Design parameter estimations for adjustable bubble size in bubble generating system

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ABSTRACT

In this study, we developed a customized low cost and low energy bubble generator that can control bubble size. Hence, it can be used not only in the water treatment process but also in various other processes. This device was able to generate bubbles with a very simple system using only a general pump and a mixing chamber. Increasing the number of partition walls in the mixing chamber reduced the bubble size. Furthermore, bubbles of a few hundred nanometers were produced by the shear stress caused by increasing the thickness of the partition wall. Although the generated sub-micron bubbles were too small for their exact size to be measured using an image analysis and particle counting method, it was possible to confirm their existence indirectly through the coalescence arising from ultrasonic irradiation. The device used in this research is simple and allows bubble size to be adjusted easily by controlling the design of the mixing chamber. Therefore, it can be applied to a water treatment process, as well as a variety of other processes.

Key words | bubble generating system, bubble generator, bubble size, dissolved air flotation (DAF) pump, nano bubble, sub-micron bubble, tailored bubble

INTRODUCTION

The sedimentation process removes particles by gravity settling, whereas dissolved air flotation (DAF) floats particles to the surface and removes them by using the buoyancy of bubbles. These bubbles represent one of the most important factors in determining the efficiency of the DAF process. According to a trajectory analysis model (Han 2001), the maximum collision efficiency between the bubbles and the particles to be removed is achieved when the size of the bubbles and the size of the particles are similar. With smaller bubbles, the removable size range of the particles is increased and the number of bubbles is increased. Hence, many researchers are studying the generation of smaller bubbles. Figure 1 shows a study of bubble size (Bennett, 1998; Clayton et al. 1991; Edzwald 1995; Han et al. 2002b; Han et al. 2004; Han et al. 2007; Zabel 1992; Jameson and Manlapig 1991).

In the flotation process, methods such as dissolved air (gas) flotation (DAF), induced air flotation, vacuum flotation, electroflotation, and microbiological auto-flotation exist depending on the method of generating bubbles (De Rijk et al. 1994). However, the DAF process is most commonly used to generate a stable bubble volume concentration. Nonetheless, these bubble generating devices have a fairly complex system, a high energy consumption, and are not capable of stable bubble generation.

If it were possible to generate bubbles in a simple manner with low cost and low energy, it is expected that this would expand the use of bubbles in water treatment process, as well as various other processes.

Therefore, the objectives of this study are to (1) develop a simple device for generating bubbles with low cost and low energy for the application of microbubbles to various processes, including water treatment, and (2) develop a device that can generate tailored bubbles by changing the design of the developed system and by analyzing the variation in the size of the bubbles.

DEVELOPMENT OF NEW BUBBLE GENERATOR

The bubble generating system, which is the most widely used method in the DAF process, has a high-pressure recycle pump, compressor, and dissolve tank wherein air is mixed with recycled water, as shown in Figure 2 (AWWA 2010). The pressure in the...
dissolve tank is maintained at 5 or 6 atm by the compressor. The high-pressure recycle pump is used to supply water to the dissolve tank. In the dissolve tank, the air is dissolved into the water using high pressure, in accordance with Henry’s law. The pressurized water, which is a mixture of gas and liquid, is released to the reactor through an outlet and a nozzle, and microbubbles are generated by the pressure difference.

However, the new bubble generator developed in this study has only a normal pump and a mixing chamber, as shown in Figure 3. The inflow rate of the air can be controlled by the installation of an air valve and an air suction pipe in the suction pipe of the pump. Air is naturally pulled through the air valve by suction, and the water flows into the pump by its operation. The air and water mix, and the bulk phase of the mixture is split into smaller phases by the impeller inside the pump. The air and water mix again, and the mixture is pressurized. The pressurized mixture is released into the reactor through the outlet, where the pressure is 1 atm, generating microbubbles as a result of the rapid drop in pressure. The bubble generator developed in this study is called the super-speed impeller bubble generator (SIBG).

