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> **Han, M.Y., Park, Y.H., and Yu, T.J. (2002). Development of a new method of measuring bubble size. *Water Science and Technology: Water Supply, 2*(2), 77-83.**

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Exhibit A to this Declaration is a true and accurate copy of the title page with library date stamp of *Water Science and Technology: Water Supply* (2002), from the University of Wisconsin-Madison Library collection. Exhibit A also includes an excerpt of pages 77 to 83 of that issue, showing the article entitled *Development of a new method of measuring bubble size* (2002). Based on this information, the date stamp on the journal title page indicates *Development of a new method of measuring bubble size* (2002) was received by the Kurt F. Wendt Library, University of Wisconsin-Madison on May 20, 2002.

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Date: December 17, 2020

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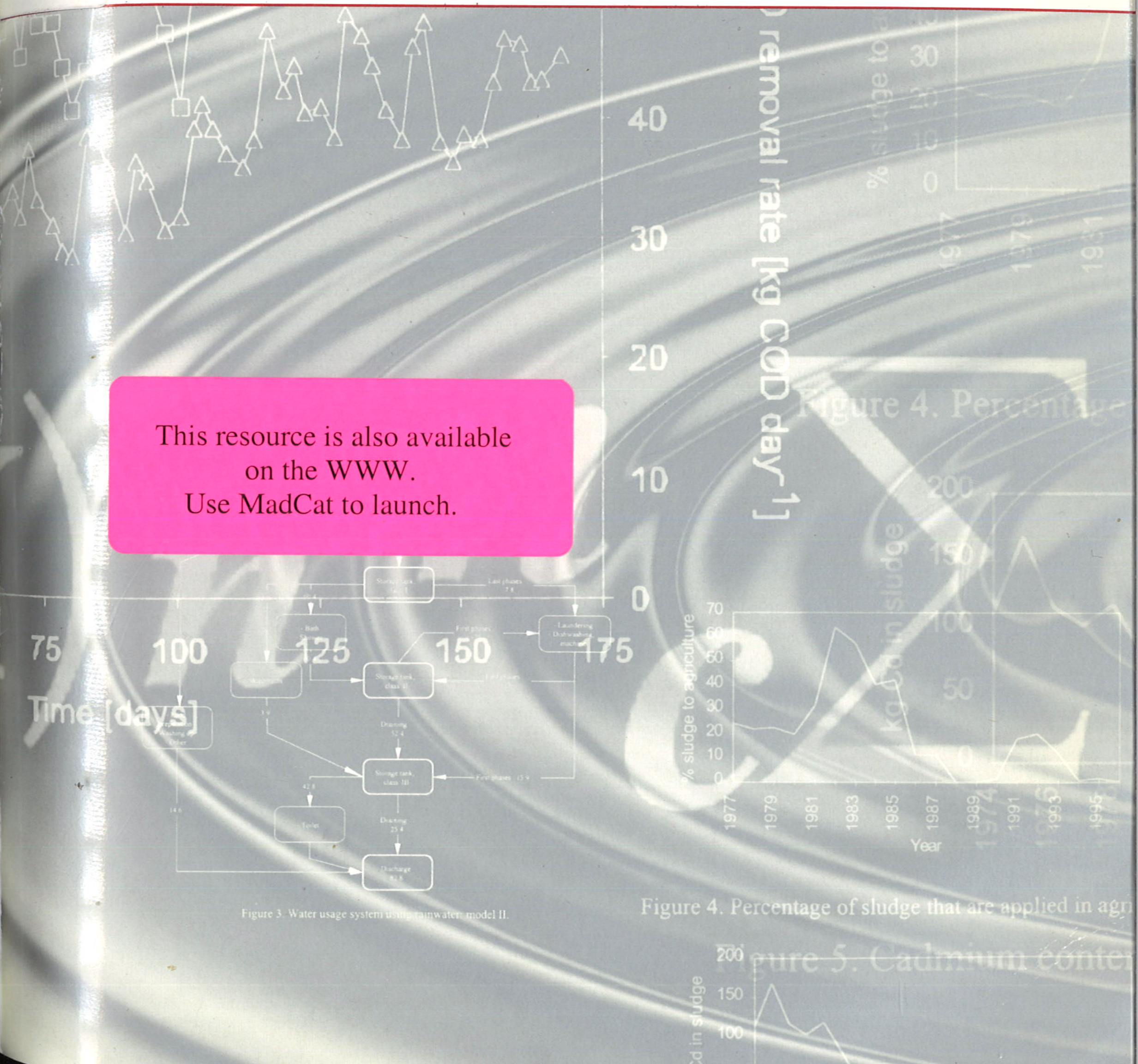

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Aims and Scope

Water Science and Technology: Water Supply publishes the selected proceedings of IWA conferences, symposia and workshops. All papers have been selected for publication after refereeing under the auspices of the conference editor(s) and the Programme Committee for each IWA event, and after review by a member of the board of editors.

