

## DETAILED OBSERVATIONS ON A STARTING MECHANISM FOR SHEDDING OF CAVITATION CLOUD

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### ABSTRACT

Cavitation is observed in a convergent-divergent nozzle using a high speed video camera. For this kind of flow, the cavitation has unsteady character with periodic shedding of cavitation clouds. The periodicity is accompanied with a re-entrant motion, the growth of vortex cavity on the separated shear layer as well as the shedding of a large-scale cavitation cloud. In this process, the formation of attached cavity is repeated with shedding of cavitation clouds.

The switching mechanism from the re-entrant motion to the formation of shedding cavitation clouds has not been fully understood. In the present study, it is shown in details by experimental results based on high speed video observations that one of the mechanisms is the leading-edge bubble collapse in the separated region to interrupt continuous supply of vorticity from upstream boundary layer and the formation of micro-vortex cavities on the separated shear layer. In addition, various appearances of cavitation bubbles are also shown from a viewpoint of unsteady cavity behavior.

### INTRODUCTION

It has been well known that the cloud cavitation, namely unsteady periodic cavitation, produces high impacts at its collapse. The mechanism on the periodic shedding of cavitation cloud has been investigated by many researchers such as Knapp [1] and Furness [2], and recent active works obtain many important results [e.g., 3-6]. Most of unstable phenomena with periodic fluctuation of cavity length in high-speed hydraulic machinery can be considered to be a vibratory phenomenon with the re-entrant motion as a feed-back mechanism. It, however, remains to be solved if the re-entrant motion consists of simple jet flow or includes other mechanisms such as pressure wave propagation [7-9].

According to the investigation on hydrofoil cavitation by Watanabe et al. [10], an unsteady cavitation of hydrofoil can be divided into two patterns due to the cavity length  $\ell$ . One is partial cavity instability for  $\ell/c < 0.75$  where  $c$  is foil chord length

and the other is transitional cavity instability for  $\ell/c > 0.75$ . The latter instability which has heavy unsteadiness peculiar to hydrofoil cavitation can be related to negative cavitation compliance. The former one which has characteristic frequency based on the cavity length can be directly related to the reentrant jet. These results are in good agreement with other experimental studies [11, 12].

On the other hand, a convergent-divergent nozzle as well as a hydrofoil is often used to investigate about the cloud cavitation [e.g., 2, 13]. For most of these works, the nozzle has a sharp throat with a reattached separated-flow zone. For higher cavitation number in such a flow, the shear-layer cavitation occurs on the separated shear layer of viscous separation bubble. With reducing cavitation number, the cavitation state shifts to partial-cavitation with an unsteady attached cavity and then to super-cavitation with clear cavity surface and cavity pressure near vapor one [14]. In the transition stage, namely from sub-cavitation to super-cavitation, severe instability often appears in cavitating flow because of the high sensibility. The relation is not very clear between this sub-super transition cavitation instability and the (hydrofoil) transitional cavity instability though it is pointed out as a possibility by Callenaere, et al. [15] that this kind of instabilities may be related to the surge-type instability.

According to the previous studies [e.g., 3, 15], the cloud cavitation is considered to be a self-oscillation phenomenon based on the re-entrant jet instability which is controlled by the thickness of separation zone and the adverse pressure gradient near the reattachment area of separation bubble. However, there are some unsolved points such as the extent of the pressure-gradient and the existence of the re-entrant jet.

In the present study a vibratory phenomenon is observed with a re-entrant motion as a feed-back mechanism in a convergent-divergent nozzle. A cavitation cloud is periodically shed downstream. The starting point of the periodical motion is an arrival of re-entrant motion at the leading part of attached cavity.

It should be noted that the propagation behavior of bubble collapses was also observed within the re-entrant motion [9].

The most part in an attached cavity is occupied by gas-liquid two-phase fluid, namely bubbly mixture because the occurrence area of cloud cavitation is before the super-cavitation stage. Therefore, the bubble behavior inside an attached cavity plays an important role in the unstable cavitation. In addition, at the present stage of investigation, there are few direct observations on the mechanism of cavity break-off though it is proposed that it can be caused by the collision or the contact of re-entrant jet with the surface of an attached cavity. Therefore the present study experimentally examines in detail about the turning process from the re-entrant motion to the shedding motion of cavitation clouds using a high-speed-video system.

