, B, C, D, E), which are spaced at 2-m intervals. The samples are taken from 1.0 m away from the sidewall using a tube tied on a pole at different depths.

RESULTS

Measurement of bubble bed depth at a pilot plant

At the pilot plant made with an acrylic wall, the existence and location of the bubble bed interface are determined easily by the naked eye, and therefore the results made by the particle counting method can be verified. Near the

bubble bed interface, there is a rapid change in the number of particle counts because of the combined effect of both particles and bubbles. There is no clear-cut position of the interface; however, there is a zone which divides a considerable number of particle counts from an insignificant number of particle counts.

As can be seen from Figure 1(a), the bubble bed is formed from the surface down to some depth, but a clear interface is hard to define, therefore a mid-depth with a certain range can be defined. In this case, the depth is defined as 53 ± 3 cm. Despite some ambiguity, it is a reasonable way of defining the bubble bed depth, because the relative depth is more important than the exact depth.

Figure 3 shows the distribution of particle counts (combination of particle and bubble counts) from five channels between 10 and 100 μm size near the interface at

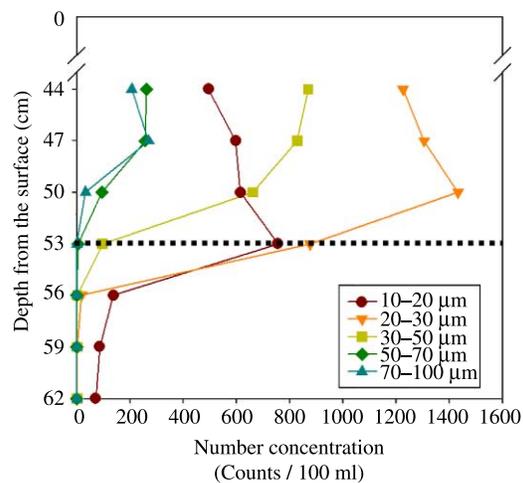


Figure 3 | Particle and bubble counts with depth in a pilot plant (operating conditions: pressure, 517 kPa; recycle ratio, 50%, separation zone loading rate, 1.4 m h⁻¹; water temperature, 7.5°C).

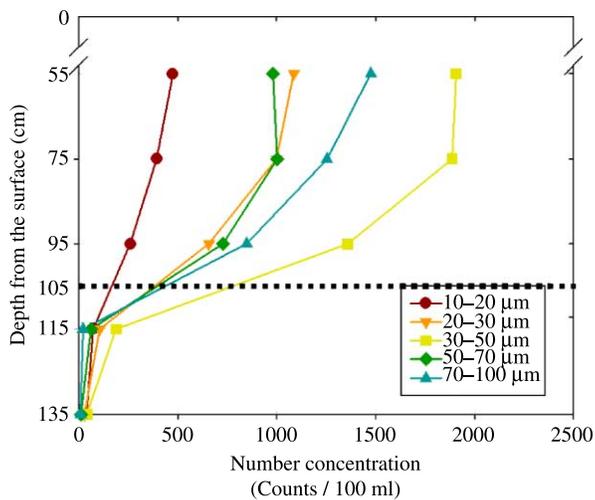


Figure 4 | Particle and bubble count at different depths at sampling position C (operating conditions: pressure, 415 kPa; recycle ratio, 6.6%; separation zone loading rate, 12 m h^{-1} ; water temperature, 7.5°C).

3-cm intervals under the conditions shown in the figure. The graph shows that the particle counts for size $10 \sim 100 \mu\text{m}$ rapidly decrease from 50 cm depth to 56 cm depth. From these results, the bubble bed interface is taken as 53 cm which is the value at the mid-point of the bubble bed interface zone.

Measurement of bubble bed depth at an operating DAF plant

Using the same method developed for the pilot plant, the bubble bed depth was measured at an operating DAF plant at Wonju. The standard operating conditions were: pressure, 415 kPa; recycle ratio, 6.6%; and separation zone loading

rate, 12 m h^{-1} . The samples were taken at five sampling positions at 2-m intervals to determine the horizontal profile of the bubble bed. At each sampling position, the water samples were taken at several depths.

Figure 4 shows one example of how to locate the bubble bed interface at sampling position C. Because the interface was not visible and there were so many samples to take for the full-scale experiment, vertical samples at 20-cm depth intervals were taken. For the operating conditions given above and listed in Figure 4, the particle and bubble counts decreased rapidly in the depth range of 95 cm to 135 cm. From this result, the bubble bed depth is determined as 105 cm.

Using the same method, the horizontal distribution of bubble bed depth was measured and drawn as in Figure 5. Under the operating conditions for this study, the bubble bed depth at the front and at the end (125 cm) is deeper than in the middle (105 cm). In this case, the ratio of volume of the tank containing bubbles to the total tank volume of the separation zone is 43%.