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Water Science & Technology: Water Supply

2nd World Water Congress: Drinking Water Treatment

Contents

Development of a new method of measuring bubble size

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Abstract The use of bubbles in water and wastewater treatment, including dissolved air flotation (DAF) and electro-flotation (EF), is attracting much interest recently. These flotation processes are governed by characteristics of the bubbles as well as the particles, and therefore it is necessary to investigate the size distribution of the bubbles that are generated. In this research, a new method has been developed to measure the bubble size, using commercially available batch-type and on-line particle counters. The results are compared with the traditional image analysis method. Although there are some discrepancies, the results show that an on-line particle counter can produce reasonably accurate size distributions conveniently and efficiently. The bubble size measurement technique developed in this study will assist understanding and improvement of the DAF and EF processes, from both theoretical and practical points of view.

Keywords Bubble size; dissolved air flotation (DAF); electro-flotation (EF); image analysis; particle counter

Introduction

The use of bubbles in water and wastewater treatment, including dissolved air flotation (DAF) and electro-flotation (EF), has attracted much interest recently. Although the fundamental characteristics of the micro-bubble/particle/solution system should affect the removal efficiency of the process, the effect of each governing physical–chemical parameter has not been investigated fully, either experimentally or theoretically. According to recent modeling of the DAF process, the most important parameters that affect the removal efficiency are the size and zeta potential of both bubbles and particles (Han *et al.*, 2001; Han, 2002).

In DAF, bubbles are generated when air-saturated water is released into atmospheric pressure. The size of bubbles is mostly affected by pressure difference across the injection system and type of nozzle (AWWA, 1999). The size range is generally reported to be 10–100 μm, with the average being approximately 40 μm, under a pressure of 4–6 atmospheres (Edzwald, 1995). In EF, hydrogen and oxygen bubbles are generated when current is applied to the solution through metal electrodes. The average size range is reported to be around 20–40 μm, which is a smaller range than that of DAF (Burns *et al.*, 1997).

Several methods have been developed to measure the size of bubbles. The most straightforward method is image analysis. Because this method requires a complicated experimental setup and is time-consuming, it is not easy to produce enough data to generate size distributions under different conditions. Another method is to measure the rising velocity of the bubbles and to calculate the sizes by Stokes' Law. However, because the sizes of bubbles are not uniform, and because the rising velocity of many bubbles is different from that of a single bubble, no general equations are available to predict the size distribution of bubbles from the rising velocities.

In this study, a new method to measure the size of bubbles, using particle counters, was developed. The bubble counting results obtained from both image analysis and particle

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counters are compared by measuring the bubbles that are generated under the same conditions in DAF and EF.

Methods

Bubble generation conditions

Dissolved-air-flotation. Air was pressurized and dissolved into water under 6 atm. To reduce interference from particles of solids, distilled and deionized water was used. Although particles smaller than 10 µm can be detected by the particle counter, only those larger than 10 µm were regarded as bubbles. To avoid over-counting the larger bubbles formed by bubble coalescence inside the tubing, the observations were made directly after the valve. Only a small volume of bubbles was generated to avoid the possibility that a high concentration might decrease the accuracy of the particle counters and increase bubble coalescence.

Electro-flotation. To generate bubbles by EF, distilled and deionized water (as above) was mixed with the same volume of tap water. Aluminium electrodes 5 cm square and of thickness 0.5 mm were used, and a DC voltage of 12 V was applied. The method relies on generation of hydrogen bubbles from the cathode. When aluminium electrodes are used, Al^{3+} ions and oxygen bubbles are generated from the anode. The aluminium ions hydrolyze in water, producing floc particles that interfere with the measurements of bubble size. To avoid this, the anode was wrapped with GF/C filters (pore size: 0.45 µm) to prevent floc particles and oxygen bubbles being introduced into the sampling tube.

Bubble size measurement

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.

Bubbles were generated inside the measuring cell to prevent the change of bubble size when bubbles are introduced into the cell through a tube in both DAF and EF. Images of bubbles were taken using the CCD camera. 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 in DAF and directly above the cathode in EF.

