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MECHANISM OF CAVITATION EROSION AT THE EXIT OF A LONG ORIFICE

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ABSTRACT

We carried out experiments to clarify the mechanism of cavitation erosion at the exit of a long orifice equipped at a pressure-reducing line in a pressurized water reactor (PWR). In order to ascertain the mechanism of cavitation erosion at the first stage and progression stage, we used a high-speed video camera. As a result, we observed cavity collapse near the exit of the orifice under oscillating flow conditions, which might be a major factor in the first stage of erosion at the exit of the orifice. To simulate the progression stage, we used an orifice with a cone-shaped flow passage at its exit, corresponding to an orifice diffuser. We observed cavity collapse near the exit, after which cavities that existed upstream in the cone shape collapsed in a manner similar to a chain reaction. The propagation speed varied with the quantity of cavities in the cone-shaped flow passage and cavities collapsed in a concentric circle pattern. Thus, the cavity collapse mechanism was concluded as follows: a pressure wave (shock wave) was generated by cavity collapse near the exit, then propagated upwards, and consequently caused cavity collapse upstream. This mechanism might promote cavitation erosion in an upward direction.

1. INTRODUCTION

Cavitation erosion occurred at the exit of a long orifice equipped at a pressure-reducing line in a pressurized water reactor (PWR) [(1)]. The exit was eroded and changed into a cone shape. At the first stage of erosion, the edge of the exit began to erode, possibly caused by the reduction in pressure downstream of the orifice during the plant startup and shutdown operations. After this shape change at the exit, continuous cavitation might occur during normal plant operation, and after several years the erosion would advance to produce the cone shape.

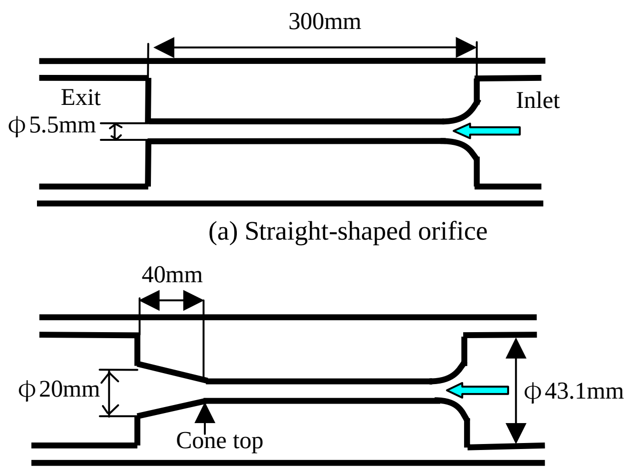
So far, a few studies have tried to clarify cavitation behavior in the orifice [(2)], which is non-curving at the inlet, and cavitation erosion at the pipe wall downstream of the orifice [(3)]. Although one study attempted to evaluate the erosion rate at the exit of the orifice [(4)], its mechanism has not been clarified. The exit of the orifice is the region in which the cavitation jet is generated at a steady state, not the collapsing region. Thus, the mechanism of cavitation erosion at the exit seems to be different from that of the pipe wall downstream of the orifice. In the region with extensive pressure oscillation, cavity generation and collapse are promoted, so it is not enough to consider only a steady cavitation flow state [(5)], but also that of an unsteady state such as cloud cavitation. In this study, we investigated the mechanism of cavitation erosion at the first stage and progression stage by setting the same cavitation number to simulate the flow pattern of the plant operating conditions and to observe the cavity growth and collapse behavior using a high-speed video camera.

