Measurement of Micro Bubbles Generated by a Pressurized Dissolution Method

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Abstract. Diameters of micro-bubbles are apt to range from about one mm to several-hundred mm, and therefore, it is difficult to measure a correct diameter distribution using a single measurement method. In this study, diameters of bubbles generated by a pressurized dissolution method are measured by using phase Doppler anemometry (PDA) and an image processing method, which is based on the Sobel filter and Hough transform. The diameter distribution and the Sauter mean diameter of micro bubbles are evaluated based on the diameters measured by both methods. Experiments are conducted for several mass flow rates of dissolved gas and of air bubbles entrained in the upstream of the decompression nozzle to examine effects of the entrained bubbles on bubble diameter. As a result, the following conclusions are obtained: (1) Diameter distribution of micro bubbles can be accurately measured for a wide range of diameter by using PDA and the image processing method. (2) The mean diameter of micro-bubbles generated by gasification of dissolved gas is smaller than that generated by breakup of air bubbles entrained in the upstream of the decompression nozzle. (3) The mean bubble diameter increases with the entrainment of air bubbles in the upstream of the decompression nozzle at a constant mass flow rate of dissolved gas.

1. INTRODUCTION

Micro-bubbles are the bubbles with diameter ranging from one to several-hundred μm, and they are characterized by large interfacial area concentration per unit gas volume and low relative velocity between gas and liquid phases. They have possibilities of improving the efficiencies of chemical reactors, water treatments and washing processes. Generation of fine micro-bubbles of high number density is required in these applications of micro-bubbles (Fujikawa et al., 2003, Sadatomi et al., 2005). Measurements of bubble diameter and bubble number density are, therefore, indispensable for development and improvement of micro-bubble generators. Several measurement methods are available to measure bubble diameter. Intrusive measurement methods such as electrical or optical probe cannot be applied to micro-bubbles due to the small inertia and the high surface tension forces caused by their small diameters. Although phase Doppler anemometry (Dominick and Durst, 1995) is one of powerful tools to measure diameters of spherical particles, it is applicable only to bubbles smaller than a couple of hundreds μm. Image processing measurements are frequently used to measure diameters of micro-bubbles. It is not easy to accurately measure the diameters of bubbles smaller than 10 μm. Hence, it is difficult to measure a correct diameter distribution of micro-bubbles using a single measurement method.

Generation methods of micro-bubbles can be classified into two groups, i.e, methods based on
bubble break-up and methods based on gasification of dissolved gas (pressurized dissolution method). The latter method is superior to the former from the point of view of generating fine bubbles. Since the void fraction of micro-bubbles generated by the latter method is determined by the concentration of dissolved gas which depends on the pressure at the dissolution section, dissolution under a high pressure condition is necessary to increase the bubble number density and the void fraction. One of the possible methods to increase the void fraction under a low pressure condition is utilization of breakup of bubbles injected in the upstream of the decompression nozzle. However, the effects of the injected bubbles on the diameter and number density of generated bubbles are not clarified yet.

In this study, diameters of bubbles generated by a pressurized dissolution method are measured by using phase Doppler anemometry (PDA) and an image processing method, which is based on the Sobel filter and Hough transform. The diameter distribution and the Sauter mean diameter of micro-bubbles are evaluated based on the diameters measured by the both methods. Experiments are conducted for several mass flow rates of dissolved gas and of air bubbles entrained in the upstream of the decompression nozzle to examine effects of the entrained bubbles on bubble diameter.

2. EXPERIMENTAL APPARATUS

Schematic of the experimental apparatus is shown in Fig. 1. Air supplied from a compressor (Hitachi, SRL-2.2DA6) flows into the dissolution tank and mixes with water supplied from the pump (Iwatani, 25AJT0751B). A part of air dissolves in water through the air-water interface in the dissolution tank, and the other part of air is exhausted from the tank. The schematic of the dissolution tank is shown in Fig. 2. Air and water flow as a bubbly flow in the inner pipe and overflows at the top of the pipe. The falling film is formed on the outer surface of the inner pipe and water flows to decompression nozzle through the tank exit located at the bottom of the outer pipe. The pressure in the dissolution tank is measured by a pressure gauge. Figure 3 shows the concentration of dissolved oxygen measured at the exit of the dissolution tank. The concentration of dissolved oxygen increases with the water level $H$. That is, the flow rate of dissolved gas can be controlled by changing the water level $H$, i.e., the interfacial area of the falling film in the dissolved tank. The maximum concentration of dissolved oxygen is achieved for $H = 50$ mm, and it depends on the liquid volumetric flux $J_L$ at the decompression nozzle. Water with dissolved gas is decompressed at the nozzle shown in Fig. 4, and
micro-bubbles are generated in the nozzle and in the downstream of the nozzle. Air can be added to
the water flow at the mixing section which locates in the upstream of the nozzle to examine the effects
of air bubbles on the generation of micro-bubbles. An example of bubble size distribution in the
upstream of the nozzle is shown in Fig. 5. The bubble injected from the mixing section mainly ranges
from 100 $\mu$m to 1 mm and its diameter takes a peak at around 300 $\mu$m. The water temperature is kept
at $25 \pm 0.2 \, ^{\circ}\text{C}$ through the experiments.

