Development of an optical imaging technique for particle number density

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Abstract
Accurate measurements of particle number density along with particle diameters and velocities are strongly required both in academic and industrial fields. A new imaging technique, through the evaluation of the effective depth of field of a camera, is developed using standard solid particles with constant diameters. To measure the effective depth of field for a wide range of particle diameters, three optical setups, named microscale, mesoscale, and macroscale setups, are used for the diameters of 50 μm – 201 μm, 201 μm – 3.97 mm, and 3.97 mm – 15 mm, respectively. The measured effective depth of field is further applied to measure the size dependence of the number density of entrained bubbles by breaking waves in a wind-wave tank. The results show that the slopes of the number density of the entrained bubbles in the experiments corresponded to those measured by a phase Doppler particle analyzer under 500 μm, and was -5 over 500 μm in both fresh and salt waters. This emphasizes that the present imaging technique can measure the diameters and particle number density with high precision and is important for measurements of droplets, bubbles, and solid particles with a wide range of diameters.

Keywords: Image analysis, Particle, Bubble, Wind wave, Shadow sizing method

1. Introduction

It is of great importance to accurately measure the number density of droplets, bubbles, and solid particles both in academic and industry. In the geophysical field, for example, the high-precision measurement of droplets and bubbles is required to determine the breaking intensity of ocean waves associated with dispersed droplets and entrained bubbles, which causes significant transport of momentum, heat, and mass across the sea surface (Wanninkhof et al., 2009; Takagaki et al., 2012, 2016a, 2016b; Ivano et al., 2013; Krall et al., 2013). Since raindrop impingements on the sea surface cause additional droplet dispersion and bubble entrainment (Takagaki and Komori, 2007, 2014; Takagaki et al., 2014), a new measurement technique is essential in the case of rain. Besides, solid particles with a wide range of diameters are used in many industrial and chemical processes (e.g., fluid bed), and there the measurements of particle number density are of great importance. Recently, a micro bubbling technique is widely used in a crystallization process of dolomite (CaMg(CO₃)₂) from concentrated brine. Since the dolomite is produced by a reaction on a gas-liquid interface, the production rate strongly depends on the size and number density of micro bubbles. So, the hot
topics in the academic area is how to accurately measure the size and number density of micro bubbles for improving the micro bubbling technique and for applying the technique to crystallization processes for various chemicals (e.g. Tsuchiya et al., 2017).

Many techniques have been used for measuring the number densities of particles such as bubbles and droplets. These techniques are, for example, a phase Doppler particle analyzer (PDA Dantec Dynamics), an image technique called the shadow sizing method (SS Dantec Dynamics) and an optical fiber technique (e.g., Mizutani et al., 2013). The phase Doppler particle analyzer (PDA) is a non-contacting measurement technique that uses interference fringe patterns generated by laser light. The diameters and number densities of solid spheres, droplets and bubbles with diameters ranging from 1 μm to 1 mm can be measured by the PDA. However, it is difficult to apply the PDA to particles with diameters larger than 1 mm. The optical fiber technique (Mizutani et al., 2013) features high-resolution measurement, but it is a contacting measurement technique. The SS is a non-contacting imaging technique that has no maximum limitation for particle diameter. Although the SS can measure the diameter and two-dimensional velocities of particles without any calibration, it must first needs to validate the effective depth of field (DOF) before measuring the particle number densities. The DOF significantly depends on the optical setup (e.g. Kashdan et al., 2007; Fdida and Blaisot, 2010), but no study has been conducted to validate the DOF for wide size range of particles.

The purpose of this study is, therefore, to develop a technique for validating the DOF for the SS. In addition, by utilizing the measured DOF, the number density of bubbles entrained by wave breaking was measured in a wind-wave tank.