Batch-type particle counters. A batch-type particle counter (Multisizer II, Coulter) was used to measure the sizes of bubbles. Figure 2 shows the configuration of the measuring cell

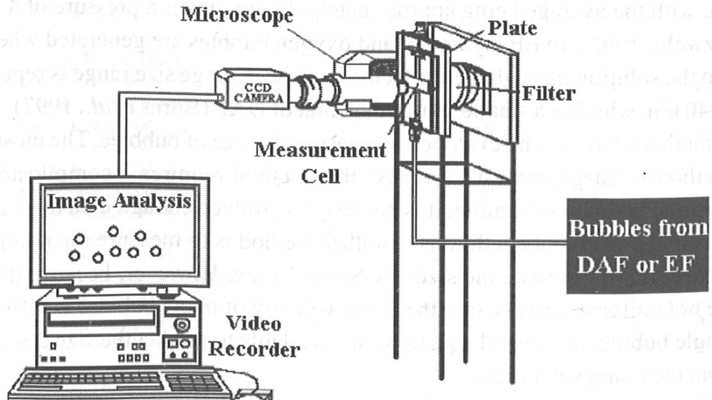

Figure 1 Image analysis system

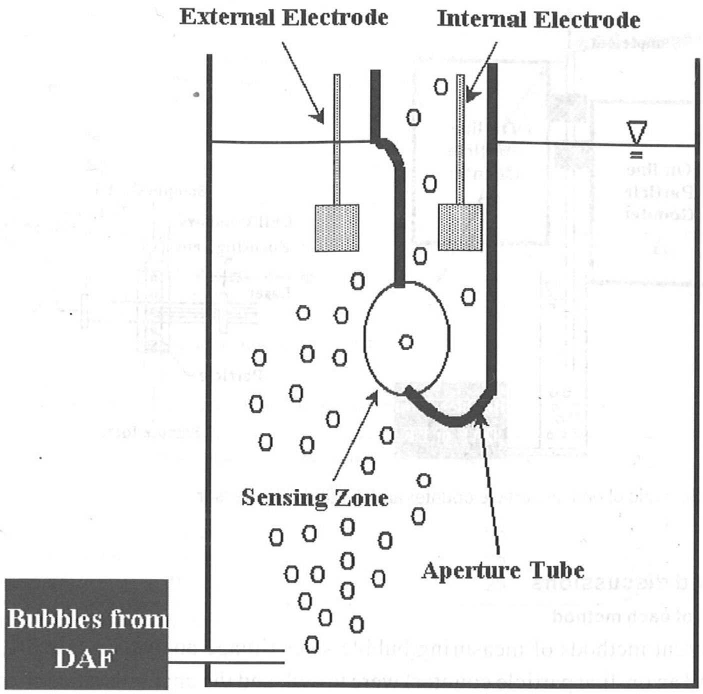

Figure 2 Schematic of batch-type particle counter

of the Multisizer II. Bubbles generated inside the cell were introduced through the opening in the aperture. An aperture size of 200 μm was used in the experiment. In this method, a constant electric current passes between the two electrodes through the electrolyte. When particles (bubbles in this research) pass through the sensing zone, the electrolyte volume decreases, which increases the resistance to the electric current. The amount of resistance is exactly proportional to the volume of particles, and this volume is converted to the size of equivalent spherical particles or bubbles. Although the result might be considered accurate because of the narrowly divided channel (256 channels), the application is limited to laboratory experiments because sampling and measuring is quite difficult. Furthermore, bubbles generated by EF cannot be measured, because of the electrical disturbance to the measuring system.

On-line particle counters. An on-line particle counter (Chemtrac Model PC2400 D, USA) was used to measure the sizes of bubbles. In this method, a laser light shines through the sensor onto the detector. When the sample passes through the sensor, the light is scattered and obscured by the particles. This scattering and obscuring of the light causes a decrease in the intensity of the light reaching the detector that is proportional to the particle size. According to the decrease, a voltage pulse is generated. Here, the number of pulses represents the number of particles, and the height of the pulse the size of the particles. This instrument can measure over the size range of 2–400 μm in seven user-definable size ranges. In this research, two identical particle counters were used to record data for 14 channels. To minimize possible bubble coalescence inside the tube, a straight tube, which was kept as short as possible, was used, and the sampling flow rate was kept at 100 ml/min which is recommended by the manufacturer.