## EXPERIMENTAL SET-UP AND METHOD

Experiments were conducted in a cavitation tunnel of small closed-type with a rectangular test section of 80mm height and 60mm width [16]. A convergent-divergent nozzle was installed on the upper wall of the rectangular test section. Three kinds of nozzles A, B and C were prepared for the convergent-divergent channel. There are two types. The first type is for sectional (side)-view observation as shown in Fig. 1-(a) and the other one is for plane-view observation as shown in Fig. 1-(b). The two nozzles for the sectional-view are a nozzle-A for divergent angle of 18.4° and a nozzle-B for divergent angle of 10°, respectively. Both of these models have a convergent angle of 45° and contraction ratio of 0.5. The sectional-view in these flow-channels can be observed for a separated-vortex type of cavitation generated from the leading edge of the divergent part. Nozzle-C for the plane-view observation has convergent angle of 45°, divergent angle of 18.4° and contraction ratio of 0.5, respectively.

The measurement system for cavitation observation is shown in Fig. 2. High-speed visualizations of cavitation bubbles were performed using either a Kodak EKTAPRO Model-4540 operated at a maximum framing rate of 40500 fps (frame per second) or an ultra-high-speed video camera operated at a maximum framing rate of 1M fps (developed by Shimazu Corp. and Kinki Univ. [17]). Two or three metal halide lamps (150W; Photoron, HVC-SL) were used for light source as typically shown in Fig.2. An accelerometer (TEAC, 501FS/FB) installed on the outer wall of the test section, in some cases, was used to make a trigger signal to synchronize the capture of the video frame with the cavitation impact [18]. Thus this system was able to catch the bubble aspects before and after the generating point of cavitation impact.

In this paper, cavitation number  $\sigma$  and Reynolds number  $Re$  are defined as follows.

$$\sigma = 2(P_{\infty} - P_v) / \rho U^2 \quad \dots \dots (1)$$

$$Re = U_c \cdot H / \nu \quad \dots \dots (2)$$

Here,  $P_v$ ,  $P_{\infty}$  and  $U$  are vapor pressure, static pressure and velocity at free stream.  $U_c$  is mean velocity at nozzle throat.  $\nu$ ,  $H$ ,  $T_w$ ,  $\beta$  and  $Fs$  are kinetic viscosity, height of nozzle throat, water temperature, dissolved oxygen in water and framing speed of video, respectively.

## EXPERIMENTAL RESULTS AND DISCUSSION

### Aspects of Re-entrant Behavior and Cavitation-Cloud Formation

Figure 3 shows a typical example of the re-entrant motion for a convergent-divergent nozzle with the diffuser angle 10°. The framing rate of high speed video camera  $Fs$  is 2250fps. The flow state within the separated region consists of bubbly fluid with high bubble density in an almost whole field which is different from single vapor phase. In the present paper, this separated bubbly region will be called an attached cavity. In Fig.3 the dense bubbly region appears to be a black silhouette portion.