2. Optical measurement technique

The SS is a particle measurement technique based on image analysis (Fig. 1(a)). The moving particles obstruct background light, leaving shadows on monochrome images. By applying the SS analysis applied to the monochrome images with particle shadows, the number and diameter of particles can be calculated. When the particles A – C in Fig. 1(a), dispersed in liquid, are captured by a charge-coupled device (CCD) camera, and only particle B is placed closer to the focus point, the image is like Fig. 1(b). The shadows of particles placed away from the focus point (particles A and C in Fig. 1(a)) appear as relatively light gray images. On the other hand, particles placed closer to the focus point, such as B, have relatively dense gray images. By choosing a threshold level for discriminating the shadow darkness, we can determine the darkness level where particles can be detected. Thus, we can set a condition where only particles near the focus point can be detected. In addition, we define the DOF as the length of the particle detection field in the depth direction. The measurement volume is given by the product of the camera’s field of view and DOF. Because the DOF changes depending on the selected threshold level and a particle size, the optimum threshold level should be determined by clarifying the DOF dependence on the particle size through a calibration experiment. Figure 1(c) shows a schematic diagram of the calibration apparatus. In the apparatus, polymeric standard particles (Thermo Fisher Scientific FJ series) and acrylic balls (Satoh Tekko PMMA) with constant diameters were placed at the bottom of a transparent acrylic tank. The images of those particles were captured from the bottom of the acrylic tank by a CCD camera (DANTEC Flow Sense 2M/E, 1200×1200 pixels). A Nd/YAG laser (New Wave Research Solo III; λ = 532 nm) was used here as a background light source, although the white or infrared light has been used in previous studies (e.g. Tokuhiro et al., 1998; Nogeira et al., 2003). The laser beam reflected by an aluminum plane mirror (SIGMA KOKI TFA-10C03-10) was first magnified by spherical surface plano-concave lenses (SIGMA KOKI: SLB-10-15NM), and then diffused using both a frost shaped diffuser plate (SIGMA KOKI DFB1-50C02-1500) and an optic-orange plastic diffuser. We can diminish laser speckles, which are bright points caused by the laser interference. The light passing through the acrylic container was reflected by an aluminum plane mirror (SIGMA KOKI TFA-10C03-10) and received by the CCD camera. The images of the particles were taken several times by the CCD camera while changing the distance between the camera and particles. In the coordinate system of the calibration experiment, the focal point of the camera was initially set to z = 0 mm. Thus, the increase in distance between the camera and particles corresponded to the increase in z in the positive direction. Table 1 shows the optical conditions for the SS and the diameters of the measured particles. Because it is impossible to calibrate the diameters of all particle sizes at the same focal length, the images in the calibration experiments were taken at three scales, named microscale, mesoscale, and macroscale. The detection rate of particles was stochastic because the pulse laser induced the fluctuations in background brightness.
Hence, the measured sizes of the particles at a certain point were averaged for over 20 captured images. Figure 1(d) shows the captured image of a particle and the gray level distribution, as explained later.

3. Wind-wave tank experiment

Figure 2(a) shows a schematic diagram of the experimental apparatus. The large wind-wave tank consists of a fan, settling chamber, contraction nozzle, test section, and an air outlet. The length of the tank is 26.7 m and the contraction nozzle has the square cross section of 1.8 m × 1.8 m. An aluminum honeycomb with the 0.2 m in length was placed in the contraction nozzle. The inlet of the test section is 0.6 m wide. The test section is 20 m long, 0.6 m wide and 1.3 m high. In order to prevent the effects of wall turbulence due to the tank bottom, the water depth was set at a sufficient
Table 1  Optical configuration for Shadow Sizing method in both calibration experiments and bubble experiments, along with measured sizes of standard solid particles in calibration experiments, and size ranges of bubbles in bubble experiments.

| photographic type                        | Microscopic | Mesoscopic | Macroscopic |
|------------------------------------------|-------------|------------|-------------|
| Magnifying power of TeleConversion Lens [-] | 3           | 1.5        | -           |
| F-number [-]                             | 4.0         | 5.0        | 4.0         |
| Focal length of front lens [mm]          | 105         | 200        | 105         |
| Length of berrows [mm]                   | 290         | 0          | 0           |
| Field of view [mm²]                      | 6.1 x 6.1   | 30 x 30    | 80 x 80     |
| Size of solid particles in calibration experiments [μm] | 50.02, 72.3, 201, 289, 494, 3970, 5560, 100, 138, 773, 1007, 7940, 12700 | 201, 3970 | 25400 |
| Size range of bubbles in bubble experiments [μm] | 50 - 200 | 200 - 4000 | 4000 - 25000 |

