# VISUALIZATION OF PRESSURE WAVE GENERATED BY COLLAPSE OF CAVITATION CLOUD USING FRAME DIFFERENCE METHOD

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ABSTRACT : *It is well known that high-speed water jet with cavitation clouds collapses near solid boundary to cause severe cavitation erosion. Visualization technique and quantitative estimate for the high-speed phenomena of cavitation cloud collapse are an important problem to solve the mechanism of cavitation erosion near solid wall. There are many small bubbles around wall impinging jet, that is, under high void condition. In this case, shock waves are easy to appear because of the decrease in sound speed. A shock wave near solid wall can be closely connected with cavitation impact and erosion. In this study, we use a high speed video camera and analyze the pictures by the frame difference method to estimate the cavitating jet and the high speed phenomena related to the jet. The frame difference is a useful image analysis method that can estimate the variation of high-speed images through the difference between two images in different time. This method is effective for qualitatively estimating the high speed motion. Applying this method to a time series of video images, we can visualize the time variation of cavitation cloud collapses.*

## 1 Introduction

It has been well known that a cavitation cloud around a jet impinging on a solid boundary causes erosion when it collapses [1],[2]. The visualization and the quantitative estimation of the high-speed phenomena during cavitation cloud collapse are important to study the mechanism of erosion. There are many small bubbles near the impingement wall, where the flow is in a high void state. Under this condition, it is easy to generate a shock wave because of the decrease in the speed of sound. The quantitative estimation of phenomena associated with the pressure wave is very useful so that the point of erosion can be predicted directly from the shock wave characteristics.

There have been many experimental and theoretical studies on the propagation of shock waves and/or pressure waves in flows containing many bubbles [3],[4]. Bubble collapse behavior that has a high impact on a nearby wall has been demonstrated in the studies on the interaction between a single bubble or multiple bubbles and a shock wave [5],[6]. Sugiyama et al. [7] examined the behavior of a shock wave and the bubble deformation through the measurement of the propagation of a shock wave in a flow containing bubbles. Wang and Brennen [8] showed the occurrence of high pressure and the speed of shock in cloud cavitation by a numerical study. Reisman et al. [9] investigated the impact and noise of a cloud cavitation on a hydrofoil under actual flow conditions through the measurement of the pressure wave. The authors have also suggested that a pressure wave due to the collapse of the shedding cloud is one of the mechanisms that trigger a reentrant motion related to the unsteady behavior of cloud cavitation [10].

Image processing technology has rapidly developed with the advances in recent computer technology. Using some techniques for the measurement of the flow field such as PIV, various methods processing the visible images of flow field have been proposed, which have mainly been applied to measurement regions in experiments. The subject of this investigation is the behavior of small bubbles or cavitation cloud that exists in water, rapidly deforms, grows and collapses. Although some techniques have been reported to quantitatively evaluate such phenomena, most of the results are for comparatively large-scale behavior of cavitating regions.

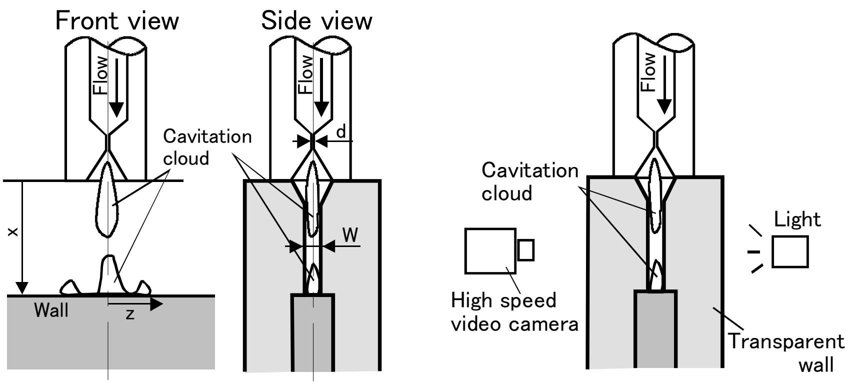
In this study we consider the behavior of small bubbles scattering on the circumference of a cavitation cloud (cluster of bubbles), which can be rapidly deformed by the pressure wave. The small bubbles on the circumference exhibit the growth and collapse behavior depending on the pressure in the flow field. That is to say, small bubbles exhibit the deformation (collapse) behavior as the pressure fluctuation caused by the pressure wave propagates. Such behavior can be observed using a high-speed video camera. However, a high-speed video image provides only instantaneously visual information. The quantification of such behavior is necessary to provide important information on the centralization phenomenon of fluid energy which causes cavitation damage.

