F-321 TOC

Proceedings of ASME FEDSM'03
4th ASME_JSME Joint Fluids Engineering Conference
Honolulu, Hawaii, USA, July 6-10, 2003

FEDSM2003-45007

GROWTH PROCESS TO CLOUD-LIKE CAVITATION ON SEPARATED SHEAR LAYER

Yasuhiro Saito and Keiichi Sato
Department of Mechanical and Mechanical Systems Engineering
Kanazawa Institute of Technology
Ishikawa, JAPAN

ABSTRACT

It is important to explain a high-speed liquid flow phenomenon because of the developments of various fluid machines. Cavitation is one of the most important phenomena in high-speed liquid flow. When cavitation appears in a liquid flow, it causes some problems such as performance deterioration, vibrations, noise, and cavitation damage. So, it is important to observe the cavity behavior to solve such problems. Especially, it is well known that a cloud cavitation has heavy unsteadiness and high impulse. In this study, a fundamental experimental research on the process of growing to the cloud-like cavitation was performed. The aspect of the cavitation in a circular cylindrical orifice and in a convergent-divergent channel was observed by the high-speed video camera.

As a result, the unsteady shedding behavior of the vortex cavity was characteristically observed in a region of the separation bubble at an inlet of a circular cylindrical orifice. There are several vortex cavities on the separated shear layer. These cavities behave pairing and coalescence with each other repeatedly and grow up into a cloud-like cavity. The cloud-like cavity is shed downstream and then generates high impulses at the collapse. In the case of a circular cylindrical orifice, the cavities can be observed clearly by using a laser sheet method. Similar behaviors of the cavity are observed on the separated shear layer in a two dimensional convergent-divergent channel. This paper discusses how the behaviors of vortex cavity relate closely to the flow pattern at non-cavitating condition on the separated shear layer and that the process of the vortex cavities develop to the cloud-like cavity.

Keywords: Cloud-like cavitation, Separated shear layer, Vortex pairing and coalescence, Unsteady shedding

INTRODUCTION

It is very important to observe the behavior of the cavitation bubble for solving problem related to vibration, noise and cavitation damage caused by the cavitation occurrence. Many observations about the cavitation behavior have been studied in the flow condition around the object (such as a hydrofoil and a circular cylinder).

Examples of visualization and observation of the cavitation flow behavior have been studied and published. First, cavitation and re-entrant flow which took place inside flow channel were observed by Knapp using a high-speed photograph [1]. Ivany et al. observed the cavitation collapse aspect in a venturi in detail using a high speed photography [2]. Ceccio et al. studied the detailed action of traveling bubble near the solid boundary [3].

Some observations were given by using a high-speed video camera. Sato et al. measured an impulsive force at the same time with observation of the bubble collapse behavior by the idea which synchronized a high-speed video camera with the impulsive force generated by cavity collapse [4,5]. Ohba et al. found a local velocity around the cavitation from the image of which took pictures with a high-speed video camera [6]. Laberteaux et al. observed the collapse behavior of the cavitation bubble by using a super-high-speed CCD camera at a photography speed of order of 10^5 frames per second [7].

Although there are many studies on cavitation, there are still many unknown cavitation problems to be solved such as unsteady shedding motion. In the development of high-speed fluid machinery such as aerospace technology, it has been required to solve the mechanism of this unsteady cavitation behavior. In addition, it has been noticed that the cloud-like cavitation showed the heavy unsteady results [1].

In this study, for the purpose of clarifying the cavitation unsteady behavior, two flow field shapes of circular cylindrical orifice and convergent-divergent channel were taken up as a first step, followed by a fundamental study. Detailed cavitation which occurred on the separated shear layer in the flow field was observed. There are few examples of unsteady cavitation studies observed dynamically in an axisymmetrical internal flow like a circular cylindrical orifice [8,9]. The authors investigated about the mechanism of self-exciting behaviors of unsteady large-scale cloud-like cavitation and showed the existence of pairing and coalescence in the cavity shedding process, and the importance of re-entrant motion[8-10]. In the