2. Experimental method and apparatus

2.1 Experimental method

2.1.1 Object of the experiment

Figure1 shows the two kinds of orifices we consider as the object of this experiment. Shape (a) is the normal shape of the orifice. The throat diameter is 5.5mm and the length is 300mm. Shape (a) changed into Shape (b), a cone shape, as a result of cavitation erosion. In the case of Fig. 1(a), the pressure decreases from the inlet to the exit due to acceleration loss and flow friction between the pipe wall, but after that it increases due to the slowdown at an enlargement of the flow region. Because a low-pressure region exists near the exit of the orifice, cavity collapse does not occur in a steady flow state and we cannot explain cavitation erosion at the exit. In the case of Fig. 1(b) the pressure decreases from the inlet to the cone top but after that, it increases. When it reaches a level higher than the



(a) Straight-shaped orifice

(b) Cone-shaped orifice

Fig. 1 Change of the flow passage at the exit of the orifice

vapor pressure, the cavity basically collapses near the exit of the cone-shaped flow passage. But cavity collapse does not occur at the cone top in the steady flow state and we cannot explain why cavitation erosion progresses upstream. Thus, this cavitation erosion may be caused by unsteady phenomenon, so the subjects in this study are as follows: (1) What is the mechanism at the biginning of the cavitation erosion? (2) What is the mechanism at the progression of erosion to a cone shape?

There was no information about an intermediate stage to the final cone shape and to reproduce the process by an experiment would be extremely time-consuming. Therefore, in this study we carried out experimental erosion tests and visualization using the straight-shaped orifice as shown in Fig. 1(a) and visualization using the cone-shaped orifice as shown in Fig. 1(b), which was tapered in order to simulate the final eroded shape.

In the plant, the orifice throat length should be 300mm in order to reduce the pressure from 15.3MPa upstream to 2.3MPa downstream. Because the maximum upstream pressure was 3.6MPa in the experiment, we did not need the same throat length for the purpose of this study, so it was shortened to 100mm. The throat diameter is the same as that of the plant.

2.1.2 Method of simulation of the plant conditions

In general, in order to simulate the same cavitation flow patterns it would be necessary to make adjustments to achieve the same cavitation number [(5)]. Thus, in this study, we defined the cavitation number as follows and adjusted it to match the plant operation conditions:

$$\sigma = \frac{P - P_V}{\frac{1}{2}\rho V^2}$$

where P is the downstream pressure, P_V is the vapor pressure at test water temperature, ρ is the water density at test water temperature, and V is the orifice throat velocity, which is estimated by dividing the flow rate measured with an electromagnetic flow meter by the cross section of the throat. The operation to reduce the pressure downstream of the orifice at the plant startup and shutdown might cause cavitation erosion at the edge of the orifice exit. Therefore, the cavitation number at the straight-shaped orifice was adjusted to σ = 0.116, corresponding to the startup and shutdown conditions. After erosion at the edge of the orifice exit, continuous cavitation might occur during plant operations, and after several years erosion would advance to the cone shape. Thus, in the case of the cone-shaped orifice the cavitation number was adjusted σ = 0.27, corresponding to normal plant operating conditions.

2.1.3 Experiment at the straight-shaped orifice

We simulated the flow condition at the beginning of erosion using the test section as shown in Fig. 2 and then confirmed whether or not cavitation erosion would occur. The test specimen was made of pure aluminum. In addition, we used another test section that was the same shape but was made of Lucite, and we observed the behavior of cavity generation and collapse near the orifice exit.

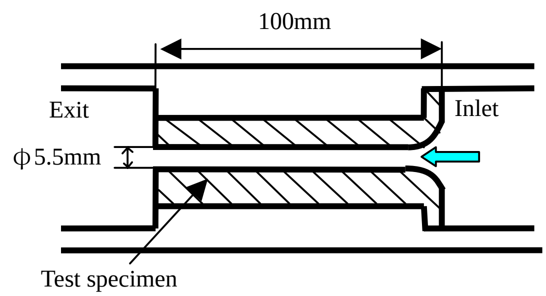


Fig. 2 Test section of straight-shaped orifice

2.1.4 Experiment at the cone-shaped orifice

We carried out the visualization of cavity growth and collapse with a high-speed video camera (PHOTORON, FASTCAM -UltimaSE, maximum framing rate 40,500fps). Impulsive force sensors were mounted on the test section as shown in Fig. 3. We used the signals from the sensor to trigger the high-speed video camera. Impulsive force sensors were fixed at 4mm, 20mm and 35mm downstream of the cone top.