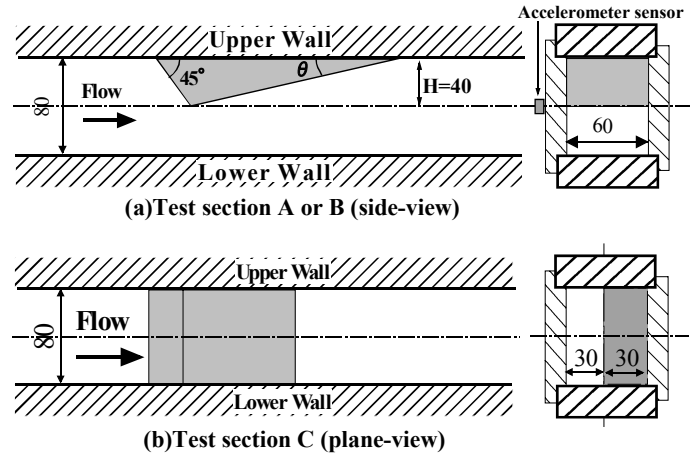


Fig.1 Convergent-divergent channel

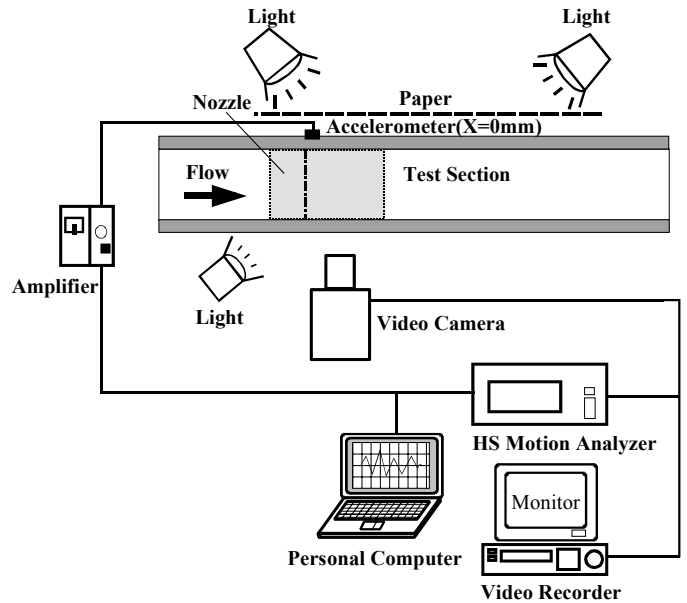


Fig.2 Schematic diagram of high-speed-video observation system

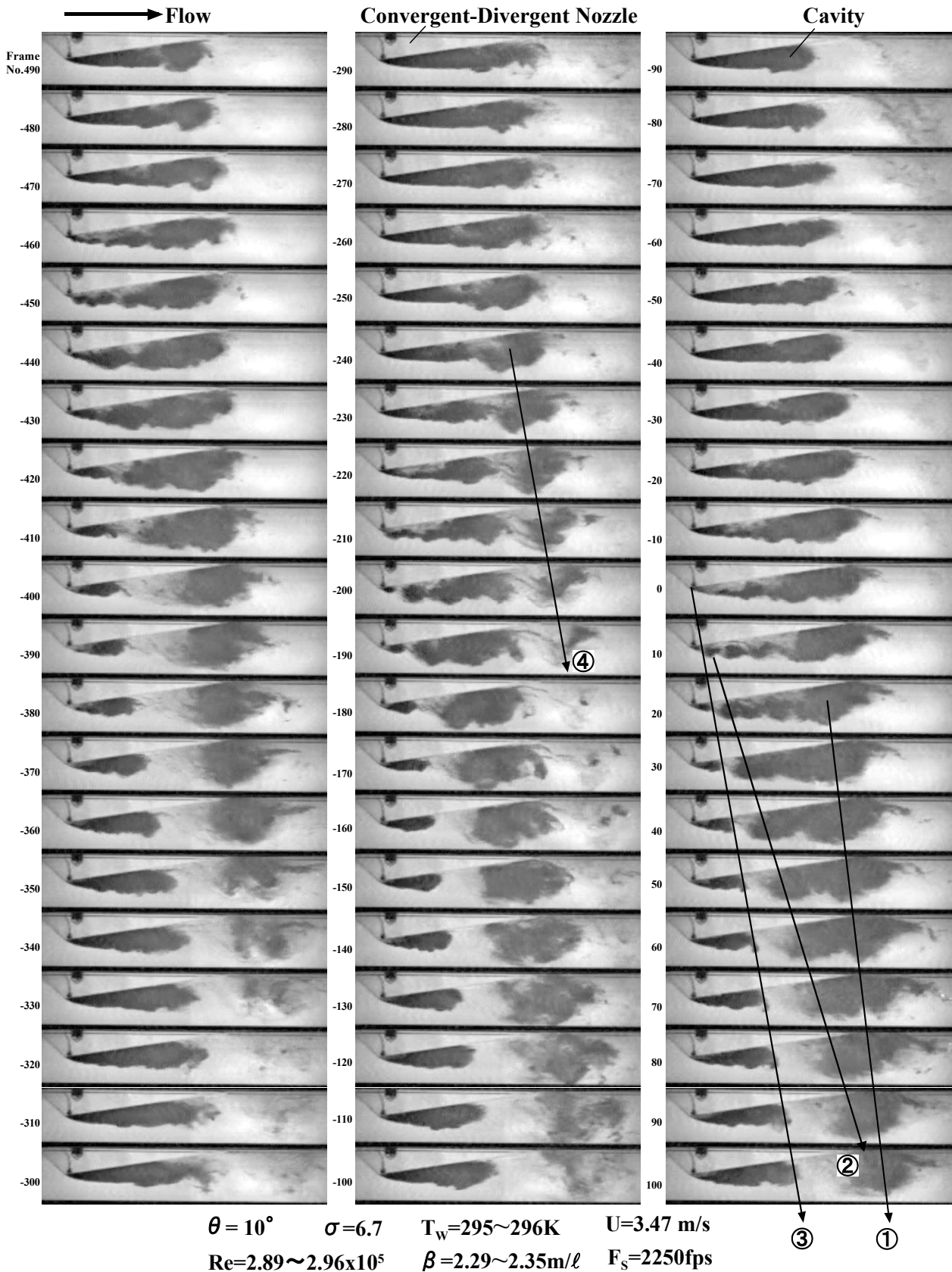


Fig.3 Periodic process of cavitation clouds in convergent-divergent channel

(① · ② shedding cavitation clouds, ② an example of coalescing cavity, ③ growth of attached cavity, ④ partial break-off)