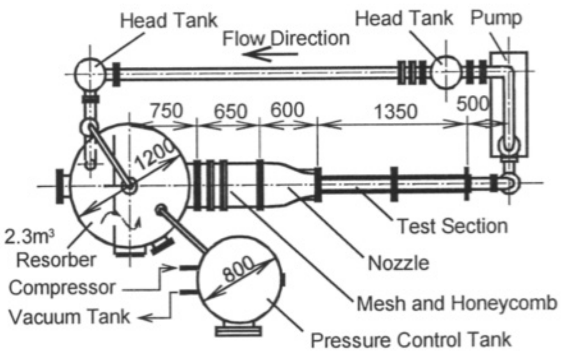


Fig.1 Cavitation tunnel

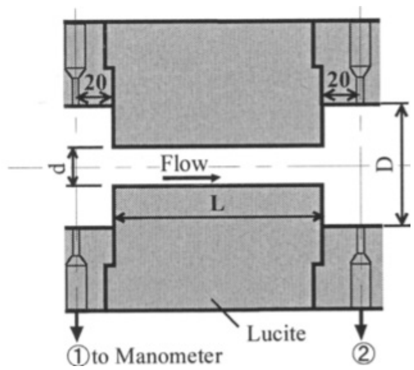


Fig.2 Details of test section

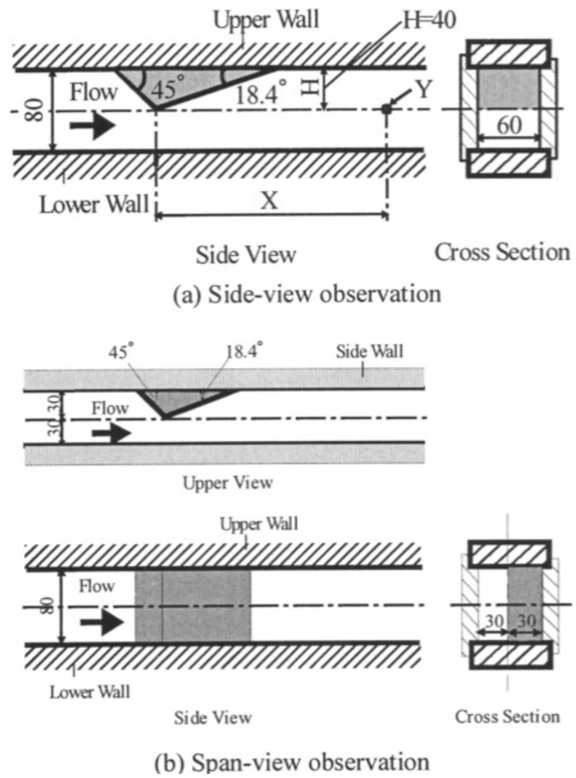


Fig.3 Convergent and divergeny channel

present work, an examination is done about an unsteady cloud-like cavity on the shear layer. The detailed observation of the small vortex cavity which occurs on the shear layer is performed. From the viewpoint of the growing process, the examination is also carried out.