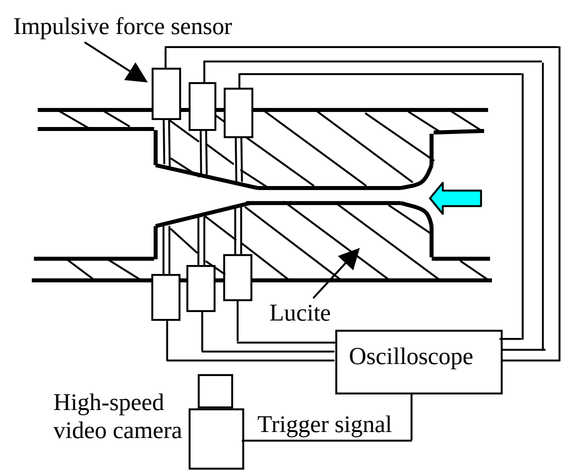


Fig. 3 Test section of cone-shaped orifice

2. 2 Experimental apparatus

2.2.1 Test loop

Tests were carried out in a closed-type cavitation tunnel,

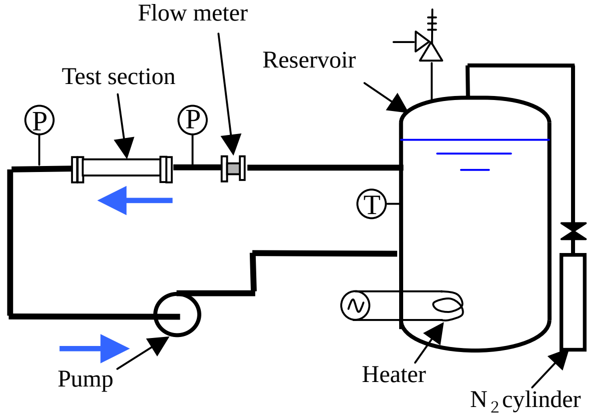


Fig. 4 Test loop

which consisted of a reservoir, pump and pipes as shown in Fig. 4. The test section consisted of a segment of the pipes. The reservoir is a pressure vessel with a capacity of 1.28m^3. The test water temperature could be adjusted with a heater fixed at the reservoir. Flow rate was measured by an electromagnetic flow meter upstream of the test section. Two pressure gauges were fixed upstream and downstream of the test section. Test water temperature was measured by thermometer fixed at the reservoir.

2.2.2 Method of adjusting test conditions

The test loop pressure was adjusted with a nitrogen cylinder equipped at the reservoir. The velocity was adjusted by the pump rotation speed, which was controlled by an inverter connected to an electric power motor. We kept the velocity constant during the experiment, but the water temperature tended to rise due to pump heat, so we adjusted the pressure downstream of the orifice to keep the cavitation number constant. Tap water was used for the test water. Because air content in the test water could affect the impulsive force at bubble collapse, we measured the concentration of dissolved oxygen in the test water before and after the test, and confirmed that no significant changes occurred during the test. We carried out the tests at a concentration of 6.45–7.88mg/l in the visualization test and 6.05–6.68mg/l in the erosion test, respectively.