To capture a high-speed image of the cavitating jet and the instantaneous phenomena, we perform a high-speed video observation and an image analysis using the frame difference method [10],[11], in which the amount of change between 2 images separated by a short time interval is evaluated by considering their difference. This analysis is applied to a time series of images to visualize the behavior change in the vicinity of a collapsing cavitation cloud and examine pressure-wave- generating behavior with lapse of time.

## 2 Acquisition of image and analysis

### 2.1 Experimental method

To acquire images of the cavitation cloud in a cavitating jet, we use the experimental apparatus




(a) Details of test section

(b) Observation method

Fig.1. Schematic diagram of test section

shown in Fig. 1. We cannot acquire a clear image near the wall due to the existence of the surrounding bubbles since the impinging cavitation cloud moves radially on the wall. Therefore, we observe the behavior of the cavitation cloud near the wall using a narrow channel, as shown in Fig. 1(a). A high-speed video camera (Photron SA1) and a digital still camera (Nikon D200) are used for observation. A cavitating region is black and the background is white in the image since the test section is illuminated by backlighting, as shown in Fig. 1(b). Here, a water jet is injected with discharge pressure $P_1$=6 MPa into still water under atmospheric pressure $P_2$. Fs, Tw and β are recording rate of a high-speed video camera, temperature of water and dissolved oxygen content of water, respectively. x is distance from the nozzle edge and d is diameter of the nozzle (d=1 mm).

## 2.2 Image analysis method

The high-speed video camera can save an image of m×n pixel to a personal computer. We use a gray scale image (256 tones) for the analysis and calculate one-dimensional gray level distributions to estimate the time variation of the phenomena as typically shown in Figs. 2(a), (b) and (c). Here, the element G(i,j) means the gray level at the cell (i,j) and Gaj is the average gray level in column j on an m×n −pixel image.

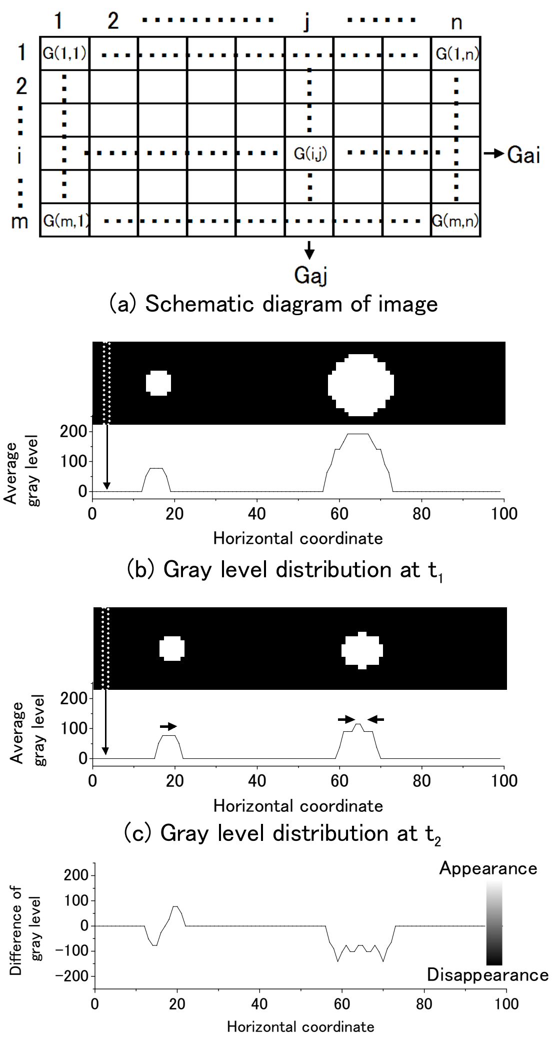
$$Gaj = \frac{1}{m}\sum_{i=1}^{m} G(i,j) \qquad (1)$$

Then we calculate the difference between the gray level distributions ΔGaj (=Gaj(t+Δt) −Gaj(t)) at different times. The initial image is generally black in the cavitating region and white in the noncavitating region (in this case, white is 0 and black is 255 in the gray scale level). A negative value of ΔGaj in a difference between the gray levels indicates the bubble collapse (or disappearance) and a positive value indicates the bubble growth (or appearance).