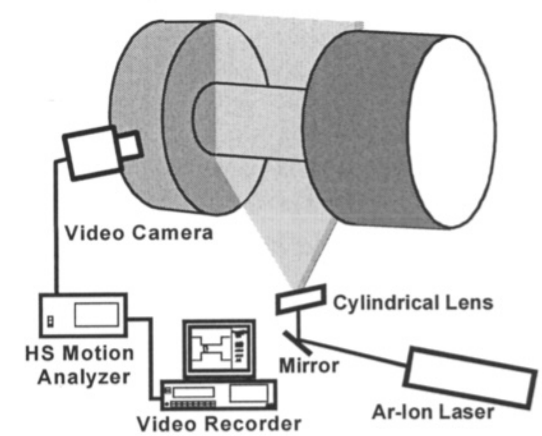


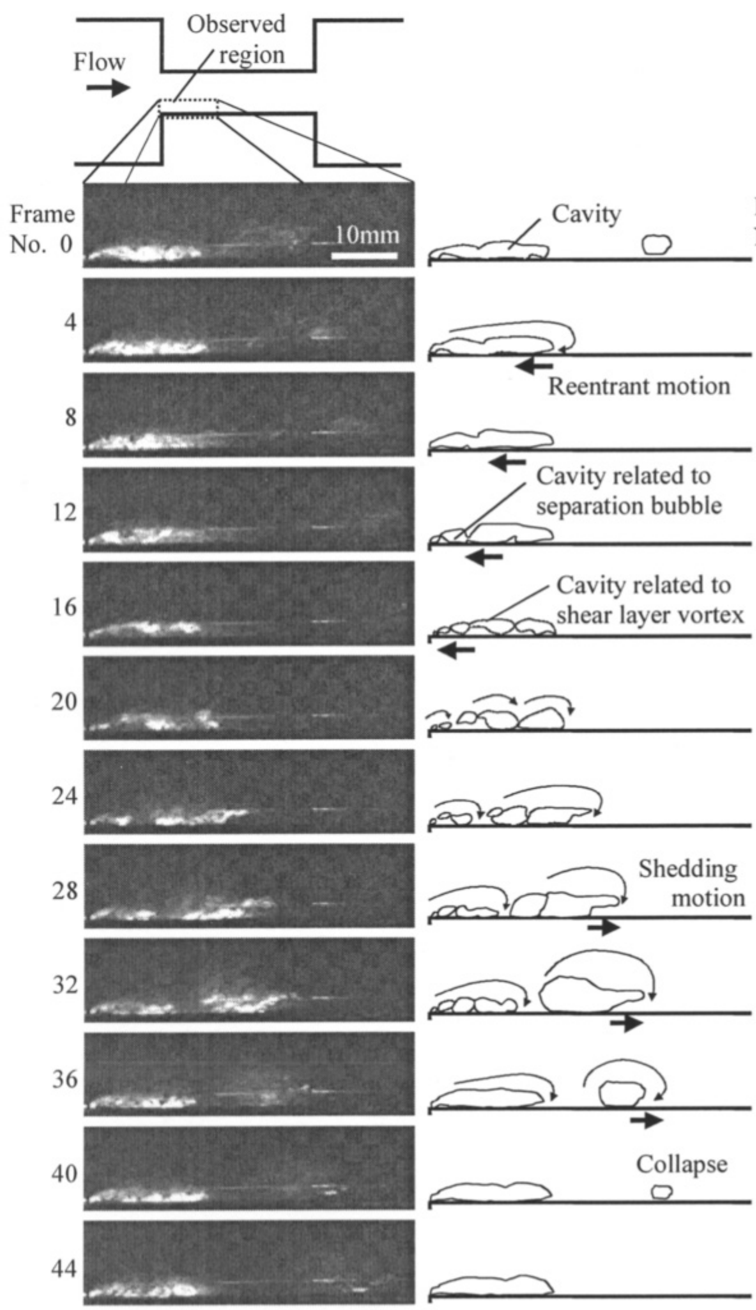
Fig.4 Laser sheet observation system

NOMENCLATURE

d: Inner diameter of the orifice
D: Outer diameter of the orifice
Fs: Recording speed of high-speed video camera
H: Throat height of nozzle of the convergent-divergent channel
L: Length of the orifice
P: Upstream static pressure of the convergent-divergent channel
P_1: Upstream static pressure of the orifice
P_2: Downstream static pressure of the orifice
P_v: Saturated steam pressure
Re_t: Reynolds number
Tw: Temperature of the water
U: Upstream average velocity of nozzle of the convergent-divergent channel
U_c: Average velocity in the orifice entrance contraction section with contraction coefficients
U_r: Average velocity of the re-entrant motion
U_t: Average velocity in the contraction division
U_v: Convection velocity of the vortex cavity
β: Dissolved oxygen of the water
ν: Kinematic viscosity of water
ρ: Density of water
σ: Cavitation number