3. RESULTS AND DISCUSSION

3.1Mechanism at the first stage of cavitation erosion

First, we carried out the erosion test at the straight-shaped orifice as shown in Fig. 2, and confirmed whether or not cavitation erosion would occur at the orifice exit. Test conditions were velocity V = 70m/s, upstream pressure 3.6MPa, downstream pressure P = 0.29MPa, water temperature T = 50℃ and cavitation number σ = 0.116 (startup and shutdown conditions). The results showed that the edge of the exit was eroded and numerous pits formed there, as shown in Fig. 5, which is tipical cavitation damage. We then investigated the behabior of cavity collapse through the visualization test. Test conditions were velocity V = 74m/s, upstream pressure 3.1MPa, downstream pressure P = 0.32MPa, water temperature T = 33℃ and cavitation number σ= 0.116. The cavity collapse behavior, which is shown in Fig. 6, was recorded by high-speed video camera at a framing rate of Fs = 18,000 frame/sec. In this case, we used another high-lift pump to increase the test velocity and reversed the flow direction of the loop as shown in Fig. 4, in which the left side of the figure corresponds to the upstream direction. According to this video picture, the flow state was oscillating, then the cavity grew and contracted erratically over and over again, and the noise level alternated between high and low. First, the cavity just below the exit started to grow as shown in Fig. 6-(1). Second, a part of the cavity began to contract as shown in Fig. 6-(2); third, it collapsed as shown in Fig. 6-(3) and finally, it recovered as shown in Fig. 6-(4). The results indicate that flow oscillation may cause cavity collapse and the first stage of erosion that occurs at the edge of the orifice exit. Other cavity collapses were recorded in series before and after the collapse (Fig. 6) with time intervals measured by the video time count as 1.11–1.95ms, that is, frequencies of 500–900Hz.

Furthermore, we cut the test specimen shown in Fig. 5 to determine where erosion occurred along the flow passage at the straight-shape test condition, but only the edge of the exit was eroded, not the remaining flow passage. These results indicate

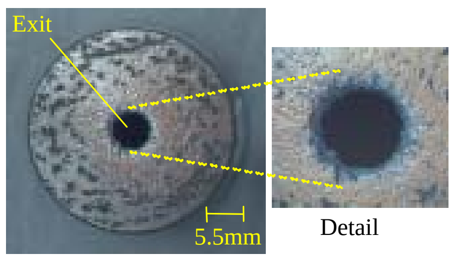


Fig. 5 Result of the erosion test

(straight-shaped orifice, V = 70m/s, σ= 0.116, T = 50℃, Aluminum)

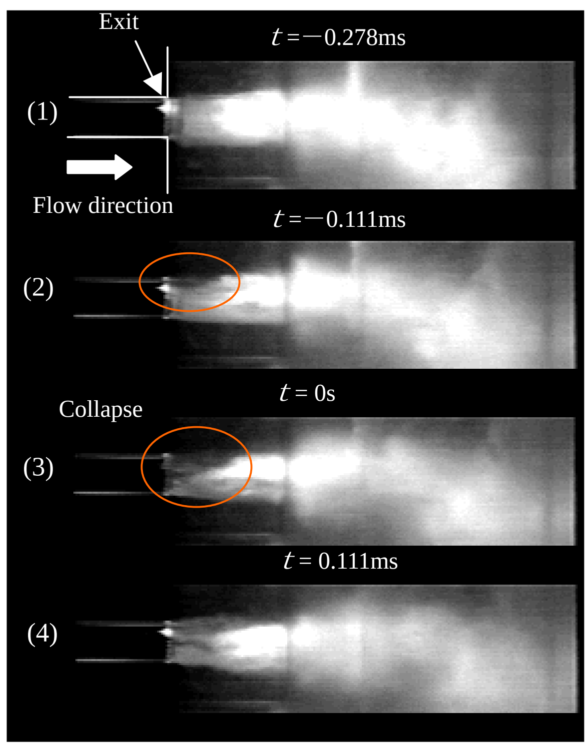


Fig. 6 Behavior of cavity collapse

(straight-shaped orifice, V = 74m/s, σ= 0.116, T = 33℃, Fs = 18000fps) that in order to form the cone shape, another mechanism of promoting cavitation erosion upstream would be needed after the stage shown in Fig. 5. We then observed the flow pattern at the cone shape and investigated its mechanism.

3.2 Mechanism at the progression stage of cavitation erosion

Cavity collapse behavior at the cone shape, as shown in Fig.7, was recorded at a framing rate of *Fs* = 27,000 frame/sec. The higher we set the test velocity, the faster the phenomenon in the cone shape changed, which made it difficult to capture clearly. Therefore, we carried out tests at the relatively low velocity of *V* = 25m/s. Other test conditions were upstream pressure 0.26MPa, downstream pressure *P* = 0.09MPa, water temperature *T* = 23℃ and cavitation number σ = 0.27 (normal operating conditions).