Change of bubble bed depth at different operating conditions

The bubble bed distributions at different operating conditions can be measured easily by changing the operating conditions of pressure and recycle ratio. Considering case 1 (pressure, 415 kPa; recycle ratio, 6.6%) as a standard, the effects of an increase in pressure (case 2) and an increase in recycle ratio (case 3) are observed, respectively, as shown in

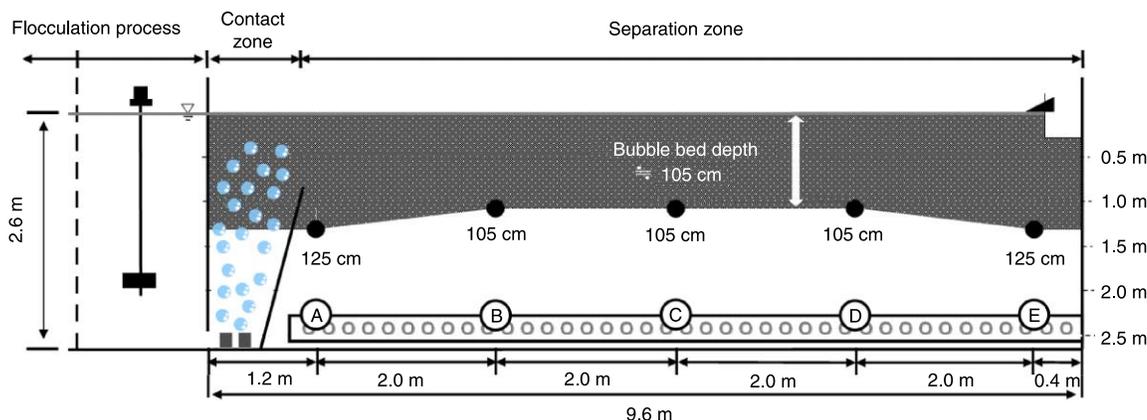


Figure 5 | Horizontal profile of bubble bed depth.

Table 1 | Bubble bed performance at different operating conditions

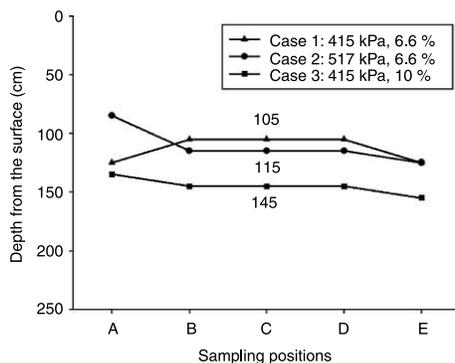
	Operating conditions (loading rate: 12 m h ⁻¹ , water temp: 7.5°C)		Bubble bed depth (cm)	Volume of tank with bubbles/total volume (%)	Ave. number of particles (1 ~ 100 μm 100 ml ⁻¹)	
	Pressure (kPa)	Recycle ratio (%)			20 cm below bubble bed interface (average of values from B, C, D points)	Effluent
Case 1	415	6.6	105	43	665	660
Case 2	517	6.6	115	49	528	518
Case 3	415	10.0	145	57	377	429

Table 1. During the experiment, the plant was operated with a separation zone loading rate of 12 m h⁻¹ and water temperature was 7.5°C.

For case 3, when the recycle ratio is increased from 6.6% to 10%, the separation zone hydraulic loading rate increases by 3.2%, which is considered negligible for the purpose of this research.

Figure 6 shows the comparison of bubble bed depth under different operating conditions. Bubble bed depth is significantly affected by the pressure and recycle ratio. By increasing the pressure from 415 to 517 kPa, the bubble bed becomes deeper by 10 cm (case 2). Also, by increasing the recycle ratio from 6.6% to 10%, the bubble bed becomes deeper by 30 cm (case 3). The depths of the bubble bed at the middle of the separation zone (Points B, C and D) are uniform. The trend near the inlet is not clear. The bubble bed at the end of the reactor is increasing in depth, probably due to the wall effect. However, the reason for such a difference is beyond the research scope of the current study.

In order to observe the effluent water quality, the particle counts (1 ~ 100 μm) at 20 cm below the bubble interface for points B, C, D and at the outlet trough were measured as

**Figure 6** | Change of bubble bed depth at different operating conditions (operating conditions: separation zone loading rate, 12 m h⁻¹; water temperature, 7.5°C).

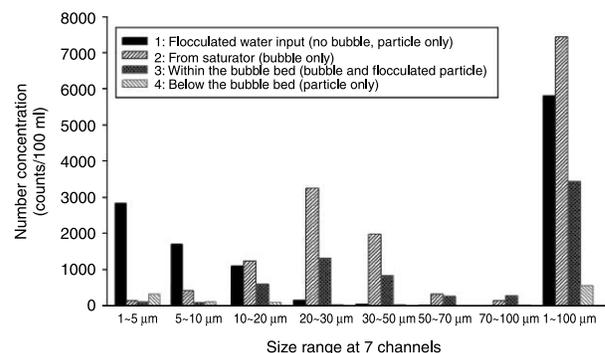
shown in Table 1. There is a clear relationship between the bubble bed depth and quality of effluent water; that is, the deeper the bubble bed, the better the effluent quality.