For example, as shown in Figs. 2(b), 2(c) and 2(d), when the white circle on the right-hand side of the picture becomes small, the difference between the gray levels shows a negative value, i.e., ΔGaj<0 in Fig. 2(d). As shown in the left-hand-side circle of Figs. 2(b) and 2(c), the right-side of the smaller white circle (in the moving direction side of the circle) shows an appearance of the white circle when the white circle moves to the right direction so that the difference between the gray levels becomes positive, ΔGaj>0, as shown in Fig. 2(d). On the other hand the value of ΔGaj becomes negative on the opposite side of the circle because of disappearance. Thus, we can estimate the region where the white circle appears and disappears. This method has an advantage because it can be used to analyze the image with reducing the background effect even though the illumination is not uniform. In the analysis results, we gradationally assign black and white colors to the negative and the positive value, respectively.

Here, we try to examine the variation of the gray level using some schematic images that simulate the propagation of the pressure wave. In the schematic image shown in Fig. 3(a) the gray level changes from the center of the image to the outward direction. Then another change propagates in the outward direction on the left of the image. To simulate the bubble collapse and rebound, the gray level changes from black to white and then the dark color (here, the size of image in Fig. 3 (a) is 30×100 pixel).

Figure 3(b) shows the time variation of the gray level in the schematic image. Two white regions which indicate the propagation of the pressure wave move in the outward direction. Since the gray level is estimated as the average value of the image, the variation of the gray level is not clear in the small white region (see Frame No. 0－10 in Fig. 3(b)). Figure 3(c) shows the result using the frame difference method. The black region ΔGaj＜0 moves to the outward direction with lapse of time. After the propagation of the primary pressure wave, another pressure wave appears at about Frame No. 20.



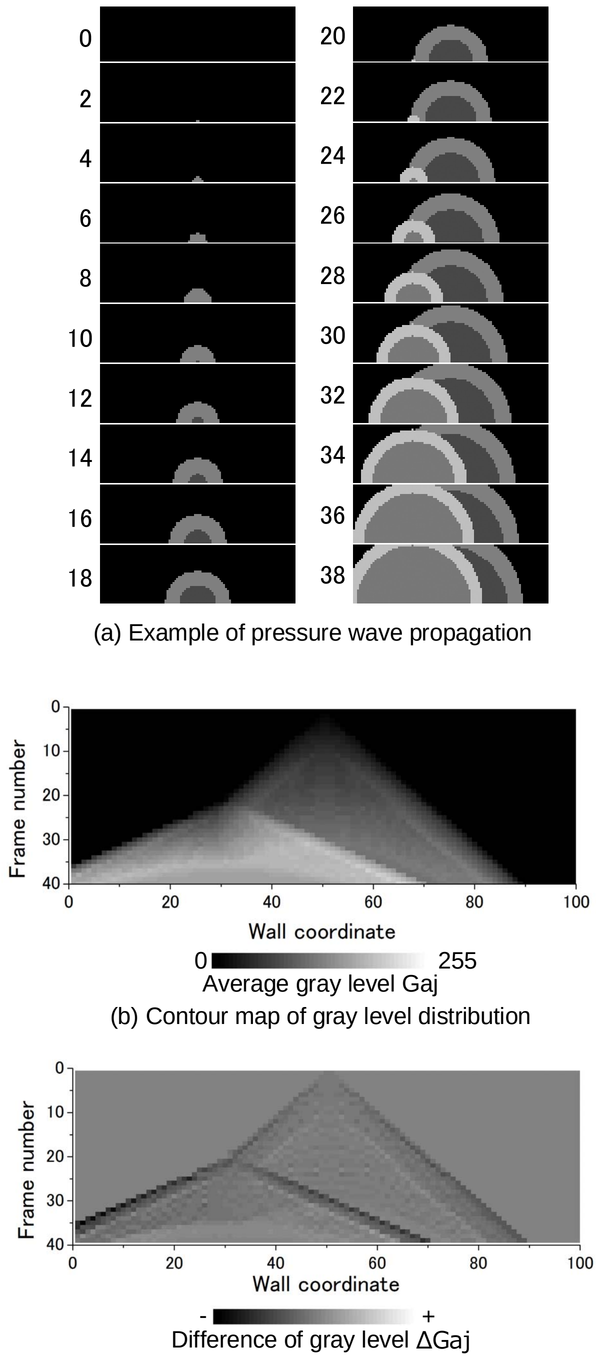

(a) Schematic diagram of image

(b) Gray level distribution at $t_1$

(c) Gray level distribution at $t_2$

(d) Difference of gray level distribution $t_2$−$t_1$

Fig.2. Example of image analysis (Frame difference method)