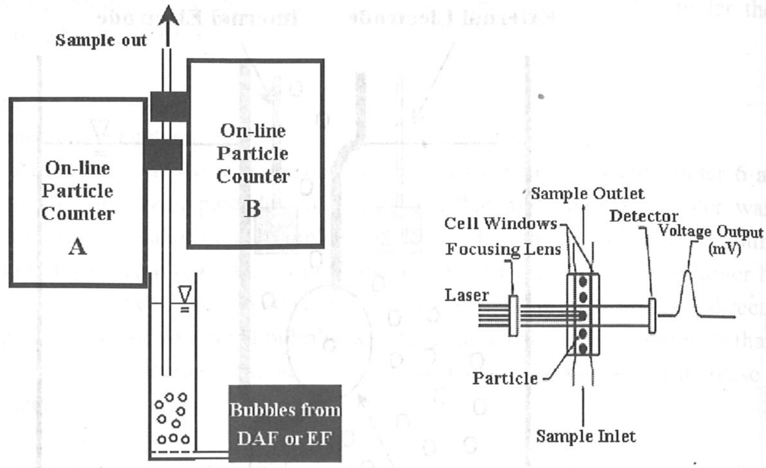

Figure 3 Schematic of on-line particle counter and details of the sensor

Results and discussions

Comparison of each method

Three different methods of measuring bubble sizes (image analysis, a batch-type particle counter, and an on-line particle counter) were tested, and the characteristics of each method are compared in Table 1. The batch-type particle counter is not suitable for bubbles generated by EF. Continuous size measurement is not possible using the image analysis method and the batch-type particle counter.

However, the results are much more accurate than those from the on-line particle counter. The most useful feature of the on-line particle counters is the very rapid rate at which data can be acquired. The time needed to measure 2,000 bubbles by each method was 3,000, 30, and 10 minutes, respectively.

Bubble size in DAF

The size and size distribution of bubbles generated from DAF were measured by image analysis, batch and online particle counters, respectively. It is important to keep the pressure constant (6 atm.) throughout the DAF experiments, because the size of the bubbles is dependent on the pressure. The results from each method are comparable, as illustrated in Figure 4 and listed in Table 2.

The average bubble size and modal bubble size recorded by each method was similar, but the size range was not. The size range of bubbles from particle counting methods is wider than from image analysis, which means that a small number of larger bubbles was detected in the particle counting methods. One possible reason for this might be the coalescence of bubbles during transport to the sensor. Another reason, applicable to the on-line particle counter, is possible overlapping of bubbles inside the sensor, which would result in counting fewer but larger bubbles. This is an inherent shortcoming of the instrument.

Table 1 Comparison of characteristics of bubble size measurement methods

	Application DAF	Application EF	On-line measurement	Size accuracy	Measuring time (min)*
Image analysis	O	O	X	Excellent	3000
Batch-type particle counter	O	X	X	Excellent	30
On-line particle counter	O	O	O	Good	10

* For measurement of approximately 2,000 bubbles

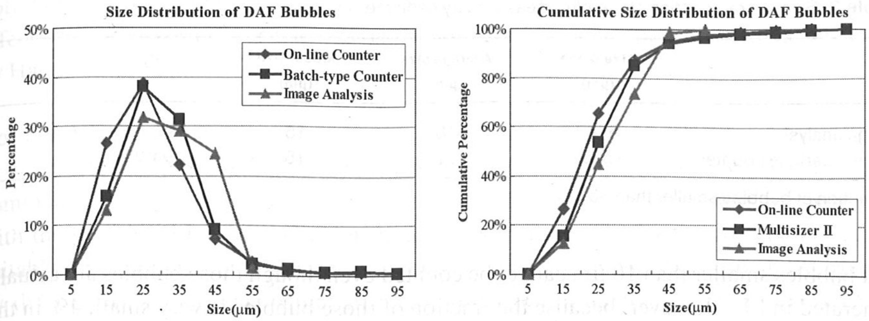

Figure 4 Comparison of bubble size distribution of DAF

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%
Batch-type particle counter	13–96	31	25	99.0%
On-line particle counter	15–85	28	25	97.6%

* Fraction of bubbles smaller than 55 μm

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 generated from DAF by a particle counter is considered good enough to be used for process monitoring. The fast response of the on-line particle counter is an especially good feature.

Bubble size in EF

Both the image analysis method and the on-line particle counting method were used to measure the size of hydrogen bubbles generated from EF. The batch-type particle counting method cannot be used for EF, as described previously. The size distribution and cumulative distribution of bubbles are compared in Figure 5. The average size, modal size, and size range of bubbles are compared in Table 3.

