

# Structure of Periodic Cavitation Clouds in Submerged Impinging Water-Jet Issued from Horn-Type Nozzle

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A high speed water jet is issued into water from a horn-type nozzle. The submerged water jet causes severe vortex cavitation and forms unsteady cloud cavitation. In the present study, a high-speed video observation was made about the cavitating water jet including the inside of the nozzle horn. The video pictures were analyzed through an image processing based on the frame difference method. As a result, it is mainly obtained that 1) a reentrant motion can be observed from the exit region of the nozzle horn to the nozzle throat at the beginning of cavitating jet issue when the cavitation cloud occurs periodically, 2) a new cavitation cloud reaches the impinging wall through a coalescing and a growing motion, 3) there are two collapse types of a jet central type and a jet peripheral type for cavitation cloud impinging on the wall and 4) The propagation of collapses plays an important role on cloud collapses in the near impinging zone.

**Keywords:** Cavitation Cloud, High Speed Video Observation, Impinging Water Jet, Periodic Motion, Pressure Wave

## 1. Introduction

Cavitation in a separated flow field for a high speed liquid flow influences the large-scale flow structure at a certain stage of development and causes flow characteristics peculiar to cavitation <sup>(1)</sup>. Especially, it should be noted that vortex cavitation caused from minute vortices on separated shear layer forms cavitation cloud which consists of micro-scale cavitation bubbles and brings about an unsteady motion <sup>(2)-(4)</sup>.

On the other hand, jet cavitation in a high speed water jet inside water also causes cavitation clouds and presents a periodic unsteady motion <sup>(5)-(8)</sup>. It is widely used for various kinds of engineering applications such as mixing, cutting, peening, atomizing and cleaning technology <sup>(9),(10)</sup>.

A highly impulsive and erosive character of cavitating water jet (CAV-WJ) can be related to the periodic occurrence of cavitation cloud. In addition, it has been made clear that the strong pressure concentration can be generated inside the cavitation cloud region under the condition of bubble density over a certain extent when the cavitation cloud shows a collapsing motion by the pressure change of the surrounding flow field <sup>(11)</sup>. But the periodicity of cavitation cloud shedding remains to be solved in many aspects though it is known that it causes a high impulsive character of CAV-WJ.

The authors, so far, have studied the mechanism of high impulsive force of unsteady cloud cavitation using a high speed video observation and an image analysis technique <sup>(12)</sup>. As a result, it is obtained that unsteady behaviors or highly impulsive phenomena are closely

combined with the occurrence of pressure wave at cloud collapse through the image analysis for the quantitative estimation on the propagation of consecutive bubble collapses.

In the present paper we investigate the periodic shedding mechanism of cavitation clouds directly related to the high impact and erosion due to CAV-WJ using a horn-type nozzle with a highly periodic character. In particular, a high speed video observation is made and the observed pictures are analyzed about a whole view of CAV-WJ from the inside of horn-nozzle to the impinging wall. As main results, it is found that the periodic structure of CAV-WJ is caused by re-entrant motion toward a horn-nozzle accompanied with the collapse of cavitation clouds and the ring-like erosion peculiar to CAV-WJ can be related to two-steps type of cloud collapses accompanied with propagation of cloud collapses near an impinging wall.

## 2. Experimental Apparatus and Method

### 2.1 Experiments

In this study, some experiments were conducted using a horn-type nozzle with throat diameter of  $d=1\text{mm}$  and aperture angle of  $\theta=60\text{deg}$  as shown in Fig.1. Tap water was used and issued into a water tank at atmospheric pressure  $P_2$  under an upstream pressure  $P_1=6\text{MPa}$  through