The signal from the impulsive force sensor fixed at 4mm downstream of the cone top was used as the center trigger and the behavior of cavity collapse was recorded. As a result, we observed cavity collapse near the exit as shown in Fig. 7-(3), after which cavities in the upper side of the cone shape collapsed in a manner similar to a chain reaction [7] as shown in Fig. 7-(4)–(7). These behaviors seem to resemble the re-entrant motion [8] in a separated flow. We then calculated that the propagation speed of this phenomenon based on time interval and distance from cavity collapse downstream to that upstream of the cone shape was about 33m/s.

Sonic speed in water is 1400m/s, but in a two-phase flow it drops to dozens of meters per second. And between the void fraction ranging from 40–60% at atmospheric pressure, it drops to 20m/s[9]. In this experiment we could not calculate the precise sonic speed because we did not measure the void fraction, but the propagation speed of about 33m/s, calculated from Fig. 7, is the same order as the sonic speed in a two-phase flow at atmospheric pressure. Because a shock wave is generated by cavity collapse [10], we predicted this phenomenon as follows: a pressure wave (shock wave) was generated by cavity collapse near the exit, then propagated upwards, and consequently caused cavity collapse upstream.

We further observed the behavior of cavity collapse to confirm this prediction. The results showed that the propagation speed of cavity collapse varied with the quantity of cavities in the cone-shaped flow passage as shown in Fig. 8. Figure 8(a) shows cavity collapse behavior in the case of high bubble density, with a propagation speed of about 27m/s. Figure 8(b) shows that in the case of low bubble density, the propagation speed was about 93m/s. The higher the bubble density became, the slower the propagation speed, which corresponds with the relationship of void fraction and sonic speed. In Fig. 9, after collapsing at the center of the cone shape, cavity collapse spreads in a concentric circle pattern. We can conclude, therefore, that these behaviors were brought about by pressure waves (shock waves).

In these tests, the point of the signals from the impulsive force sensor near the cone top corresponded to the rebound after the cavity collapse, which indicates that impulsive force occurred at the rebound.（the time interval for propagation of impulsive force through the pressure detection rod is within 0.01msec, while time intervals in these tests were much longer）.