**BUBBLE SIZE CONTROL DEPENDING ON MODIFICATIONS OF BUBBLE GENERATOR DESIGN**

**Effects of number of partition walls in mixing chamber**

**Modifications of bubble generator design**

The mixing chamber for the SIBG has the same role as the pressure dissolve tank used in the DAF process. Porous partition walls are installed in the mixing chamber to create the same conditions as in the pressure dissolve tank, where the air is effectively mixed with the water, and an appropriate pressure is produced. The bubble size was measured according to the changes in the number of partition walls installed in the mixing chamber. The various mixing chamber structures with different numbers of installed partition walls are roughly described in Figure 4. A mixing chamber equipped with three partition walls was called SIBG(M1) and one with five partition walls was called SIBG(M2).
Changes in bubble size depending on number of partition walls

Bubbles generated from various bubble generators were measured by the particle counting method (PCM). PCM is a method of measuring bubbles by sampling the bubbles in the same way as measuring particles using a particle counter, taking into account that microbubbles behave like particles. Han et al. (2002a, 2002b) compared the results of image analysis to demonstrate the effectiveness of PCM.

The size of the bubbles generated by the conventional bubble generating system operated under a pressure of 6 atm in the DAF process was introduced in the graphs to evaluate the applicability of SIBG(M1) and SIBG(M2) in Figure 5.

The x-axis represents the size of the bubble, and the y-axis represents the percentage of the bubble size. Hence, the bubble size distribution for each bubble generator can be identified.

The average size and peak size of the bubbles are listed in Table 1 according to the type of bubble generating system.

In the DAF process, various design and operating conditions affect the size of the bubbles, such as the nozzle shape, bubble generation pipe length, and pressure. However, the most dominant factor in controlling the bubble size was the pressure of the saturator. For SIBG(M), smaller bubbles were generated by SIBG(M2), which had more partition walls than SIBG(M1). The peak points in the size distributions of both SIBG(M1) and SIBG(M2) were equal to 15 μm, which was smaller than the bubble size for DAF (6 atm).

A comparison of the size distributions generated by SIBG and DAF shows that SIBG(M) generated more bubbles with a size of 5–30 μm than DAF (6 atm). Bubbles smaller than 10 μm were generated only by SIBG(M). Moreover, the average size of the bubbles generated by SIBG(M2)
was 22 \( \mu m \), which was 10 \( \mu m \) smaller than the bubbles generated by the DAF process.

Effects of thickness of mixing chamber partition wall

Modifications of bubble generator design

The bubble size was investigated in relation to changes in the thickness of the partition walls. The changes in the structures of the mixing chamber are roughly shown in Figure 6. The thickness of the partition wall in the mixing chamber and the number of mixing chambers were changed. The partition wall was made several times thicker than that shown in Figure 6(a), which is the structure before the change, SIBG(M1). Figure 6(b) shows SIBG(N), which had thicker partition walls than SIBG(M1). SIBG(N) consisted of two mixing chambers connected in series. The details of the pump and mixing chamber utilized in SIBG(N) are summarized in Table 2.

Changes in bubble size depending on thickness of partition walls

No bubbles were observed by the naked eye when bubbles were generated by SIBG(N). No bubbles were counted by PCM, which is able to measure bubbles larger than 2 \( \mu m \). Therefore, either the bubbles were smaller than 1 \( \mu m \) or no bubbles were formed.

To more clearly prove the generation of sub-micron bubbles, the bubbles were investigated using an image analysis device. This image analysis device (Han et al. 2006) can measure up to 700 nm, which is less than the measurement range of PCM. As a result of analyzing the size of the bubbles using the image analysis device, some bubbles with a size of about 700 nm could be observed. However, a large number of bubbles could not be captured because of the limitations of the device. Figure 7 shows photos of the sub-micron bubbles generated by SIBG(N). The average size of the sub-micron bubbles shown in the photograph on the right was 854 nm. This makes it possible to estimate that very small bubbles of less than 854 nm were generated in SIBG(N).