Figure 3 shows a re-entrant motion during about 2.5 periods. Frames No.-460, No.-220 and No.0 correspond to the images in which the re-entrant motion arrives at the leading edge of an attached cavity. Therefore the averaged period  $T$  of these arrivals can be estimated to be 0.10s from the video-framing rate and the non-dimensional frequency  $S=\ell/T/V_t=0.32$ , based on average throat velocity  $V_t$  and maximum cavity length  $\ell$ . The value of  $S=0.32$  drops within the range of many previous data [e.g., 3, 19]. In addition a partial break-off and the shedding can be also discerned on the way of the re-entrant process around the images from Frames No.-250 to -170, though the re-entrant motion continues to the leading edge of the attached cavity irrespective of such interruption.

For the images from Frames No.-90 to No.100 with the center of No.0, it is found out in the first place that the boundary line between the dense part (black one) and the sparse part (gray one) of bubbles goes upstream along the divergent surface. The bubble disappearance area increases largely with approaching the leading part of the attached cavity so that the dense bubbly area is mainly limited to the two regions near the upstream interface and in the rear of the attached cavity where many cavitation bubbles still remain without disappearance (Frames No.-10 to No.0). Some small vortex cavities can be observed in a clear rotational manner near the leading part of the attached-cavity interface.

After the arrival of re-entrant motion at the leading edge of the attached cavity around Frame No.0, the small vortex cavities grow to a larger scale by coalescing with preceding vortex cavities and finally coalesce with large cavitation cloud remaining in the rear of the attached cavity to form a large cavitation cloud (Frames No. 10 to 90). The final large cavitation cloud is shed downstream to produce severe cavitation impact.

### Transitional Aspect from Re-entrant Motion Stage to Cavitation-Cloud Formation Stage

It is difficult to catch the detailed aspect near the nozzle throat by Fig.3 using a framing rate of  $F_s=2250\text{fps}$ . Figure 4 shows an example of video pictures taken by a framing rate of  $F_s=100000\text{fps}$  (diffuser angle  $=18.4^\circ$ ). A cluster of bubbles collapses one after another toward the nozzle throat (Frames No.15 to No.70) and shows the propagation behavior of bubble collapses (see, black arrows). It should be noted that the positions of collapsed bubbles show little change, independently of the following bubble collapses. The bubble or bubbly cloud near the nozzle throat reaches the minimum diameter around Frame No.74 and then shows a rebounding motion. The small-scale cloud of rebounded bubbles appears to be composed of very fine bubbles. It is found out in particular that the rebounded cloud rushes out into the main stream by breaking through the interface of the separated bubbly region (attached cavity). At this point the supply of vorticity from the upstream boundary layer is temporarily suppressed to form a characteristic vortex cavity emerging from the attached-cavity inside.

Figure 5 shows the case of the nozzle with the diffuser angle of  $10^\circ$ . It also shows the rushing-out of a bubbly cloud into the main stream just after the arrival of the re-entrant motion at the leading edge of the attached-cavity. As shown in

Frames No.5 to No.70 in Fig.5, the bubbly cloud indicated by arrow-A forms a small-scale vortex cavity and coalesces with preceding small vortex cavities on the separated shear layer to grow a larger scale