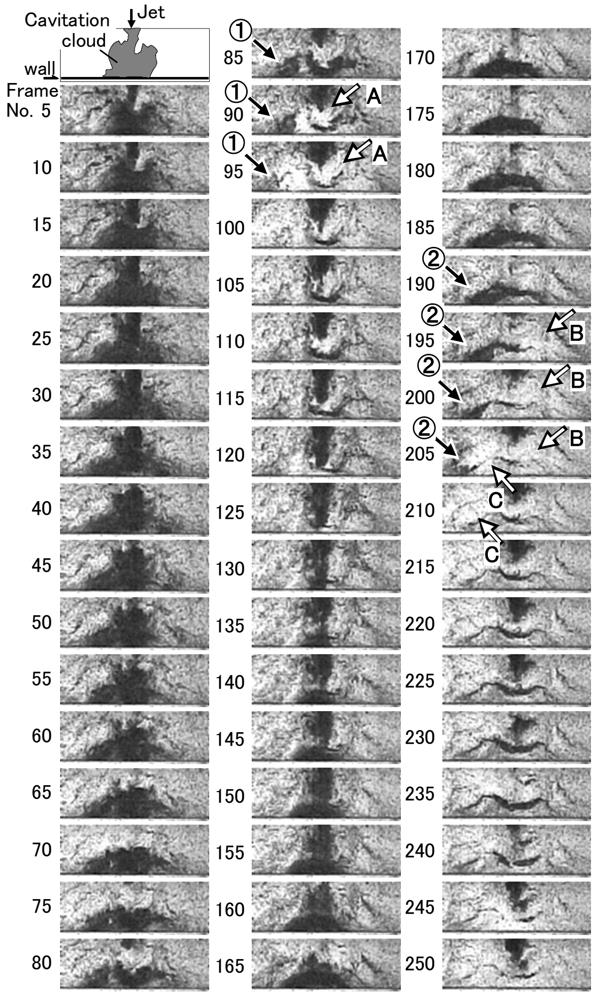



(a) Example of pressure wave propagation

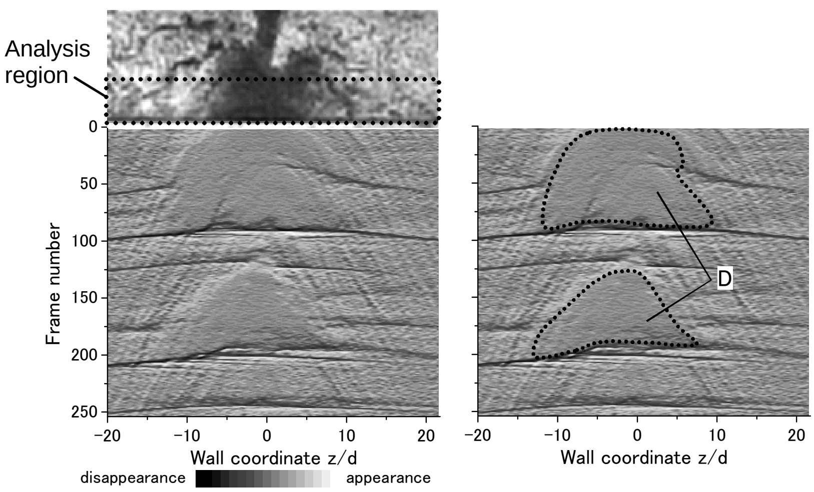
(b) Contour map of gray level distribution

(c) Contour map with frame difference method

Fig.3. Schematic diagram of pressure wave propagation and image analysis




(a) Collapsing behavior of cavitation clouds




(b) Image analysis of cavitation clouds

$P_1$=6MPa, $P_2$=0.1MPa, Tw=290K, $\beta$ =7.2mg/ℓ, d=1mm, x/d=30, Fs=100000fps

Fig.4. Collapsing behavior of cavitation clouds observed at 100kfps

As shown in Fig. 3(b), a sharp-pointed black region appears at a position and time when the pressure wave is generated. We can estimate the location and time at which the pressure wave generates and investigate the pressure wave phenomenon by comparison with the images taken by a high-speed video camera.