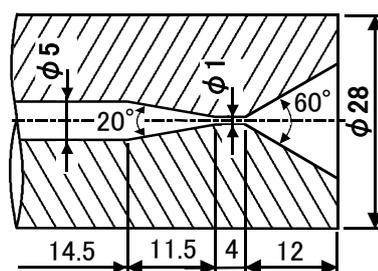


Figure 1. Horn nozzle

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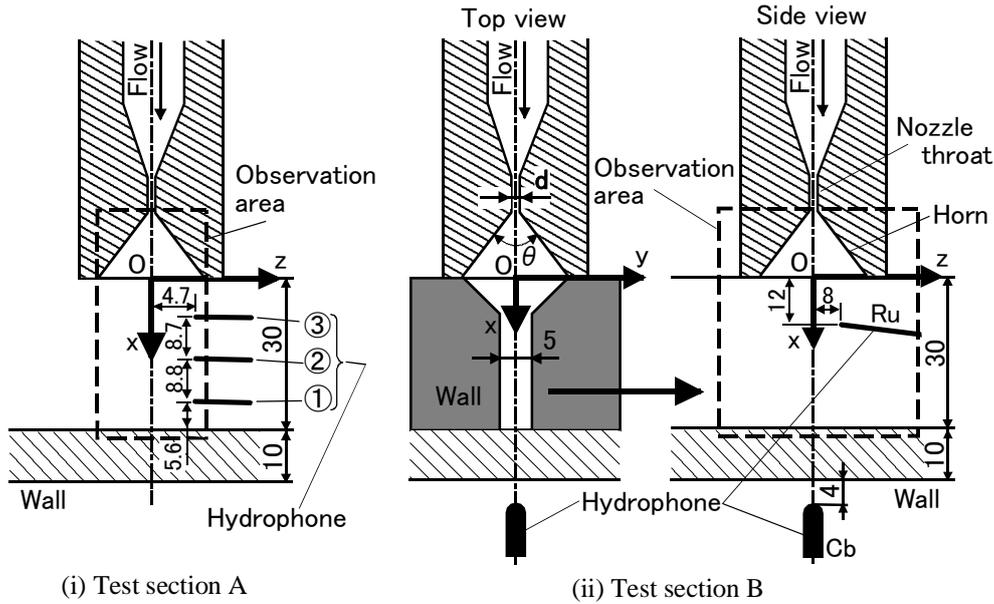


Figure 2. Schematic diagram of test section

a high pressure pump. Two kinds of test sections were used where test section A was a normal open-type and test section B was a constrained type with flow passage width of 5mm to two-dimensionally observe a bubble collapsing behavior near jet-impinging wall as shown in Fig.2. Both test sections had an impinging wall made of transparent acrylic resin plate installed in the position of standoff  $x/d=30$  and normal to a center axis of nozzle. The exit of horn part in the nozzle was chosen as the original point, the direction of the nozzle center axis as x-axis, and the directions normal to it as y or z-axis along the impinging wall surface. In order to examine the impulsive characteristics, some microphones (B&K; 8103 and Muller; Platte Needleprobe) and an accelerometer (Teac; 703FB) were installed inside the tank and on the backside of the impinging wall depending on the experimental conditions.

2.2 Video observation and image analysis

The behavior of cavitation clouds was observed using two kinds of high speed video cameras (Kodak; Model HS4540 and Photron; FASTCAM SA1) with three kinds of frame speeds  $Fs=27000, 54000$  and  $100000$ fps. Air content in test water was measured in the term of dissolved oxygen content.

The frame difference method for cavitating flow<sup>(12)</sup> was used in the present image analysis. The usefulness of the method was experimentally verified about the behavior analysis of high speed liquid flow accompanied with growth and collapse of bubbly cloud like the present study. The outline of the method is shown in Fig.3. Figure 3(a) shows a gray level averaged in the vertical direction of the image at time  $t_1$  and Fig. 3(b) at time  $t_2$ . In the image the white colored portion corresponds to a cluster of micro-bubbles, namely a cavitation cloud. Thus Fig. 3(c) shows the difference between the former image Fig. 3(a)

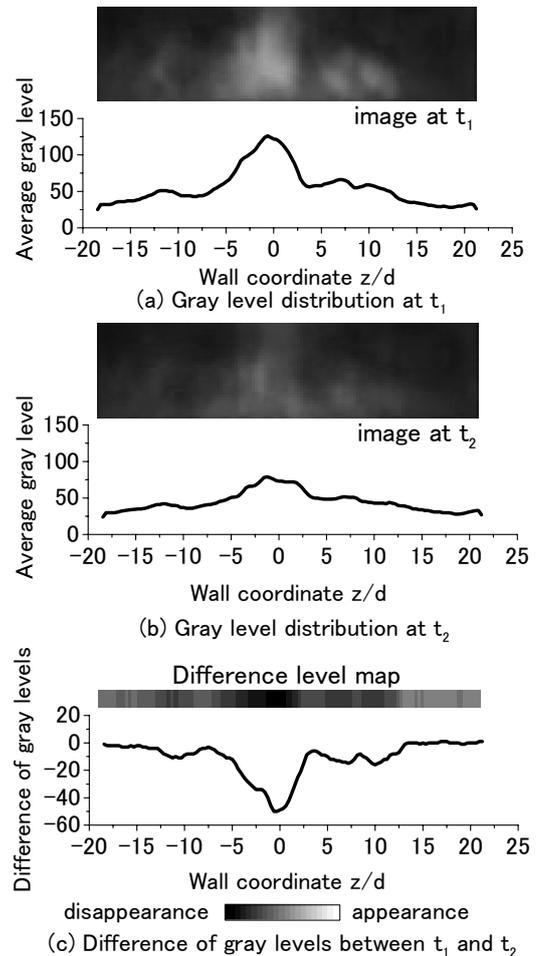


Figure 3. Image analysis using frame difference method for cavitating flow

and the latter image Fig. 3(b) at the time interval  $\Delta t=t_2-t_1$ . From the result of Fig. 3(c) we can find the region or layer where the



gray level changes rapidly which means a cavitation cloud rapidly disappears or appears. Through the difference analysis applied to the whole images, we can obtain the final image analysis.