Experiments are conducted for several mass flow rates of dissolved gas and of air bubbles entrained
in the upstream of the decompression nozzle to examine effects of the entrained bubbles on the
diameter and number density of micro bubbles generated by the pressurized dissolution method.
Experimental conditions are summarized in Table 1. The mass flow rate of gasifiable dissolved gas $W_{GD}$ is the mass flow rate of dissolved gas in the upstream of the decompression nozzle subtracting the
mass flow rate of dissolved gas under the saturated condition at the atmospheric pressure. The
dissolved oxygen in the upstream of the decompression nozzle is measured by a DO meter (HACH,
LDO101-01 HQ30d), and $W_{GD}$ is evaluated from the measured oxygen concentration based on the
Henry’s low. The mass flow rate of bubbles $W_{GB}$ is the mass flow rate of air injected in the mixing
section, which is measured by a flow meter (Japan Flow Cell, SPO-4). The $W_{GDm}$ is the maximum
value of the mass flow rate of dissolved gas which is achieved by using the present dissolution tank. In
cases 1 – 3, the total mass flow rate $W_G (= W_{GD} + W_{GB})$ is the same whereas the ratio of $W_{GD}$ to $W_G$ is
different. On the other hand, the mass flow rate of bubbles $W_{GB}$ is changed from 0 to $W_{GDm}$ for cases 1,
4 and 5 under the constant $W_{GD}$ condition. The liquid volumetric flux at the nozzle is ranged from 9 to
14 m/s. Note that $W_{GDm}$ depends on the liquid volumetric flux $J_L$ since the pressure in the dissolution
tank depends on $J_L$.

![Fig. 3 Performance of the dissolution tank](image)

![Fig. 4 Decompression nozzle](image)

![Fig. 5 Bubble size distribution in the upstream of the decompression nozzle (Case 4, $J_L = 14 \, \text{m/s}$)](image)
Table 1 Experimental condition

| Case | $W_G$ | $W_{GD}$ | $W_{GB}$ | $W_{GD}/W_G$ |
|------|-------|----------|----------|--------------|
| 1    | $W_{GDM}$ | $W_{GDM}$ | 0        | 1            |
| 2    | $W_{GDM}$ | 0.5 $W_{GDM}$ | 0.5 $W_{GDM}$ | 0.5         |
| 3    | $W_{GDM}$ | 0        | $W_{GDM}$ | 0            |
| 4    | 1.3 $W_{GDM}$ | $W_{GDM}$ | 0.3 $W_{GDM}$ | 0.77        |
| 5    | 2 $W_{GDM}$ | $W_{GDM}$ | $W_{GDM}$ | 0.5         |

3. MEASUREMENT OF BUBBLE DIAMETER

The diameter of micro-bubbles generated by using the pressurized dissolution method ranges from about one to several-hundred $\mu m$, and therefore, it is difficult to measure the bubble size distribution by using single measurement method. Hence, the bubble diameter is measured by using a combination of a phase Doppler anemometry (PDA) and an image processing method. The measurable diameter ranges of these methods are 0 - 150 $\mu m$ for PDA and 80 - 1000 $\mu m$ for the image processing method. The measurement position locates 250 mm downstream of the nozzle exit.

The PDA system (DANTEC, 60X) consists of a transmitter, a receiver and a processor. The scattering angle, i.e., the angle between the transmitter and the receiver, is 90 degree. The sample number of bubbles is 20 000.

An image processing method (Zhang et al., 2008) is used to measure bubble diameter distributions in the range of 80 - 1000 $\mu m$. Since bubbles are to be distributed throughout the channel, we have to remove out-of-focus bubbles from recorded images. We therefore adopt the Sobel filter to reject out-of-focus bubbles. Its applicability to bubbly flow was confirmed by Bröder and Sommerfeld, 2007. In the research of Bröder and Sommerfeld, 2007, bubble sizes were comparable to the depth of focus, and therefore, they did not need additional image processing for the detection and separation of overlapped bubble-images. Since bubble sizes in this study are smaller than the depth of focus (1.0 mm), it is necessary to detect and split overlapped bubble-images. Hence, we adopt a normal-line Hough transform to detect and separate the overlapped bubble-images (Yu et al., 2006).