## 3 Behavior of cavitation cloud in cavitating jet

Figure 4(a) shows the behavior of cavitation clouds impinging on a solid wall taken by the high-speed video camera at 100 Kfps. The observation region is 40 mm in width about the jet axis and 15 mm in height from the wall surface.

The cavitating jet impinges periodically on the wall. Figure 4(a) shows the images of about two cycles of cavitation cloud. The cavitation cloud impinges on the wall and moves in the outward direction (Frame No. 30−70 and No. 130−170). Then the cavitation cloud divides into some bubble clusters and collapses as shown in Fig. 4(a) ① and ②. This behavior corresponds to a ring-shaped cavitation cloud that causes the ring-shaped erosion pits [1].

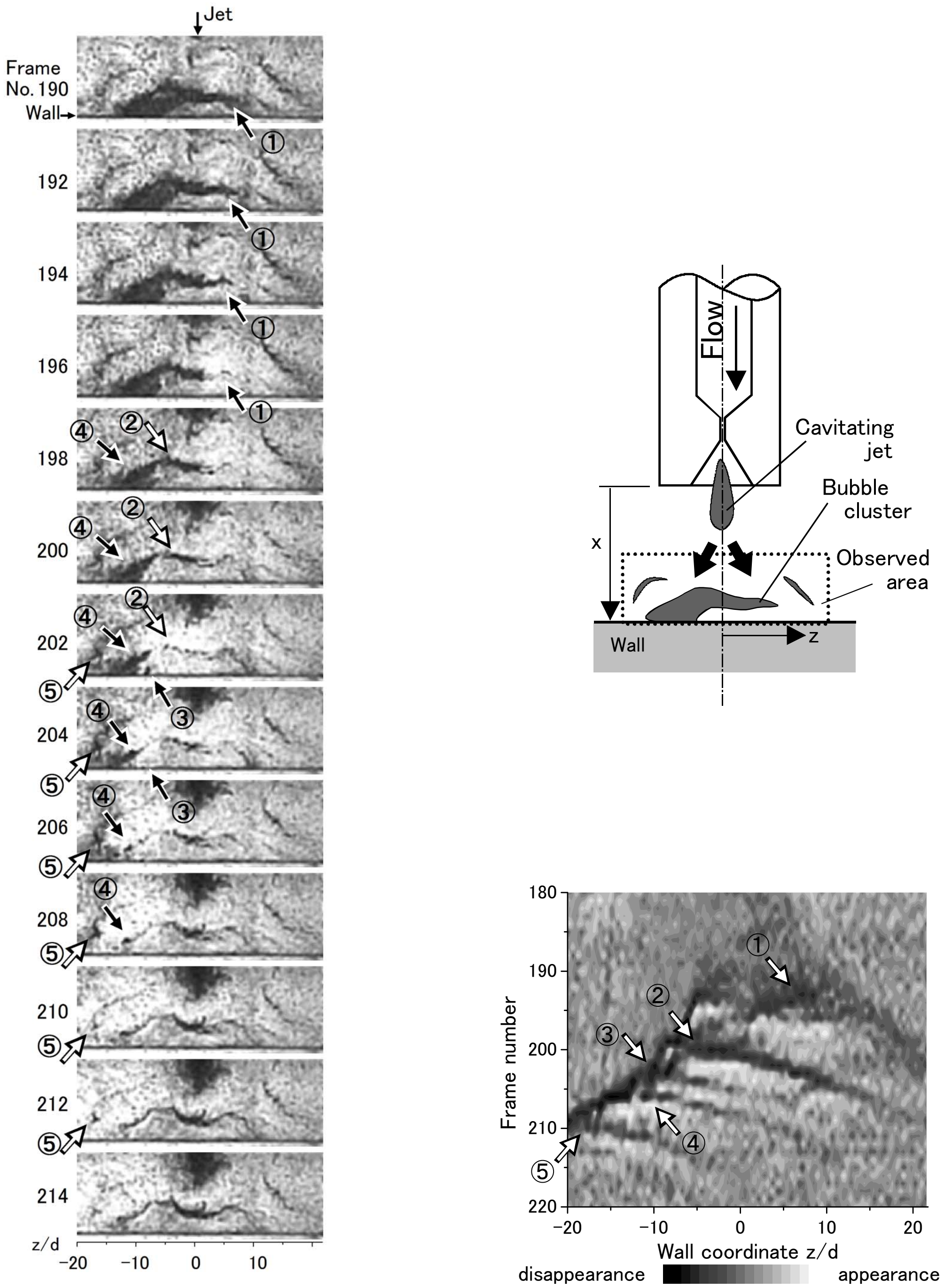
There are small bubbles around the impinging cavitation cloud. The background of the image becomes brighter when the bubble cluster collapses (A, B and C in Fig. 4(a)); thus, these small bubbles appear to collapse. The bubble collapse region propagates in the outward direction. In Fig. 4(a) ① and ②, a relatively large bubble cluster collapses along with the surrounding small bubbles. This shows that the propagation of the pressure wave generated by the bubble cluster collapse causes the successive collapses of bubble clusters. This interaction between the bubbles and the pressure wave is worth noting that it causes the asymmetric collapse of the bubbles and consequently a high impact [5]−[8].