Fig. 2  Schematic diagram of (a) the large wind-wave tank and (b) Shadow Sizing method. Spanwise length (DOF = 0.32 m) of measurement area in Fig. 2b shows the maximum DOF for measurement of largest bubbles with D = 10 mm.
Depth of 0.7 m. The sides and bottom are made of transparent glass and the top is made of acrylic. Further, the settling chamber is smoothly connected to the contraction nozzle at a contraction ratio of 9:1. To generate the steady air stream, an axial flow fan (Showa Electric AV-8KM) was driven by a 15 kW inverter-based three-phase motor, and the air stream flowed to the test section. The tank in the test section was filled with tap water purified by a 5-μm micropore filter. The air stream above the tank in the test section generated the waves on the air-water interface by wind shear. To prevent wind wave reflection, a wave absorber was set at the end of the test section. In the measurement coordinate system, $x$ is the streamwise direction, $y$ the vertical direction, and $z$ the span direction. The coordinate origin was set as the center of the test section inlet with a stationary water level. Free stream wind speeds were measured by a forward scattering laser Doppler velocimeter (LDV; Dantec Dynamics LDV P60) at $x = 13.5$ m and $y = 0.3$ m. The light source for the LDV was an Ar+ laser (LEXEL model 95-2; $\lambda = 514.5$ nm).

Figure 2(b) shows a schematic diagram of the bubble measurement system by the SS. The CCD camera (Dantec Dynamics Flow Sense 2M/E, 1200×1200) was used for capturing the images of entrained bubbles in the large wind-wave tank under the same optical conditions described above. The bubble measurements in the water was carried out at the position of $x = 13.5$ m and $y = 0.10$ m. Measurements were conducted out in both fresh water and salt water. The salt water had the same level of salinity 3.5 wt% as in natural oceans.

4. Results and discussion

In order to precisely measure the diameters of entrained bubbles by the SS, the measurement volume must be estimated accurately. As explained in the previous section, the measurement volume can be estimated by the product of the camera’s field of view and DOF. In addition, DOF depends on the threshold level chosen by the user. Therefore, we determined the optimum threshold levels to reduce the measurement error. Figure 1(d) shows the captured image of a particle and the gray level distribution. The $G_c$, $G_h$, and $G_D$ in the figure represent the maximum gray level of the camera, average gray level of the background, and the gray level difference between $G_h$ and the darkest part of the particle shadow, respectively. The $G_T$ and $G_H$ are the threshold levels used in the image analysis. The threshold level $G_T$ is the main parameter that helps to define the size of the particle. The threshold level $G_H$ is another parameter that determines the particle detection condition. Particles are detected only when $G_D$ is larger than $G_H$, that is, when the edge of particles are sharper than a threshold level given by a user. The particle diameter and number of detected particles are significantly affected by $G_T$ and $G_H$ values. Therefore, it is of great importance to determine the optimum values of $G_T$ and $G_H$. The particle diameter is estimated by

$$D_{\text{measure}} = \sqrt{\frac{4}{\pi} A},$$

where $A$ is the area enclosed by the isopleth curve of threshold level $G_T$ (Fig. 1(d)). The method to determine $G_T$ and $G_H$ is the same for the microscale, mesoscale, and macroscale measurements; therefore, only the analysis method for the mesoscale measurement is discussed here. The $G_T$ is determined so that the square sum of error $E$ for all particle sizes measured at $z = 0$ takes a minimum. The error $E$ is defined as

$$E(G_T) = \sum_{D_{\text{true}}} \left(1 - \frac{D_{\text{measure}}(G_T)}{D_{\text{true}}} \right)^2,$$