In the present paper, the appearance region of cloud is expressed as a white and the disappearance region as a black. Through this process of the image analysis it is possible that we can quantitatively estimate the high speed phenomena such as rapid and consecutive collapses of cavitation clouds and pressure wave formation. It should be noticed that their phenomena are clear in the view of high speed movie, but are not clear in the view of still pictures because of the information shortage on the change rate of images.

### 3. Periodic Behavior of Cavitating Water Jet near Horn Nozzle

#### 3.1 Periodic shedding appearance of cavitation clouds near horn nozzle and whole appearance of CAV-WJ

Figure 4 shows a series of cavitation cloud movements including the appearance inside the horn nozzle. Here, the frame speed is  $F_s=54000\text{fps}$  and  $t_p$  is a lapsed time from an arbitrary point. White colored portion corresponds to a zone of CAV-WJ issued from the nozzle throat located at the left edge of picture though the nozzle horn part also appears to be partly white because of the light reflection. The picture near the right edge region appears obscure because of the jet spread on an impinging wall.

Here, we will explain a life history of cavitation clouds based on an example of observation. First, at lapsed time  $t_p=3.0\text{ms}$  a main CAV-WJ expands to the almost middle position of the test section in the discharge tank. The leading part of the main CAV-WJ moves gradually toward the direction of impinging wall and then shows a shrinking motion in the diameter of CAV-WJ around the exit region of the horn after approximately  $t_p=3.11\text{ms}$ . Next, it should be noted that the reentrant motion can be discerned around  $t_p=3.185\text{ms}$  when the cloud shrinking motion removes toward the upstream direction. At the same time, some downstream clouds which have already made a shrinking motion change to a growing stage and translate toward the downstream direction as shown in the arrow at  $t_p=3.296\text{ms}$ .

This reentrant motion reaches the leading part of horn (nozzle throat) around  $t_p=3.333\text{ms}$  and then changes to a new shedding motion of cavitation cloud in the reverse direction. In some pictures around  $t_p=3.407\text{ms}$  as shown in arrowed portion it is found that there is a discontinuous part of cavitation cloud which is caused by the arrival of reentrant motion at the leading part of horn. The leading part of new CAV-WJ positioned by the discontinuous point moves downstream at a certain speed (approximately  $v=70\text{m/s}$  in this case). As a result the new CAV-WJ grows and develops in a coalescing manner with some clouds existing downstream as shown in around  $t_p=3.370$  to  $3.519\text{ms}$ ,

and then moves downstream from the horn nozzle as shown in after  $t_p=3.556\text{ms}$ . The translational speed in the leading part of CAV-WJ keeps almost constant through the beginning, the inside of horn and the outside of horn.

On the other hand, most remaining parts of the preceding CAV-WJ positioned downstream of the discontinuous point moves toward an impinging wall though a part of them coalesces into the new CAV-WJ. The behavior of local clouds as shown by the arrow at  $t_p=3.519\text{ms}$  is also interesting as an intermediate stage of a large-scale collapse. As a result the gap is created between a new CAV-WJ and a preceding CAV-WJ as shown in the arrow at  $t_p=3.574\text{ms}$ . This boundary region keeps downstream as a gap and appears to be a break-up of cavitation cloud.

Next, the preceding CAV-WJ reaches the impinging wall and shows a collapsing motion to the disappearance while the new CAV-WJ moves and develops downstream. The leading part of the preceding CAV-WJ reaches the near impinging zone (approximately 10d-region from the wall) around  $t_p=3.9\text{ms}$  and the impinging wall around  $t_p=4.0\text{ms}$  in this case. The cloud behavior in the near impinging zone may be very interesting because of the direct relation to the wall impact and erosion mechanism (see the next our paper).