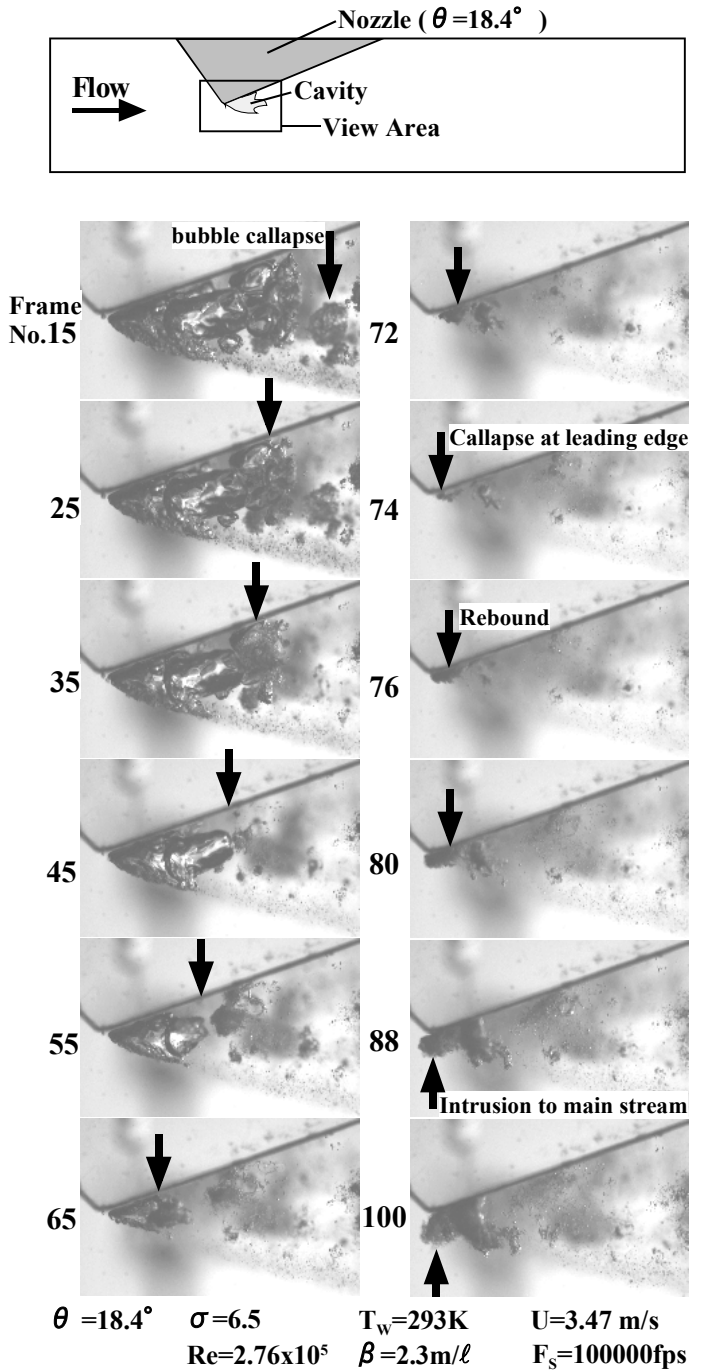


Fig.4 Details of re-entrant motion (propagation of bubble collapses) near leading-edge of separated region and intruding motion into main stream using ultra-high-speed video camera

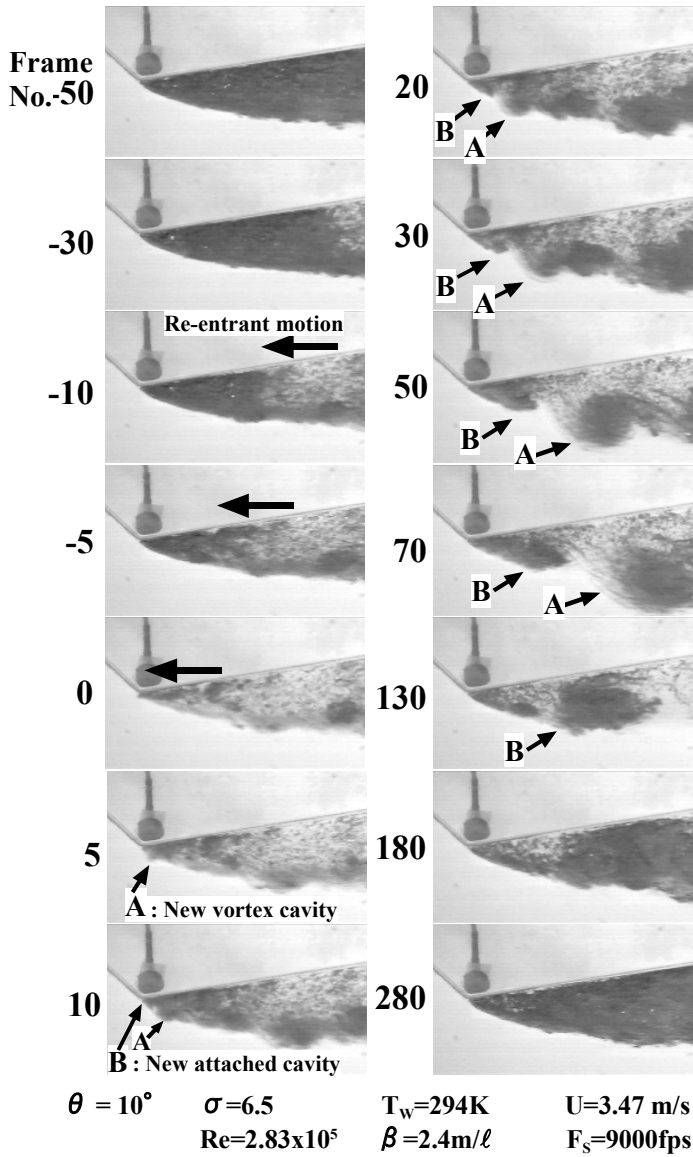
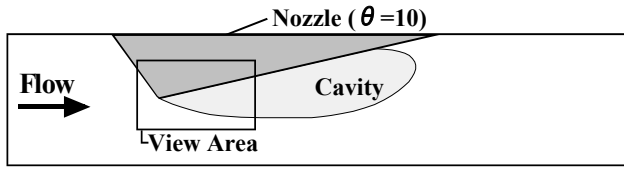