DISCUSSION

It can be deduced that microbubble generation by SIBG occurs as a result of three major principles.

First, microbubbles were generated by the split phenomenon. The bulk of the sucked air was split by the impeller rotating at high speed in the pump. In addition, microbubbles were generated by the incremental flow velocity and friction split when the bulk of the air passed the orifice with several partition walls.

Second, microbubbles were generated by high saturation.

The packing materials used in the DAF process aid in the contact between the air and recycled water in the dissolve tank (AWWA 2010). The impeller rotated at high speed, and the porous partition walls played a role similar to the packing materials to aid in the saturation.

Third, microbubbles were generated by pressure differences.
The discharge rate decreased as the partition walls increased in, as discussed in the section, Effects of number of partition walls in mixing chamber. The pressure in the mixing chamber might have caused this phenomenon. In fact, 4.1 atm of pressure was measured by a pressure gauge installed at the top of the mixing chamber for SIBG(M1). The flow is described in Figure 8 when magnifying the orifice at the porous partition walls in the mixing chamber. De Rijk et al. (1994) described rapid drops in pressure using Bernoulli’s equation when the flow was passing through a narrow orifice.

When the pressurized water passed through the orifice, the velocity was high and the pressure was low. After passing the orifice, a mixing zone was produced where the flow was rapidly mixed. \(P_k\) was very low and \(v_k\) was very high at the orifice, where a turbulent jet stream was generated, and a negative pressure zone was generated. Thus, microbubbles were generated by the pressure difference, as shown in Figure 9.

A similar phenomenon occurs in the DAF process because of the use of a similar device in this process, which has a nozzle at the outlet of the air-dissolve tank. However, the significant difference was the number of partition walls. When the number of partition walls increased, the phenomenon creating the pressure difference was repeated several times. For this reason, a larger number of bubbles with a size of 5–30 \(\mu\)m were generated in SIBG(M) than in the DAF process, and the bubble sizes of SIBG(M1) and SIBG(M2) were different.

The sub-micron bubble generation in SIBG(N) is considered to be a result of the thickness of the orifice. The orifice of a thickened partition wall can be regarded as a tube. According to Hazen-William’s equation, when the length of the tube increases, the head loss increases. Therefore, the pressure difference is greater by Bernoulli’s equation. By conducting turbulent \(k\epsilon\) modeling and a cavitation tube experiment, Hu et al. (1998) demonstrated that the pressure difference is greater at the outflow part of a cavitation tube and negative pressure can occur in a relatively short tube of 5 cm. Based on these principles, when the length of the tube is increased (the thickness of the partition wall is increased), a greater pressure difference can appear. In particular, through the momentum equation of the fluid (Crowe et al. 2008), the shear force of the tube appeared to be proportional to the internal pressure difference and length of the tube. The tube’s internal pressure difference increases along its length. Thus, if the length increases, the shear force can be seen to appear greater. For these reasons, it is considered that the high shear force inside the tube caused the suctioned air to break up and sub-microbubbles to be generated.

**CONCLUSION**

The new bubble generating system (SIBG) developed in this study was able to generate microbubbles with a
simple configuration. Moreover, the microbubble generation principles could be presented, along with a method for controlling the bubble size. By analyzing the bubble size dependent on the design of the partition walls in the mixing chamber, eventually it was possible to generate sub-microbubbles. By considering and measuring the properties of the bubbles in relation to a variety of design and operating conditions that were not covered in this study such as the opening ratio of the air inhaling valve, the rotational speed of the pump, and the orifice size of the partition walls of the mixing chamber, it will be possible to develop a tailored bubble generating system with low cost and low energy. These results can be applied to the DAF process as well as a wide variety of other applications and processes.

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REFERENCES


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