#### 3.2 Image analysis due to frame difference method for cavitating flow

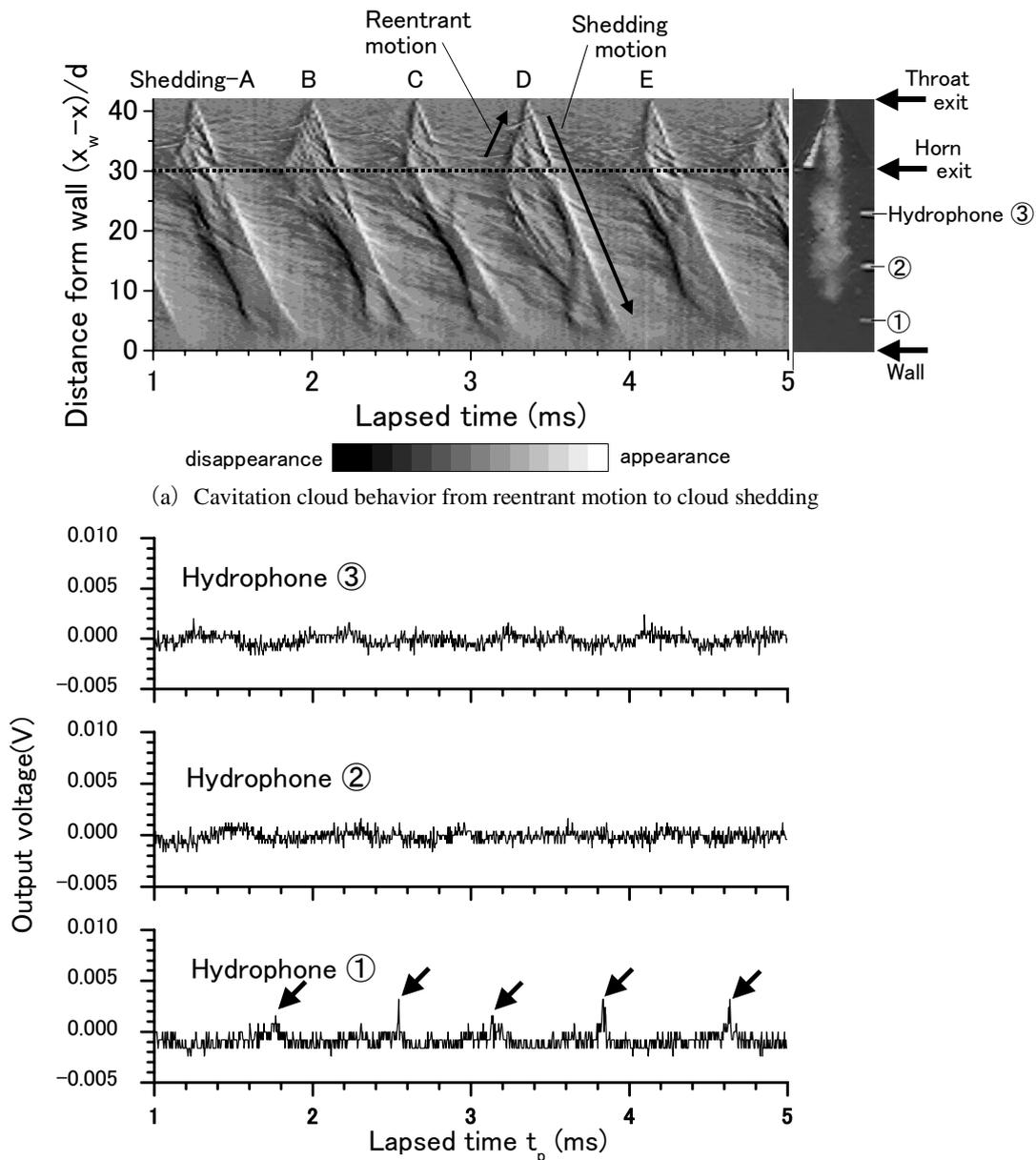
Figure 5(a) shows an image analysis result for high speed video observation shown in Fig. 4 together with a sound pressure measurement along the water jet region shown in Fig. 5(b). The image analysis was conducted using the frame difference method for cavitating flow to quantitatively examine the rapid behavior change in cavitation cloud which consists of many minute bubbles as mentioned in section 2.2.

In Fig. 5(a) the difference value of gray levels between two consecutive images is shown as another gray level. The distance from the impinging wall is chosen against a lapsed time  $t_p$ . In this figure a white region means an appearance of bubbly region at the position from the wall where the color is expressed as an averaged value over the image width and a black region means the disappearance. Here the sound pressure is used for reference to indicate the existence of pressure peak and simply expressed in the term of voltage (the nominal value  $1.6 \times 10^{-5} \text{ mV / Pa}$ ).