where $D_{\text{measure}}$ is the particle diameter obtained by image analysis and $D_{\text{true}}$ is the true particle diameter. When determining the optimum $G_T$, $G_H$ is not set in the image analysis. The relationship between $G_T$ and $E$ for the mesoscale measurement is shown in Fig. 3. Here, $G_T$ is normalized by $G_C$. In this case, the optimized value for $G_T/G_C$ is 33 %, where $E$ has a minimum. Figures 4(a) and 4(b) show the $z$ distributions of the particle detection rate and the measured particle diameter. At $z = -5$ to 5 mm, the particles were perfectly detected and values of $D_{\text{measure}}$ are close to $D_{\text{true}}$. On the other hand, at $z = -20$ to -5 mm and $z = 5$ to 23 mm, the particles were mostly detected and values of $D_{\text{measure}}$ differ from $D_{\text{true}}$. This means that particles with large error were also detected. In Fig. 4(a), DOF was computed by determining the $z$ range where the particle detection rate is above 50%. In this example, DOF was 43 mm, because the $z$ range showed $z = -20$ to 23 mm, and the maximum error of the measured particle diameter is approximately 60%. Figures 4(c) and 4(d) show the $z$ distribution of the particle detection rate and the measured particle diameter for analysis, where $G_T$ and $G_H$ were applied to the same images used in the previous analysis. In this case, DOF is 33 mm.
Fig. 3  Relationship between the square sum of error $E$ and threshold level $G_T$ in the mesoscale measurement for solid standard particle. $G_T$ is normalized by $G_C$.

Fig. 4  Distributions of (a) detection rate conditioned by threshold ($G_T$), (b) diameter conditioned by threshold ($G_T$), (c) detection rate conditioned by thresholds ($G_T$, $G_H$), and (d) diameter conditioned by thresholds ($G_T$, $G_H$), at the mesoscale measurement. $DOF$ is the effective depth of field for a solid standard particle with $D_{true} = 494 \, \mu m$; the dashed line shows the diameter, $D_{true}$. 
and the maximum error of the measured particle diameter is approximately 30%. By introducing the $G_H$ parameter, $DOF$ is shortened and the measured diameter error decreases. Hence, more accurate analysis is achieved. In order to decrease the measurement error, the $G_H$ with the highest value is required. However, a very high $G_H$ prevents particle detection. Therefore, the highest $G_H$ was determined, under the condition that all particles in the mesoscale measurement are detected at $z = 0 \text{ mm}$. The optimum values of $G_T$ and $G_H$ in the mesoscale measurement are 33 % and 15 % of $G_C$, respectively. The optimum $G_T$ and $G_H$ values determined by the calibration method for each measurement scale are shown in Table 2.

By applying the $G_T$ and $G_H$ parameters to the image analysis, $DOF$ for each particle size was computed. Figures 5(a) and 5(b) show the relationship between $DOF$ and particle diameter $D_{\text{true}}$ for the microscale and mesoscale measurements. Here, the straight lines represent the best fitting curves. In both microscale and mesoscale measurements, $DOF$ has a linear relation with particle diameter $D_{\text{true}}$. In the macroscale measurement (Figs. 5(c) and 5(d)), the particle detection rate at the rear and front fields of the focus position are very different. For example, at $D_{\text{true}} = 4 \text{ mm}$, values of $DOF$ values are 65 and 85 mm in Figs. 5(c) and 5(d), respectively. It can be explained that when large particles approach the diffuser plate, the figure of the particle blurs, causing a decrease in the detection rate. Therefore, the dependence of $DOF$ on the particle diameter $D_{\text{true}}$ was distinguished as $DOF_{\text{front}}$ on the front side (negative $z$) and $DOF_{\text{rear}}$ on the rear side (positive $z$), as shown in Figs. 5(c) and 5(d), respectively. This is because the increase in the distance between the camera and particles corresponds to the increase in $z$ in the positive direction. Furthermore, because the present bubble measurements were carried out at the center of a tank with 600 mm wide as explained below, the maximum $DOF_{\text{rear}}$ was set to 300 mm. The relations between the particle diameter and $DOF$ for all measurement conditions, are represented by the following experimental formulas:

\[
\begin{align*}
DOF & = 1.470 \times 10^2 D^{1.140}, \quad \text{(Microscale measurements, } 50.02 \leq D \leq 201 \mu\text{m}) \quad (3) \\
DOF & = 6.916 \times 10 \ D^{1.033}, \quad \text{(Mesoscale measurements, } 201 \leq D \leq 3.97 \times 10^3 \mu\text{m}) \quad (4) \\
DOF_{\text{front}} & = 1.249 \times 10^2 \log_{10} D - 3.848, \quad \text{(Macroscale measurements, } 3.97 \times 10^3 \leq D \leq 1.5 \times 10^4 \mu\text{m}) \quad (5) \\
DOF_{\text{rear}} & = 1.896 \times 10 \ D^{1.050}, \quad \text{(Macroscale measurements, } 3.97 \times 10^3 \leq D \leq 1.5 \times 10^4 \mu\text{m}) \quad (6) \\
DOF_{\text{rear}} & = 3.000 \times 10^2, \quad \text{(Macroscale measurements, } D \geq 1.5 \times 10^4 \mu\text{m}) \quad (7)
\end{align*}
\]

In fact, the $DOF$ for the same diameter particles depends on optical setups. For example, for the particle with $D_{\text{true}} = 0.2 \text{ mm}$, $DOF$ by the microscope setup (Fig. 5(a)) was larger than that by the mesoscope setup (Fig. 5(b)). However, according to the definition of $DOF$, the number density $\Theta(D_{\text{true}})$ for two optical setups takes the same value because the detected number of particles by the microscope setup is larger than that by the mesoscope setup due to the increase of $DOF$.

The large wind-wave tank described in the previous section was used in the bubble measurement experiment (Fig. 2(b)) with the same optical conditions as in the calibration experiments (Tables 1 and 2). The bubble number density $\Theta(D)$ is defined as

\[
\Theta(D) = \frac{N(D)}{(L_y - D)(L_y - D)DOF}, \quad (8)
\]
where, $N(D)$ is the measured average number of bubbles with diameter $D$ per unit image. In the present study, 4000, 4800 and 8000 images were taken for the microscale, mesoscale, and macroscale measurements, respectively, and Figs. 6(a) – 6(c) show sample images for each setups. Actually, there are some difference between the shadow of the solid particle in calibration experiment (Fig. 1(d)) and bubble experiments (Fig. 6). The differences are caused by the penetrated light in the center of bubbles, deformation of bubbles, and overlapping due to multiple bubbles. The differences will be discussed later. $L_x$, $L_y$, and $DOF$ in Eq. (8) are the width, length, and depth of the field of view, respectively, and $DOF$ is given by Eqs. (3) – (7). $\theta(D)$ is the number density of bubbles normalized by the total number density of bubbles $\Theta$

$$\theta(D) = \frac{\Theta(D)}{\Theta}, \quad (9)$$

where $\theta(D)$ satisfies

$$\int_{D_{\min}}^{D_{\max}} \theta(D) dD = 1. \quad (10)$$

Here, $D_{\min}$ and $D_{\max}$ are the measured minimum and maximum diameters, respectively. Figure 7 shows the relationship
between bubble diameter $D$ and the normalized number density of bubbles $\theta(D)$. In order to investigate the effects of the measured $DOF$ in calibration experiments on $\theta(D)$, $\theta(D)$ was estimated under the assumption that whole bubbles are detected in the tank with the width of 0.8 m, that is, for the constant $DOF$ value of 0.8 m, and the $\theta(D)$ is shown by the plus symbol (+) in Fig. 7. First, the comparison of $\theta(D)$ estimated using calibrated $DOF$ values in Eqs. (3–7) (● in Fig. 7) with $\theta(D)$ estimated using the constant $DOF$ value of 0.8 m (+ in Fig. 7) shows that the former $\theta(D)$ is approximately 100 times larger than the latter one for $D = 66 \mu m$. On the other hand, the former $\theta(D)$ is close to the latter one for $D = 1–10$ mm, because $DOF$ for $D = 1–10$ mm was relatively close to the width of the tank in present tank experiments. This mean that the proposed calibration method on the size distribution is important for accurately estimating the values of $\theta(D)$.
Previously, Misumi et al. (2000) measured entrained bubbles with diameters ranging from $D = 50 - 500 \, \mu m$ in a small wind-wave tank with fresh water by a PDA, and proposed an empirical curve with -3.66 slope (see dashed line in Fig. 7). As we explained in the introduction, the PDA can measure $D$ with higher precision and smaller diameter range than the SS, as well as measurement of $\theta(D)$ without preliminary calibration. From Fig. 7 for $D = 50 - 500 \, \mu m$, the present $\theta(D)$ perfectly corresponds to Misumi’s empirical curve by the PDA. This implies that the present calibration method on $DOF$ using standard solid particles can be applied to the measurements of the bubble size distribution $\theta(D)$. Finally, we also found that the present slope of $\theta(D)$ over $D = 500 \, \mu m$ was -5 in both fresh and salt waters. However, in more details, by comparing $\theta(D)$ in salt water to that in fresh water, we can see that $\theta(D)$ in fresh water is smaller and larger than that in salt water in the ranges of $D < 2 \, mm$ and $D > 2 \, mm$, respectively. This trend is also confirmed by Craig et al.(1993) and the present technique can accurately detect such a small difference in $\theta(D)$ between fresh and salt water.