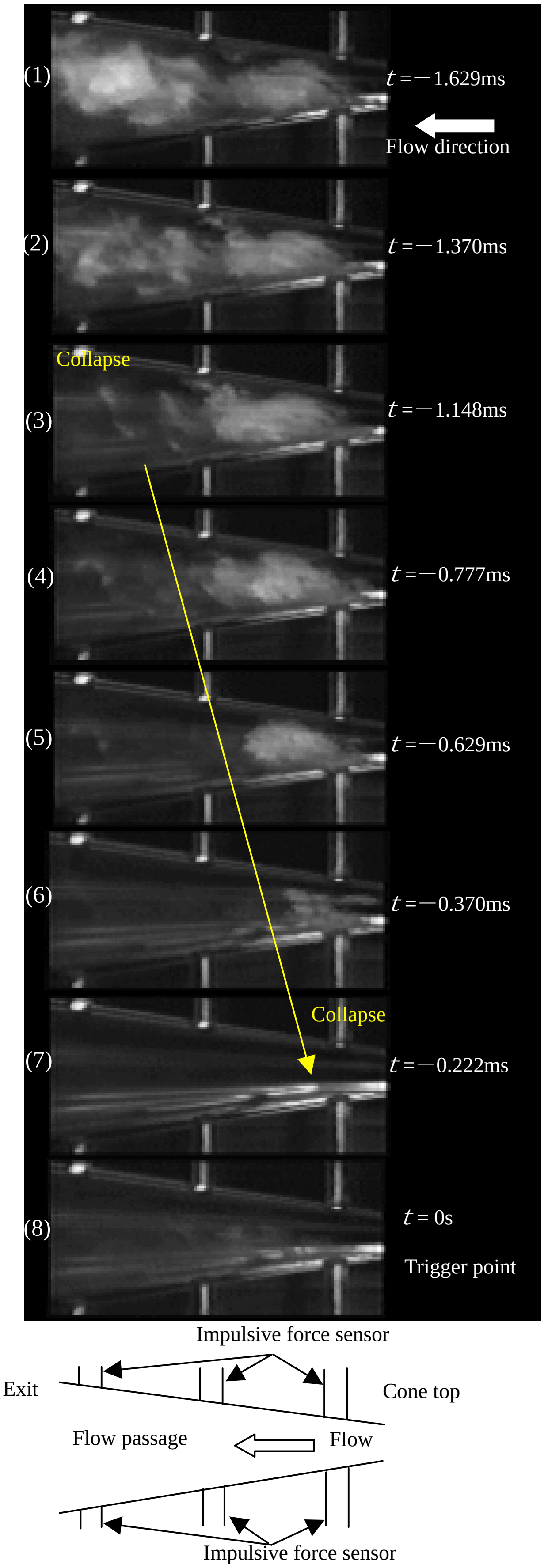
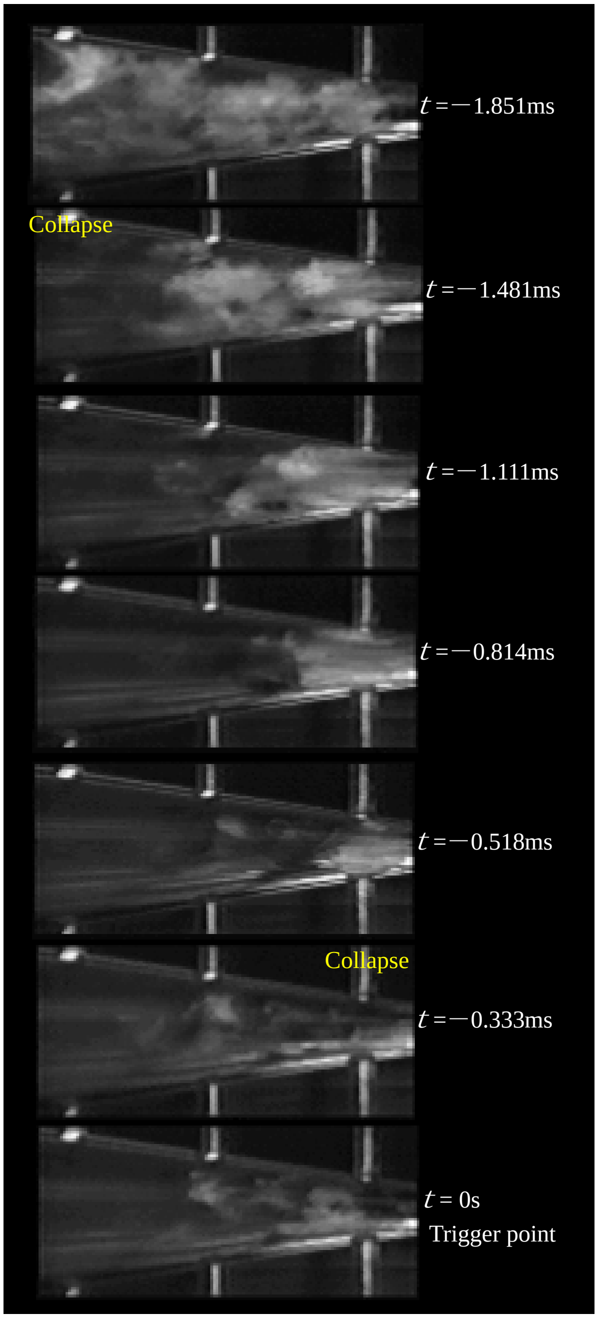