In Fig. 5, a relatively long time range is chosen to include other shedding cases of CAV-WJ besides the time range in Fig.4. Here, five sheddings A to E of CAV-WJ are shown and the following results are obtained,

- 1) cloud shedding is almost periodic (about  $0.73\text{ms}$  in this case),
- 2) reentrant motion is discerned always prior to a shedding of cavitation cloud.

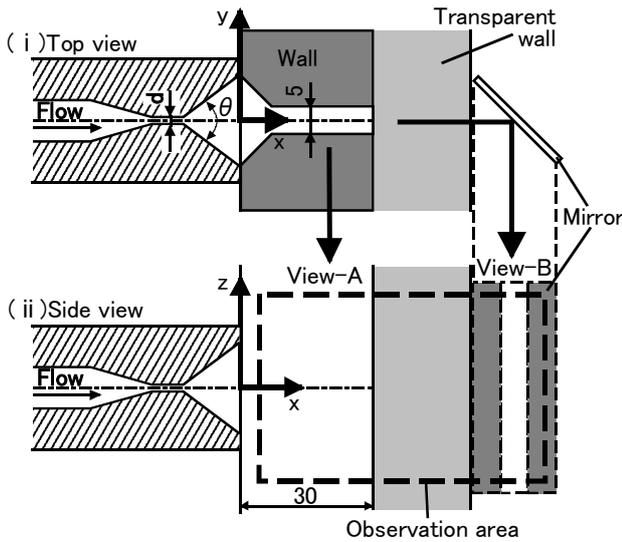
These facts are in an exact agreement with the results of video observation in Fig. 4.



(a) Cavitation cloud behavior from reentrant motion to cloud shedding  
 (b) Sound pressure measured with hydrophone  
 $P_1=6\text{MPa}$ ,  $P_2=0.1\text{MPa}$ ,  $T_w=288\text{K}$ ,  $\beta=5.1\text{mg}/\ell$ ,  $d=1\text{mm}$ ,  $x/d=30$ ,  $F_s=54000\text{fps}$   
**Figure 5.** Image analysis and output of hydrophones

Let us explain about the shedding D shown in Fig. 5 corresponding to the images of Fig.4. The reentrant motion toward the inside of horn nozzle can be found around the exit region of nozzle horn around  $t_p=3.2\text{ms}$  as shown by the arrow and reaches the leading point of the horn part around  $t_p=3.36\text{ms}$ . After that, it is clearly found that the white band-like region expands in a linear manner to the impinging wall with its speed of about  $v=70\text{m/s}$ . In response to the cloud arrival at the near impinging zone some sound pressure peaks can be detected by microphones installed in the flow passage region. Further it is noted that a white or black colored region in the analysis area can be related to some local behaviors of cavitation clouds.

In most cases, the reentrant motion starts around the exit region of the horn part though in a rare case it occurs at a sufficiently downstream point. The phenomenon appears to be a chain-reaction behavior of cloud shrinking or disappearance and can be related to a propagation of pressure wave. A starting mechanism may be the existence of high pressure distribution due to the rapid enlargement after the horn exit though further examination will be necessary. According to the measurement of hydrophone an increase of pressure is actually measured near the horn exit. A new cloud shedding motion starts at the upstream leading edge of horn part and reaches the impinging wall through a growing and coalescing process with small existing clouds. In some case there may be a relatively large coalescence between a



**Figure 6.** Test section for simultaneous observation from two directions

new cloud and an existing cloud as shown in the shedding C. The boundary between the new cloud and the preceding cloud appears to form a break-off of CAV-WJ. It should be noted that the latter part of preceding CAV-WJ forms a part of new CAV-WJ and the collapse of existing clouds can also make a local break-off of CAV-WJ.