Figure 4(b) shows the result of analysis using the frame difference method. In this study, the black region indicates the bubble collapse or disappearance and the white region shows the bubble growth or appearance. The black region corresponding to bubble collapse, appears periodically and moves from the jet center in the outward direction with lapse of time. Here, the regions inside the dotted line D in Fig. 4(b) can not be analyzed since the images are out of the range because of the filling of cavitation clouds.

## 4 Estimation of cavitation cloud and/or bubble cluster collapse by frame difference method

We estimated the details of the cavitation cloud collapse in Fig. 4. Figure 5 shows the cavitation cloud and/or the bubble cluster collapse behavior around Frame No. 190 in Fig. 4. As a result of the high-speed observation, we can see that the pressure wave appears and the small bubbles around the jet collapse continuously as shown in Fig. 5. The cavitating jet and the surrounding small bubbles are shown in black color in Fig. 5(a). The cavitating jet impinges on the wall and moves in the outward direction. The bubble cluster collapses at ① in Fig. 5(b) and then bubble clusters ②−⑤ collapse one after the other with the collapses of surrounding small bubbles. These continuous collapses are closely related to the pressure wave generated by the collapse of cavitation clouds and/or bubble clusters around the jet.

Figure 5(b) shows the analysis result of this behavior. Here, the analysis is performed in a wall vicinity region of 23×192 pixel and its spatial resolution is 4.6 pixel/mm. The black region moves from the region indicated by arrow ①, as previously shown in Fig. 5(a) in the outward direction with lapse of time. In this case, the propagation speed of bubble collapse is estimated to be about 150−300 m/s. The frame difference method makes it possible to observe that the bubble cluster indicated by ② in Fig. 5(b) collapses due to the effect of the pressure wave generated by the previous collapse of




(a) Collapsing behavior of cavitation clouds

(b) Image analysis of cavitation clouds

$P_1$=6MPa, $P_2$=0.1MPa, Tw=290K, $\beta$=7.2mg/ℓ, d=1mm, x/d=30, Fs=100000fps

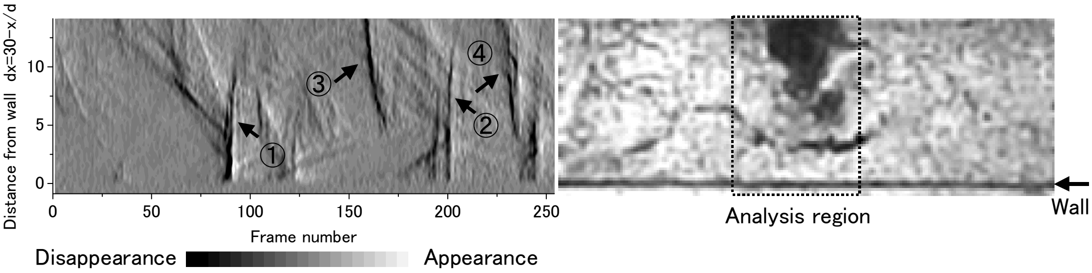
Fig.5. Successive collapses of cavitation clouds and occurrence of pressure waves

bubble cluster and then the collapsed bubble cluster also generates a new pressure wave. After that, bubble clusters ③–⑤ also collapse as a result of the pressure wave, and emit a pressure wave when they collapse in the same manner as mentioned above.