Figure 6 is an example of an image at each processing step. First, the Sobel filter is applied to the original 8-bit grayscale image (Fig. 6 (a)) recorded by the high-speed video camera to obtain the gradient of the brightness level (Fig. 6 (b)). Then, the edges of bubbles located within the depth of focus are detected by binarizing the gradient distribution based on a predefined threshold level (Fig. 6 (c)). Applying the normal-line Hough transform to the binary image yields a vote function, which is used in the Hough transform to express the degree of certainty of the presence of the center at each position. The bubble center is detected by searching the maximum point in the vote function using an interpolation (Fig. 6 (d)). Finally, bubble diameters are evaluated for all the detected bubble centers as shown in Fig. 7. That is, pixels on a bubble edge are detected by scanning the binary image shown in Fig. 6 (c) in a predetermined range of the radius ($r_{min}$ to $r_{max}$) for each detected bubble center. The bubble radius is evaluated by calculating the mean distance between the center and the pixels on the edge. Since bubble shapes in this experiment are spherical as shown in Fig. 6 (a), the error in the image processing using the Hough transform due to non-sphericity is negligible. The sample number of bubbles is 20 000.

The probability density function $P_{PDA}(d_B)$ of bubble diameter measured by using PDA is merged with the pdf $P_{IP}(d_B)$ measured by using the image processing method by matching the probabilities, $\alpha$ and $\beta$, in the diameter range of 80 - 150 $\mu m$ to obtain the probability density function $P(d_B)$ of bubble diameter in the wide diameter range (Fig. 8):
The Sauter mean diameter $d_{32}$ is calculated from the resultant bubble size distribution. The bubble number density $n_{B,PDA}$ based on the PDA measurement is evaluated from the data acquisition rate $N_{PDA}$ in the PDA measurement:

$$n_{B,PDA} = \frac{N_{PDA}}{S_{PDA} V_L}$$  \hspace{1cm} (4)$$

where $S_{PDA}$ is the cross-section of the PDA measurement volume and $V_L$ the liquid velocity at the measurement point which is evaluated from the measured velocities for bubbles smaller than 30μm. Then the bubble number density is corrected based on $P(d_B)$:

$$n_B = \frac{\alpha + \beta - \alpha \beta}{\beta} n_{B,PDA}$$  \hspace{1cm} (5)$$
Fig. 8 Schematic of bubble size distributions measured by using PDA and the image processing method

4. RESULTS AND DISCUSSIONS

Figure 9 shows turbidity in the upper tank measured by a turbidity meter (OPTEX, TC-3000). The turbidity tends to increase with the number density of micro-bubbles. The solid line denotes the maximum mass flow rate $W_{GDm}$ of dissolved gas which is attained by using the present dissolution tank. Since the pressure in the dissolution tank increases with $J_L$, $W_{GDm}$ also increases with $J_L$. The turbidity increases with $J_L$ except case 3 in which all the gas is supplied as air bubbles ($W_{GD} = 0$). When $W_{GD}/W_G$ increases at a constant $W_G$ (cases 1 – 3), the turbidity decreases for low $J_L$ ($J_L < 12$ m/s) and it increases for high $J_L$ ($J_L \geq 12$ m/s). To the contrary, the turbidity increases for low $J_L$ ($J_L < 12$ m/s) and it decreases for high $J_L$ ($J_L \geq 12$ m/s) when $W_{GB}$ increases at a constant $W_{GD}$ (cases 1, 4, 5). That is, the turbidity decreases with increasing $W_{GB}$ for high $J_L$ whereas the total mass flow rate of gas $W_G$ increases with $W_{GB}$.

Figure 10 shows the measured Sauter mean bubble diameter $d_{32}$. For the constant $W_G$ cases (Fig. 10 (a)), the mean bubble diameters for $W_{GB}/W_G = 0$ (dissolved gas only) are smaller than those for $W_{GB}/W_G = 1$ (air bubble only). This indicates that the mean diameter of micro-bubbles generated by gasification of dissolved gas is smaller than that generated by breakup of air bubbles entrained in the upstream of the decompression nozzle. The mean bubble diameter increases with $W_{GB}$ not only for the constant $W_G$ cases (Fig. 10 (a)) but also for the constant $W_{GD}$ cases (Fig. 10 (b)). That is, entrainment of air bubbles in the upstream of the decompression nozzle decreases the mean bubble diameter.
generated by using the pressurized dissolution method. The Sauter mean diameter of generated bubbles $d_{32}$ is roughly correlated with the ratio of the mass flow rate of entrained air bubbles to the total mass flow rate, $W_{GB}/W_G$, for all the cases as shown in Fig. 12.