DISCUSSION

Contribution of particles and bubbles in particle count measurements

Because the particle counter used in this research is based on light blockage principle, it does not differentiate the counts between particles and bubbles. Nonetheless, we need to find a simple and easy method to characterize the bubble bed interface.

For this purpose, four samples in a DAF pilot plant were taken and the particle and bubble size distribution of each sample was measured. Sample 1 was used to measure particles in the flocculated water that comes into the bottom of the contact zone, which does not contain any bubbles. Sample 2 was used to measure bubbles released into the saturator, where only small numbers of particles exist. Sample 3 was taken from the middle of the bubble bed,

**Figure 7** | Particle and bubble count data at various locations in the DAF process (case 2).

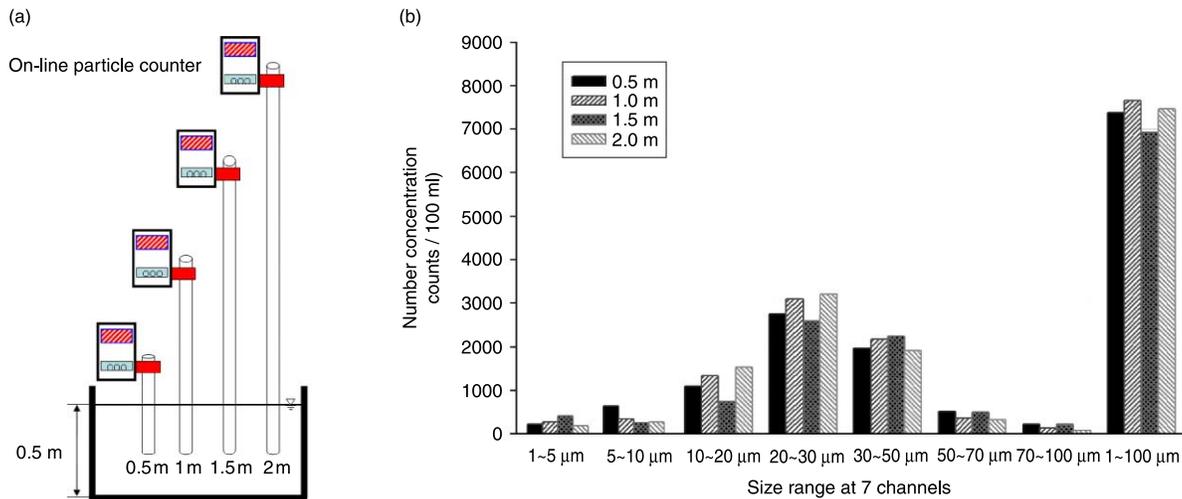


Figure 8 | The effect of length of sampling tubes (internal diameter, 3 mm) in a continuous reactor: (a) experimental setup with sampling tube and particle counter; (b) bubble size distribution.

which contains both bubbles and flocculated particles. Sample 4 was taken from far below the bubble bed interface, where there are no bubbles.

The particle and bubble size distribution of the four samples were measured during one of the experimental conditions (case 2) and the results are presented in Figure 7. The particle counts of sample 3, which is the combination of bubbles and flocculated particles, are different from the sum of those from sample 1 and sample 2. Possible reasons are bubble coalescence, particle flocculation and removal of particles from the top of the tank. When we compare the particle counts of samples 3 and 4, it is obvious that there exists a bubble bed interface at a depth between the sample locations. Therefore, this method can be used to locate the bubble bed interface without ambiguity.

The effect of sampling tube length

When the length of sampling tube is too long, the particle counts may be different as a result of coalescence or many other possible reasons. In order to avoid this problem, the length of tubes should be as short as possible. However, in a full-scale experiment at a WTP, the vertical tube that is immersed under water cannot be shortened.

Therefore, in order to assess the length effect of the sampling tube, a separate set of experiments was conducted

in a lab using tube lengths of 0.5 m, 1.0 m, 1.5 m and 2.0 m of internal diameter 3 mm.

The continuous reactor of 50 cm depth is filled with bubbles made from a bubble generator. Bubble samples are taken from the mid-depth of the continuous reactor (Figure 8(a)). Distilled water is used for this experiment to avoid the effect of particles. Only bubbles without particles are transferred through tubes of different lengths. The bubble count for each length is shown in Figure 8(b). All four samples show similar bubble counts. Therefore, it can be concluded that the effect of tube length is negligible up to the length of 2 m. In the actual plant, other effects may exist, but are not addressed in this research.

CONCLUSIONS

This study shows the existence of the bubble bed interface and describes how to locate the bubble bed depth. The bubble bed depth can be easily determined by measurement of particle-bubble size distribution by using a commercially available particle counter. This simple method was proved at a pilot plant constructed with a transparent acrylic wall by comparing the result with that observed by the naked eye. The coalescence effect during particle counting and length effect during sampling that might occur at an actual plant were found to be insignificant. The bubble bed depth profile of an operating DAF plant can be drawn under

different operating conditions. The deeper the bubble bed depth, the better the quality of effluent obtained. From this study, the relationship between higher loading rate and deeper bubble bed depth can be explained and therefore the possibility of optimizing the operation of DAF plant is suggested by using this simple method.

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