Fig.5 Aspects of the turning from re-entrant motion to shedding motion near the nozzle throat

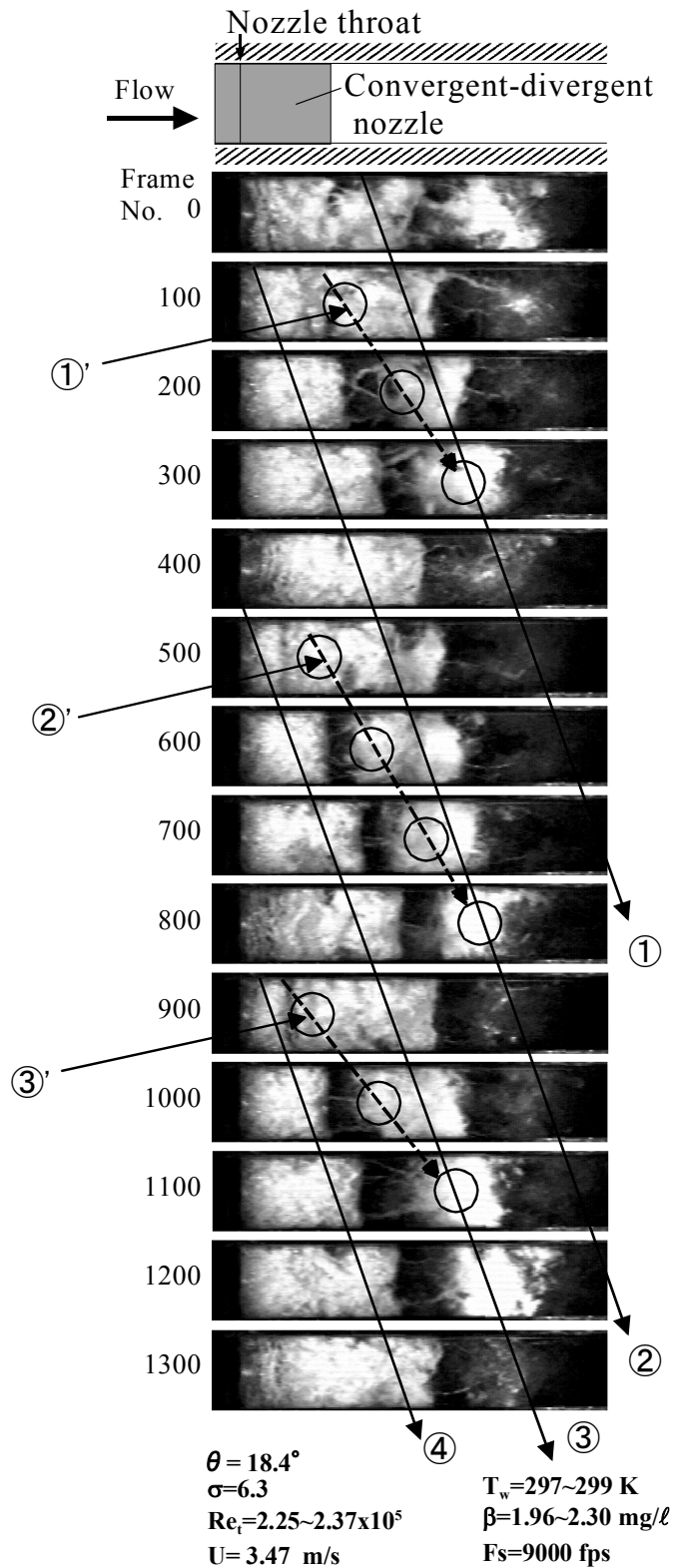
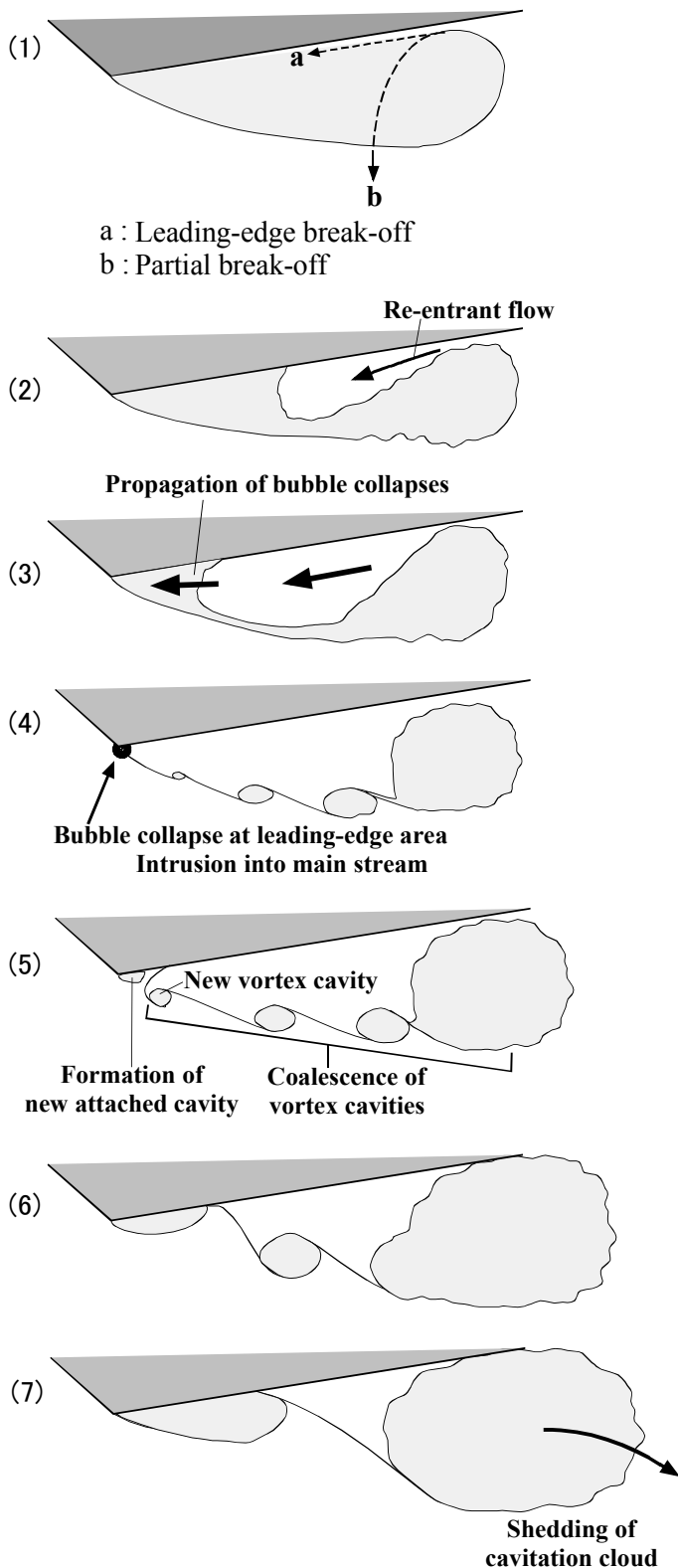


Fig.6 coalescing and shedding behaviors of cavitation cloud (Plane-view observation)



**Fig.7 Schematic view on the process of re-entrant motion, cavity formation and cloud shedding**

cloud. At the final stage a large cavitation cloud is generated as shown in Fig.3. After the small bubbly cloud-A, a new attached cavity indicated by arrow-B begins to be formed along the diverging surface downstream of the nozzle throat through the supply of vortices from the upstream boundary layer. Thus a new periodic motion is generated and repeated.