There are some differences between the shadow of the solid particle in calibration experiment (Fig. 1(d)) and bubble experiments (Fig. 6), that is, the differences may be caused by the penetrated light in the center of bubbles (bubble B in Fig. 6(b)), blur shadow of bubbles (bubble A in Fig. 6(a)) due to multiple light reflections inside the bubble and defocus, deformation of bubbles (bubble D in Fig. 6(c)), and overlapping due to multiple bubbles (Fig. 6(c)). Calibration experiments using bubbles instead of standard solid particles are not realistic, since it is difficult to generate the same size bubbles and to keep them on the thin water pool. To confirm the applicability of present calibration method with standard solid particles to bubble measurements, $\theta(D)$ measured by the PDA is useful. In fact, the comparison of $\theta(D)$ measured by the PDA to $\theta(D)$ measured by the SS is shown by a dashed line in Fig. 7, and it is found that $\theta(D)$ measured by the PDA (Misumi et al., 2000) well agree with $\theta(D)$ measured by the SS in the range of $D = 50 - 500 \, \mu m$. This implies that the present calibration method on $DOF$ using standard solid particles can be applied to the measurements of bubble size distribution $\theta(D)$. The overlapping problem due to multiple bubbles is also very important. Although previous studies were often conducted in the dense bubble concentration field (e.g. $1 - 5 \%$ in Broder and Sommerfeld, 2007), present bubble experiments are conducted in dilute bubble concentration cases with the void fraction of $7 \times 10^{-4} \%$. Therefore, there is few overlapping in microscale and mesoscale setups (see Figs. 6(a) and 6(b)). On the other hand, there is overlapping in macroscale setup (Fig. 6(c)). In macroscale setup, we detect only the bubbles larger than 4 mm, and therefore the measurement error of the diameter of the large bubble might be small, even if the large bubble detection is affected by the overlapping due to small bubbles.

Finally, we note how to use our calibration equations. Actually, our calibration equations (Eqs. 3 – 6) are only applicable under the same optical setups with the bellows, teleconversion lens, lens, diffuser, frost diffuser, and Nd:YAG laser as used in this study. Since we provided the detailed optical setups in the previous section, any user can measure the number density of particles by the calibration equations of $DOF$ without performing the careful calibration. However, if the user wants to measure the number density of particles with different optical setups from ours, the user should perform the calibration by following our careful calibration method.

5. Conclusions

Through the calibration of $DOF$ in the SS, an original optical imaging technique for measuring the particle number density was developed. The new technique was applied to measure the number density of the bubbles entrained into the water by waves breaking in the wind-wave tank. The results show that the slope of the number density of the entrained bubbles in the experiments corresponds to those measured by a PDA under 500 $\mu m$, and is -5 over 500 $\mu m$ in both fresh and salt waters. This emphasizes that the SS with the present imaging technique can measure $D$ and $\theta(D)$ with high precision and is important for measurements of droplets, bubbles, and solid particles with a wide range of diameters.

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