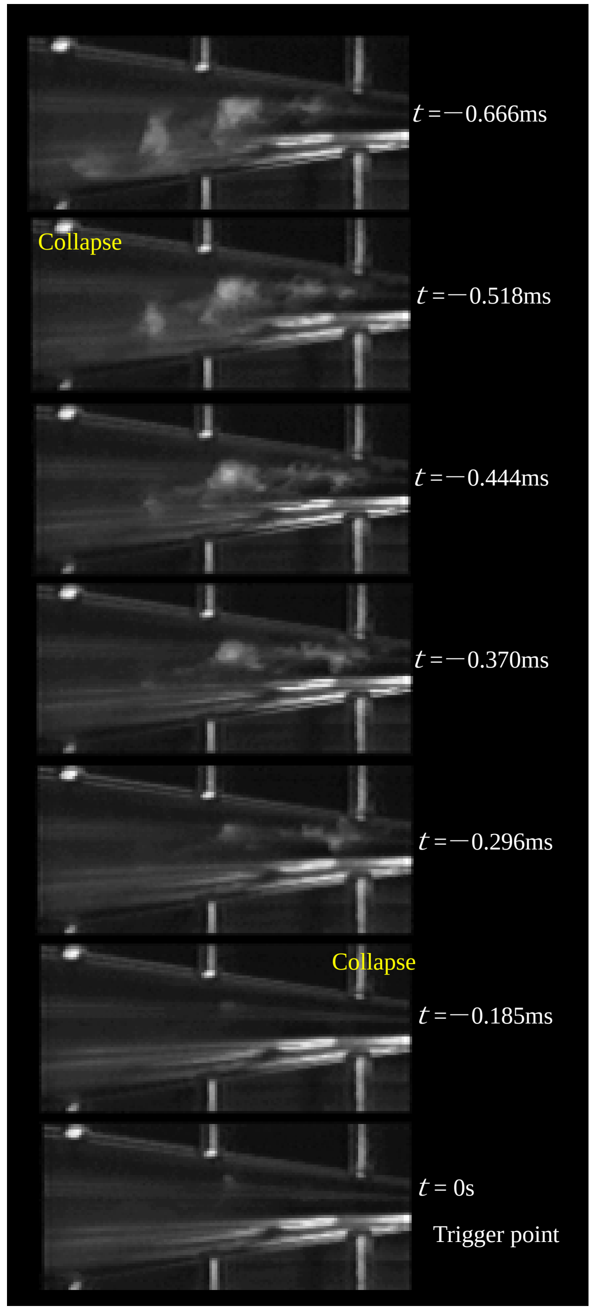