4. Behavior of Cavitating Water Jet in Near Impinging Zone

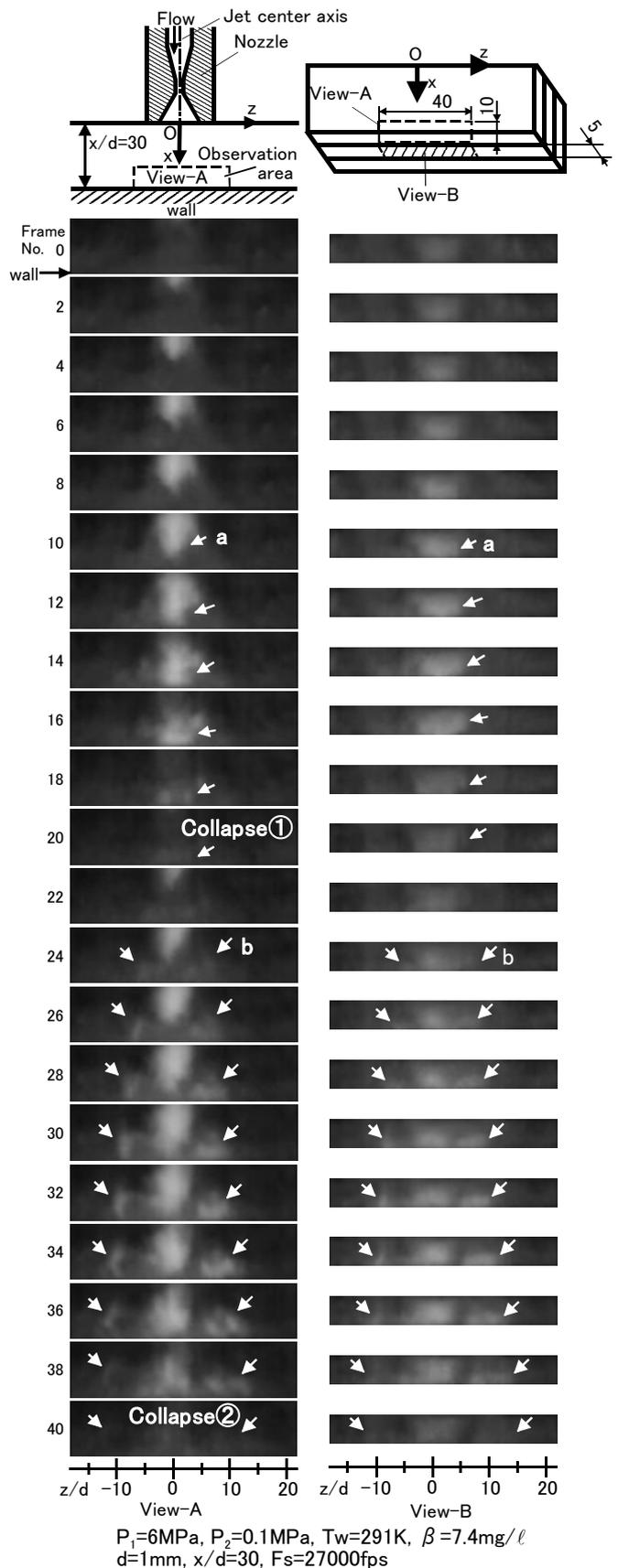
4.1 Collapsing appearance of cavitation clouds in near impinging zone and whole appearance

As shown in Fig. 6, a high speed video observation with a frame speed of  $F_s=27000\text{fps}$  was made using a reflection mirror installed behind the impinging wall to observe CAV-WJ impinging the wall from two directions of a side-view and a sectional-view in the cavitating jet.

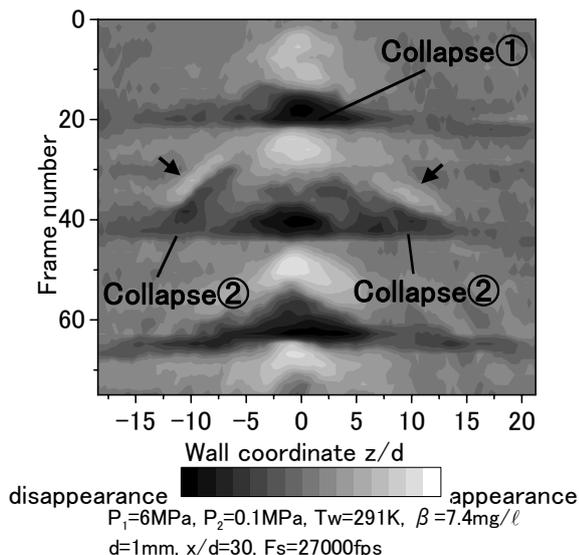
Figure 7 shows the observation results, where the images of View-A are taken from the jet-side direction at the stand-off of  $x/d=20$  to 30. The observation area of View-A is indicated in the dotted zone of  $10\times 40\text{mm}$  as shown at the top in the schematic. In a similar manner the observation area ( $5\times 40\text{mm}$ ) of View-B is in a jet-axis direction.

From the result of Fig. 7, it is found that CAV-WJ has an unsteady behavior as a whole and the cavitation cloud periodically impinges on the wall. There are at least two patterns in the collapsing behavior of cavitation cloud in the near impinging zone. The two collapsing patterns are shown as the arrow “a” and the arrow “b” in Fig. 7.