As the result of DAF experiments, a wider bubble size range was observed for the on-line particle counter compared with image analysis. The reason for this is expected to be the same as with DAF. The difference between the two methods for average bubble size and d_{35} is slightly larger than observed for DAF. This is because of disturbance by the floc particles produced during electrolysis. Another error in the application of the new method in EF is

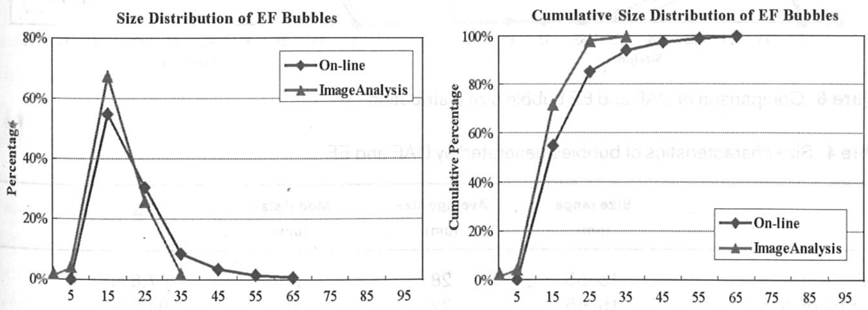

Figure 5 Comparison of bubble size distribution of EF

Table 3 Size characteristics of bubbles measured by each method

	Size range (μm)	Average size (μm)	Modal size (μm)	d_{35}*
Image analysis	5–40	18	15	99.6%
On-line particle counter	15–65	22	15	94.2%

* Fraction of bubbles smaller than 35 μm

that bubbles smaller than 10 μm cannot be counted even though those bubbles are actually generated in EF. However, because the fraction of those bubbles is very small, 4% in this study, the new method is considered to be quite acceptable also in EF in spite of these problems.

Bubble size comparison between DAF and EF

Since it is found from above experiments that the on-line particle counting method can produce data of reasonable accuracy, the sizes of bubbles generated from DAF and EF are compared as in Figure 6 and Table 4.

The size of bubbles produced in DAF is in the range of 15–85 μm and the average size is around 28 μm, whereas the size produced by EF is in the range of 15–65 μm and the average is 22 μm. This result supports the generally known fact that DAF generates larger bubbles than EF does.

The average size of the bubbles produced by DAF in this work is smaller than those sizes reported in the literature. The reason is that in this study the bubbles are measured immediately after release from a 6 atm 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, valve, and orifice. Lower pressures tend to increase the size of the bubbles. In addition, because the chance of bubble coalescence increases with the time between generation and measurement, the size of bubbles will increase.

In practice, it has been a generally accepted concept that smaller bubbles are preferred in order to achieve a larger bubble surface area and so to maximize mass transfer. However, if the collision and attachment mechanisms are considered in DAF and EF processes, the

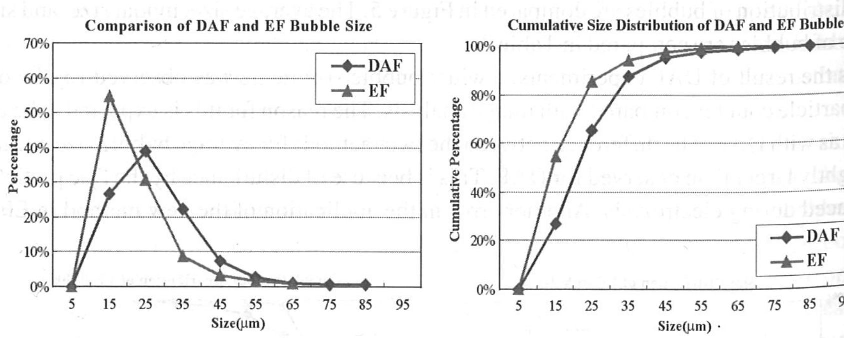

Figure 6 Comparison of DAF and EF bubble size distribution

Table 4 Size characteristics of bubbles generated by DAF and EF

	Size range (μm)	Average size (μm)	Modal size (μm)	d_{35}*
DAF	15–85	28	25	87.6%
Electro-flotation	15–65	22	15	94.2%

* Fraction of bubbles smaller than 35 μm

optimum size of bubbles should be dependent on the size of particles to be removed. The effect of bubble size and particle size on the collision efficiency in DAF has been modeled by Han (2001).

Conclusion

In this research, a new method to measure bubble size distribution was developed by using commercially available batch-type and on-line particle counters. The results compare well with the traditional but laborious image analysis method. The batch-type counter is not suitable for measurement of the size of bubbles generated from EF because of disturbance by the EF electric current. Although there are some discrepancies, the on-line particle counter can produce reasonably accurate results in a very short time.

The bubble counting method described in this paper will be helpful for research in DAF and EF processes, either theoretically or practically. The mechanism of bubble and particle collision and its effect on the removal efficiency can be described. An optimum operating condition of the bubble generation system and/or pretreatment system can be diagnosed by measuring the size of bubble at several places in the reactor and processes.

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