Fig. 7 Behavior of cavity collapse
（cone-shaped orifice, *V* = 25m/s, σ= 0.27, *T* = 23℃, *Fs* = 27,000fps）



(a) A case of high bubble density



(b) A case of low bubble density

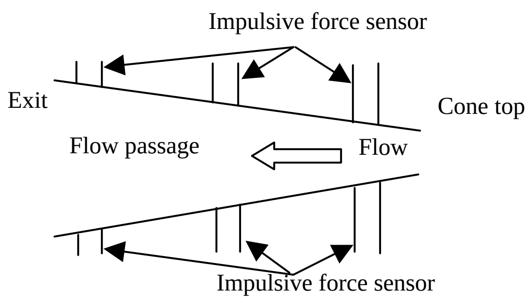


Fig. 8 Difference of the propagation speed of cavity collapses between a case of high bubble density and a case of low bubble density
(cone-shaped orifice, V = 25m/s, σ = 0.27, T = 23℃, Fs = 27,000fps)

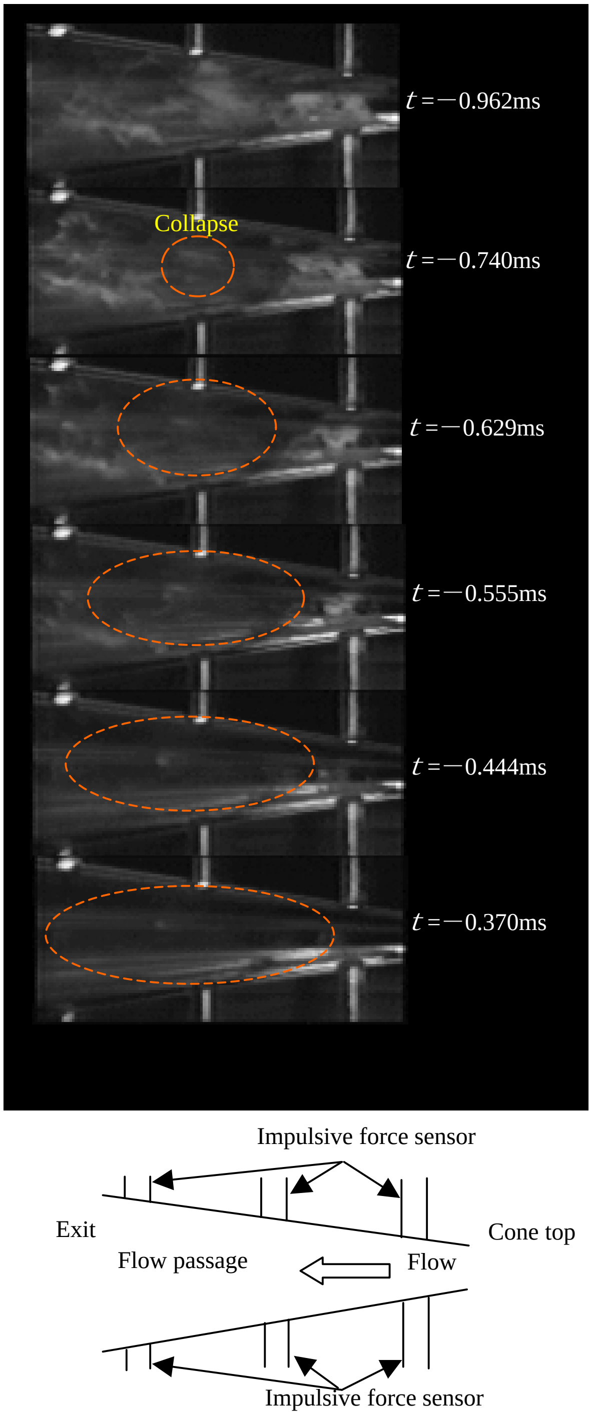


Fig. 9 Behavior of cavity collapses spreading in a concentric circle pattern (cone-shaped orifice, V = 25m/s, σ= 0.27, T = 23℃, Fs = 27,000fps)

4. CONCLUSIONS

We carried out an experimental investigation to clarify the mechanism of cavitation erosion at the exit of a long orifice equipped in a PWR, and obtained the following conclusions:

(1) Mechanism at the first stage of cavitation erosion

In a steady flow state, cavity collapses downstream of the exit of the orifice, so we cannot explain cavitation erosion at the edge of the orifice exit. In the visualization test, we observed heavy cavity collapse under oscillating cavitation flow and the cavity grew and contracted erratically. The results indicate that the flow oscillation may cause cavity collapse and the first stage of erosion at the edge of the exit.

(2) Mechanism at the progression stage of cavitation erosion

In a steady flow state, cavitation erosion occurs near the exit of the cone-shaped flow passage, so we cannot explain cavitation erosion at the cone top and its upward propagation. The results of observing the behavior of cavity collapse show that cavity collapses propagated upwards after collapsing near the exit. The propagation speed varied with the quantity of cavities in the cone-shaped flow passage and cavities collapsed in a concentric circle pattern. We presumed that this propagation of cavity collapse was caused by a pressure wave (shock wave). Thus, a shock wave was generated by cavity collapse near the exit, then propagated upwards, and consequently caused cavity collapse upstream. This mechanism might, therefore, promote cavitation erosion in an upward direction.

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