First, in the case of Collapse-1 indicated by “a”, the cavitation cloud impinging on the wall collapses near the nozzle center axis as an almost single cluster. Here, a cavitation cloud approaching the wall (indicated by arrow “a” in Fig. 7)



**Figure 7.** Two patterns of collapsing behavior in cavitating jet

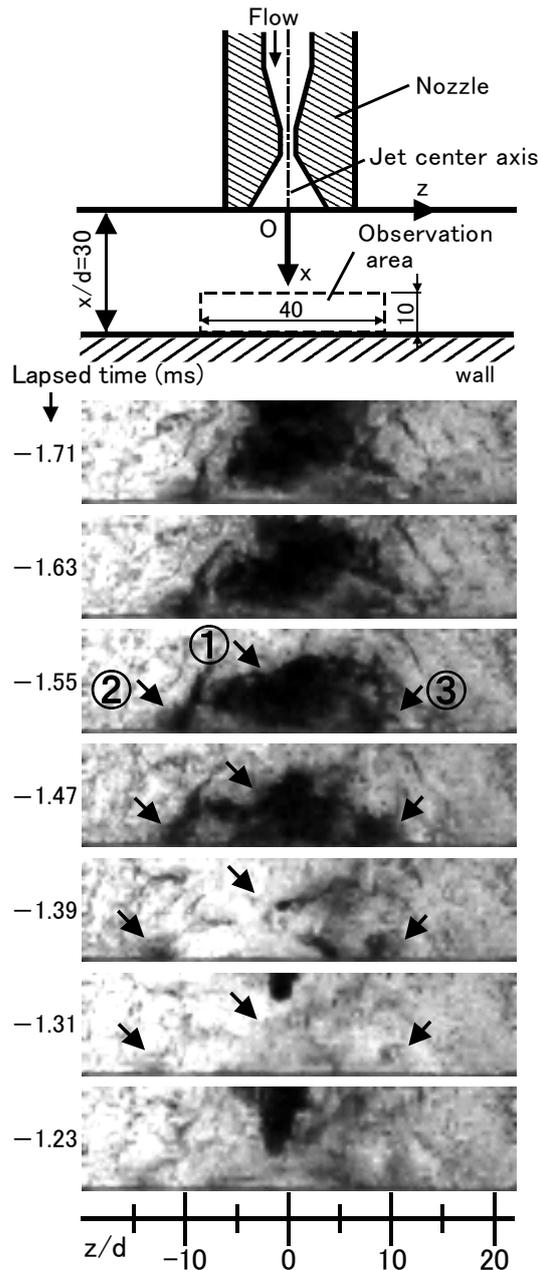


**Figure 8.** Image analysis of cavitation clouds for two collapse patterns

reaches to the wall around Frame No.12, deforms near the wall around Frame No.14 to 18 and collapses near  $z/d=0$  as an almost single cluster around Frame No.20. We can also observe from View-B that the cavitation cloud collapses as a single cluster around the area of  $z/d=-5$  to 5.

The other pattern of Collapse-2 is shown as the arrow “b” in Fig. 7 where the jet impinging to the wall collapses as cavitation clouds at the peripheral area with a spreading motion toward an outward direction. The peripheral clouds appear around Frame No.24, grow and translate outward around Frame No.26 to 38, and collapse around the position of  $z/d=\pm 10$  to  $\pm 15$  and Frame No. 40. From View-B, the outward spreading motion can be also observed as shown by the arrow “b”.

Figure 8 shows the result of the image analysis to the high speed video observation shown in Fig. 7 using the frame difference method for cavitating flow explained in Section 2.2. In Fig. 8 the white and black colored zones alternately appear with a lapse of time. This corresponds to the fact that cavitation clouds periodically impinge on the wall and collapse. In addition it is found in Fig. 8 that a white region appears after Frame No.0 and a black region continues to around Frame No.20. This means that the cavitation cloud impinging on the wall shown by the arrow “a” in Fig. 7 collapses near the center of the impinging jet. After that, around Frame No. 22 in Fig. 7 the next cavitating jet is approaching so that a white region appears near the area of  $z/d=0$  from Frame No. 22 in Fig. 8. It should be noted that there are two oblique white bands spreading outward in the peripheral area as shown by the arrows. This means that the cavitation cloud shown by the arrow “b” in Fig. 7 appears around Frame No.24 and spreads



**Figure 9.** Collapsing behavior of cavitation cloud in near impinging zone

toward the surrounding direction. Therefore the collapses of clouds spreading outward correspond to the black colored region around the position of  $z/d=\pm 10$  to  $\pm 15$  and Frame No. 40 in Fig. 8.