### Plane View of Cavitation-Cloud Formation

Figure 6 shows a high-speed video observation (the framing rate  $F_s=9000\text{fps}$ ) from the plane view about a shedding process of cavitation clouds in a convergent-divergent nozzle. The white part corresponds to a cavitating area. These pictures show the shedding process of cavitation clouds, especially the coalescence aspect of vortex cavitation clouds. The motions shown by the lines 1-4 correspond to those of cavitation clouds which consist of a backward part of an existing attached cavity and several developed cavities from small-scale vortex cavities on the interface of the separated region. Typical coalescing motions of the latter developed cavities are shown by the dotted lines 1'-3', where the cavities near the leading edge are chosen as a typical example. Frames No.0, No.400, No.800 and No.1300 in Fig.6 correspond to the pictures at the time when a re-entrant motion almost arrives at the leading edge of the separated region (namely, nozzle throat). At this moment, the re-entrant motion turns to the shedding motion of cavitation cloud.

### Summary on Periodic Motion of Cloud Cavitation in the Present Research

Figure 7 shows a model of the re-entrant motion and the shedding process of cavitation clouds observed in the present study. First, as shown in Fig.7-(1), an attached cavity separated from the nozzle throat grows downstream to a large scale. The attached cavity consists of bubbly mixture with reverse rolling flow at the closure part. The reverse fluid flows into the attached cavity to fill it as shown in Fig.7-(2) and as a result the bubbles tend to disappear inside the attached cavity. At this time a small-scale break-off of cavity can, in some cases, occur as shown in Fig.7-(1)-b (see, Frames No.-250 to -170 in Fig.3) though the occurrence condition remains unsolved.

The sparse bubbly area goes upstream as shown in Fig.7-(2), (3). The mechanism of this advancing motion remains to be completely solved whether the motion is caused mainly by the re-entrant jet or mainly by the propagation of bubble collapses due to pressure. For the present study, the latter mechanism as shown in Fig.7-(3) appears to be main or dominant at the last stage of the re-entrant motion because the detailed observation near the nozzle throat (see, Fig.4) indicates that the collapse of bubbles propagates upstream at some speed while the translational speed of bubbles seems to be very small.

As shown in Fig.7-(4), when the re-entrant motion reaches the leading edge of attached cavity and the bubble collapses there, a rushing-out of fluid into the main stream from the cavity inside occurs together with a rebounding motion of bubble (see, Figs.7-(4) and (5)) and the formation of a small-scale vortex cavity from the attached-cavity inside occurs on the separated shear layer. At this time the supply of vorticity may be suppressed momentarily from the upstream boundary layer.

As shown in Figs.7-(5) and (6), a vortex cavity formed by the fluid from the attached-cavity inside grows through the coalescence with existing vortex cavities and is shed downstream as a large cavitation cloud (see, Fig.7-(7)). Figure 7-(5) shows the formation of a new vortex cavity from the upstream boundary layer just after the formation of vortex cavity from the inside mentioned before. The new vortex cavity grows along the divergent part of the nozzle as a new attached cavity (see, Figs.7-(6) and (7)).

It is necessary to further discuss whether the process explained above can apply the hydrofoil sheet cavitation [20] based on thin laminar separation bubble or not. On the other hand, it is also necessary to examine the usefulness of the simple re-entrant jet model because most partial cavities consist of bubbly mixture. In addition, there may be several patterns of re-entrant motion. The propagation of bubble collapses appears to be in different manners and at different speeds though the existence of bubble-collapse propagation is introduced in this study.

## CONCLUDING REMARKS

A behavior of unsteady cavitation was experimentally investigated using a high-speed-video camera in a convergent-divergent nozzle. The attached cavity separated from the nozzle throat has an inside structure of bubbly mixture and consists of many small bubbles. The main points obtained are summarized as follows.

1) A periodic unsteady cavitation observed in a convergent-divergent nozzle has a re-entrant motion as a feed-back mechanism and sheds cavitation clouds to the downstream direction.

2) The re-entrant motion appears to be not simple reverse jet because the existence of upstream propagation of bubble collapses can be also observed especially near the leading-edge region of bubbly attached-cavity.

3) From the present observation at the time when the re-entrant motion reaches the leading edge of bubbly attached-cavity region near the nozzle throat, the following process can be proposed: [Stage-1] a collapse of bubble occurs at the leading-edge area of bubbly attached-cavity, [Stage-2] at this time the supply of vorticity is suppressed from the upstream boundary layer, [Stage-3] a formation of small vortex cavity occurs on the boundary surface from the inside of the bubbly attached-cavity, [Stage-4] the vortex cavity from the inside grows through the coalescence with existing vortex cavities and finally is shed downstream as a large cavitation cloud, [Stage-5] a new vortex cavity is formed by the upstream supply of vorticity, just after the formation of vortex cavity at Stage-3, [Stage-6] The new vortex cavity grows to a large scale along the divergent part of nozzle as a new attached cavity.

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