We examined the propagation of bubble collapse not only in the direction parallel to the wall surface but also in the normal direction. Figure 6 shows a result of the image analysis around the center region (70×50 pixel) of the cavitating jet axis. In this case, the gray level distribution Gai averaged in the direction parallel to the wall surface is calculated as follows.

$$Gai = \frac{1}{n}\sum_{j=1}^{n} G(i, j) \tag{2}$$

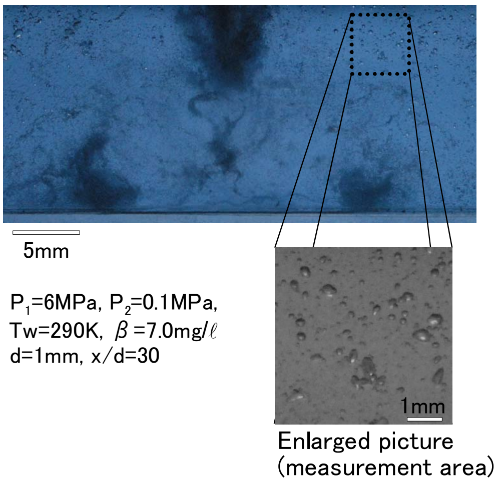
The black lines corresponding to bubble collapse extend toward the opposite side of the wall with lapse of time, as indicated by ① and ② in Fig. 6. The propagation speed of bubble collapse can be estimated to be about 300 m/s due to the result of Fig. 6(a). In addition, such propagation behaviors of the bubble collapse associated with pressure wave also appear from the upstream direction of the jet, as shown in Fig. 6 ③ and ④.




(a) Image analysis (b) Cavitating jet image

$P_1$=6MPa, $P_2$=0.1MPa, Tw=290K, $\beta$=7.2mg/ℓ, d=1mm, x/d=30, Fs=100000fps

Fig.6. Image analysis in the direction normal to the wall (Fig. 4(a))




$P_1$=6MPa, $P_2$=0.1MPa, Tw=290K, $\beta$=7.0mg/ℓ d=1mm, x/d=30

Fig.7. Instantaneous picture of cavitating field to measure void ratio

Figure 7 shows an image taken by a still camera which has higher resolution than the high-speed video camera. It can be found that the cavitation cloud consists of small bubbles. There are also many small bubbles around the cavitating jet. The void ratio is estimated to be about 0.1-1.0% under the assumption that the bubbles are spherical in the picture representing $5\times5$ mm$^2$. In the case of a flow containing bubbles the speed of sound $v_a$ can be roughly calculated by the following equation (3) [12].

$$v_a = \sqrt{\frac{\kappa P}{\alpha(1-\alpha)\rho_L}} \tag{3}$$

where P, $\kappa$, $\alpha$ and $\rho_L$ are pressure, specific-heat ratio, void ratio and density of water, respectively. The speed of sound is estimated to be about $v_a$=120−380 m/s under the assumptions as P=101 kPa, $\kappa$=1.4, $\alpha$=0.1−1% and $\rho_L$=1000 kg/m$^3$. This value corresponds to the propagation speed of bubble collapse obtained from the image analysis as mentioned above.

It was found that the behavior of pressure wave and/or bubble deformation can be clearly estimated using the frame difference method and that the pressure wave interacts with surrounding bubble clusters and/or small bubbles, and causes the consequent collapse. However, further investigation is required for the collapsing times of different bubble sizes.

## 5 Conclusions

The flow field around the cavitating jet impinging on the wall shows very complicated aspects because of the collapse of cavitation clouds (bubble cluster) and the consequent pressure wave. In this study, we examined the cavitation cloud collapsing behaviors associated with the impinging water jet by applying the frame difference method to the high-speed video observation.

1) The image analysis using the frame difference method is one of the most effective methods to quantitatively visualize the cavitation clouds near the wall on which the cavitating jet impinges.

2) The behavior of pressure wave and/or bubble deformation in gas-liquid water jet can be clearly estimated using this analysis method.

3) The bubbly cloud in the cavitation impinging jet collapses at various positions near the wall, such as the vicinity of jet axis and the jet circumference wall region.

4) It is observed that the cavitation clouds collapse successively from the center of the impinging jet to the circumference wall region due to the pressure wave generated around the center of the jet.

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