**4.2 Collapse propagation of cavitation clouds in near impinging zone**

Figure 9 shows a typical example of high speed observation with a frame speed of  $Fs=100000$ fps to observe the details of cloud behavior in the near impinging zone of CAV-WJ. The

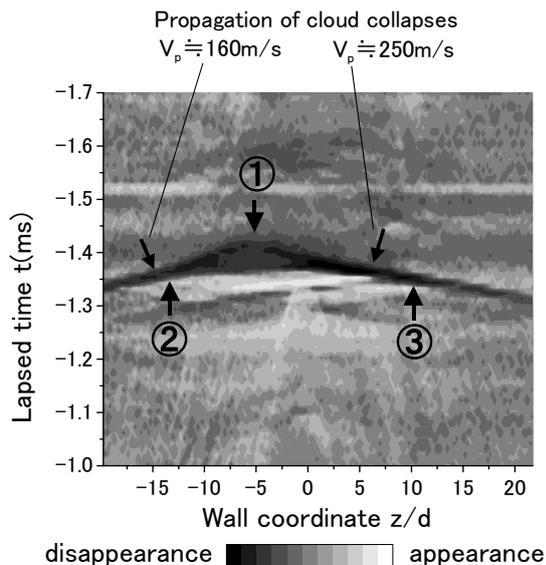


Figure 10. Image analysis for propagation of cloud collapses

observed area of 40 x 10mm is shown at the top in Fig. 9. In the picture at  $t_p = -1.71$ ms we can see that there are cavitation clouds in the whole area centered by jet axis. With a lapse of time cavitation clouds near the impinging wall tend to a disappearance motion under the influence from the surrounding pressure field. First, a cavitation cloud near the jet center axis disappears at a short distance from the wall as shown by the arrow-1 in Fig. 9. After that, it is found that the disappearance area propagates toward the peripheral direction. Especially it should be noticed that there are two attached clouds on the wall at the position of approximately  $z/d = \pm 10$  as shown by the arrow-2 and arrow-3 in Fig. 9. These two cavitation clouds on the wall finally collapse around  $t_p = -1.31$ ms.

From the collapsing appearance shown in Fig. 9 it is found that the cavitation clouds spreading outward collapse near and/or on the wall due to the influence from the preceding collapse near the jet center axis. In order to confirm the details of consecutive collapses the result due to the image analysis is shown in Fig. 10 using the frame difference method for cavitating flow. Here, the lapsed time of video observation is chosen to express the cavitation cloud behavior against the space coordinate on the impinging wall surface. It is found from Fig.10 that there are several black or gray lines corresponding to a series of cloud collapses, namely, the consecutive cloud collapses which are caused by the propagation of pressure wave. The inclination of the line means the speed because time coordinate is expressed against space coordinate. The propagation speeds in these two cases are estimated to be about  $v_p = 160$  and  $250$ m/s respectively which are rather smaller than the sound speed in water because of the void in gas-liquid flow.

From the high speed video observation and the image analysis as above explained, it is found that cavitation clouds on the wall in the surrounding area of cavitating jet can cause a severe collapsing behavior by the propagation effect from the primary collapse of cavitation cloud at a short distance from the wall near the jet center area. The rapidly collapsing behavior on the wall can be closely related to the highly impulsive characteristics of cavitation<sup>(13)</sup>. In addition, the collapses in the peripheral area of cavitating jet are approximately located at the zone of  $z/d = \pm 10$  which is in good agreement with the experimental data<sup>(14)</sup>. This peripheral type of cloud collapses suggests the relationship with the ring-like erosion distribution peculiar to CAV-WJ.

### 5. Conclusion

An experimental study was conducted to investigate the characteristics of cavitating water jet which deserved an attention because of the highly impulsive cavitation cloud with a periodic unsteady behavior. Main results from high speed video observations and the image analysis based on the frame difference method are summarized as follows.

- 1) A periodic shedding of cavitation cloud is caused by reentrant motion toward the nozzle throat of the leading point of nozzle horn. The reentrant motion starts around the exit region of the horn part and can be related to a propagation of cloud shrinking or disappearance along the jet.
- 2) A new cavitation cloud reaches the impinging wall through a coalescing and a growing process at an almost constant speed of the leading part of CAV-WJ. The existing small clouds formed in the preceding cloud influence the characteristics of CAV-WJ through the local behavior.
- 3) For cavitation cloud impinging on the wall there are two collapse types. The first one is a jet central type that cavitation cloud collapses in the jet center area as an almost single cluster. The second one is a jet peripheral type that cavitation cloud collapses in the peripheral area of jet.
- 4) It is found that the propagation of cavitation cloud collapses plays an important role on cloud collapsing motion in the near impinging zone. The cloud collapse of the central-type can cause the peripheral-type collapse of clouds on the wall surface through this propagation effect.

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