Figure 12 shows the measured bubble number density $n_B$. For the constant $W_G$ cases (Fig. 12 (a)), the bubble number density decreases with increasing $W_{GB}/W_G$. This is due to the decrease of bubble diameter shown in Fig. 11 (a) since the total mass flow rate of gas is constant for each $J_L$ condition. For $W_{GB}/W_G = 1$, the bubble number density increases with $J_L$. This is because the strong shear flow of the liquid phase in the nozzle due to high $J_L$ enhances bubble breakup in the nozzle and increases the bubble number density. Note that the bubble diameter also decreases with increasing $J_L$ and it is clear in the ensemble averaged bubble diameter (61 $\mu$m for $J_L = 10$ m/s, 45 $\mu$m for $J_L = 12$ m/s and 32 $\mu$m for $J_L = 14$ m/s) whereas it is not clear in the Sauter mean diameter shown in Fig. 10(a). For the constant $W_{GD}$ cases (Fig. 12 (b)), the bubble number density increases with $W_{GB}$ for low $J_L$ due to the increase of the total mass flow rate of gas $W_G$. To the contrary, it decreases with increasing $W_{GB}$ for high $J_L$. This indicates that a part of dissolved gas desorbs from water into air bubbles and the number of micro-bubbles generated by gasification of dissolved gas decreases. The present experimental results clearly indicate that the entrainment of air bubbles in the upstream of the decompression nozzle
deteriorates the performance of the micro-bubble generator. Note that the magnitude of the bubble number density is comparable to the number density of bubble nucleus used in numerical simulations of phase change (Hirt et al., 1976).

Figure 13 shows the product of the bubble number density and probability density function, which indicates the bubble number density for each bubble diameter. The number of small bubbles ($d_B < 50 \mu m$) decreases with increasing $W_{GB}$. On the other hand, the number of large bubbles ($d_B > 100 \mu m$) increases with $W_{GB}$. Figure 14 is the ratio of the total volume of each bubble class to the total bubble volume. Addition of air bubbles in the upstream of the decompression nozzle clearly decreases the volume fraction of bubbles smaller than 100 \mu m and increases that larger than 100 \mu m. These results indicate that the addition of air bubbles in the upstream of the decompression nozzle strongly affects the generation of micro-bubbles due to gasification of dissolved gas. It decreases the number of the micro-bubbles generated by the gasification due to the absorption of dissolved gas into the entrained air bubbles, whereas the number of bubbles generated by breakup of entrained air bubble increases.

![Figure 12 Bubble number density](image1.png)

(a) Cases 1, 2 and 3

![Figure 13 Number density distribution](image2.png)

Fig. 12 Bubble number density

![Figure 14 Volume fraction distribution](image3.png)

Fig. 13 Number density distribution

![Figure 14 Volume fraction distribution](image4.png)

Fig. 14 Volume fraction distribution
5. CONCLUSIONS

Diameters of bubbles generated by a pressurized dissolution method are measured by using phase Doppler anemometry (PDA) and an image processing method, which is based on the Sobel filter and Hough transform. The diameter distribution and the Sauter mean diameter of micro bubbles are evaluated based on the diameters measured by both methods. Experiments are conducted for several mass flow rates of dissolved gas and of air bubbles entrained in the upstream of the decompression nozzle to examine effects of the entrained bubbles on bubble diameter. As a result, the following conclusions are obtained:

1. Diameter distribution of micro bubbles can be accurately measured for a wide range of diameter by using PDA and the image processing method.

2. The mean diameter of micro-bubbles generated by gasification of dissolved gas is smaller than that generated by breakup of air bubbles entrained in the upstream of the decompression nozzle.

3. The mean bubble diameter increases with the entrainment of air bubbles in the upstream of the decompression nozzle at a constant mass flow rate of dissolved gas.

NOMENCLATURE

- $H$: water level in a dissolved tank [m]
- $J$: volumetric flux [m/s]
- $W$: mass flow rate [kg/s]
- $W_{GDm}$: the maximum mass flow rate [kg/s]
- $r$: bubble radius [m]
- $d_B$: bubble diameter [m]
- $d_{32}$: Sauter mean diameter of bubbles [m]
- $P$: probability density function
- $n_B$: bubble number density [1/m³]

Greek Letters

- $\theta$: volume of bubbles [m³]

Subscripts

- $L$: liquid phase
- $G$: gas phase
- $GD$: dissolved gas
- $GB$: bubble
- $PDA$: phase Doppler anemometry
- $IP$: image processing

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