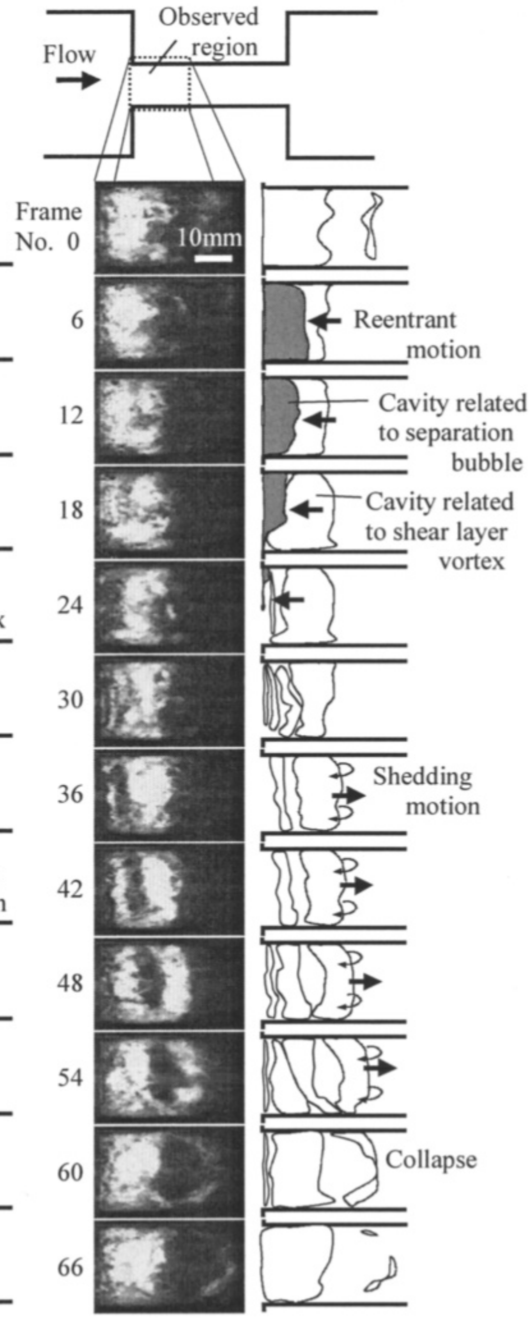
EXPERIMENTAL APPRATUS AND PROCEDURE

The experiment was carried out using a cavitation tunnel shown in Fig.1. The tunnel has a pressure control tank, and it is possible to adjust the pressure of the whole tunnel and controls the condition of the cavitation. It has the circular cross section of 80 mm diameter D, and a circular cylindrical orifice of 22 mm diameter d, and 100 mm long L, without the entrance roundness (see Fig.2). The experiment can be observed through the transparent acrylic resin at the outer test section. It equips with pressure taps at the upstream and downstream 20 mm from the both end of contraction section. A 60 mm × 80 mm



σ=0.94, Re_t=2.2×10^5, β=5.5 mg/ℓ, U_t=9.6 m/s, Tw=295 K, Fs=9000fps

(a) Section views showing the shedding cavities using laser sheet method



σ=0.94, Re_t=2.2×10^5, β=5.4 mg/ℓ, U_t=9.6 m/s, Tw=298 K, Fs=13500 fps

(b) Plan view of shedding cavities

Fig.5 Observation of shedding cavities

rectangle channel shown in Fig.3 was used for the two-dimensional convergent-divergent channel experiment. Two flow channel geometries were prepared in order to observe from two directions. The blockage ratio of both channels is 1/2, and each channel has a similar cross-section.

The observation of the behavior was mainly carried out using the high-speed video camera (KODAK EXTAPRO MODEL4540, The maximum framing rate was 40500 fps (frames per second)). The framing rates of high-speed video camera mainly used in this study were 9000, 13500 and 18000 fps. The continuous light was used. The exposure time per frame almost corresponds to the reciprocal of recording frame number. A metal halide lamp (PHOTORON, HVC-SL, 150W) and an argon-ion laser (SOC, GLG3482, 4W) were used as a light source for the visualization of the cavitation. The argon-ion laser was spread like sheet with a cylindrical lens, as shown in Fig. 4, and the orifice central cross section parallel to the cylindrical orifice axis was illuminated. The thickness of the laser sheet was 3 mm in this case. The visualization experiment of the cavitation was performed in a constant flow velocity condition and a cavitation number was set by changing the static pressure of the whole tunnel slowly.

Cavitation number σ and Reynolds number Re_t used in this paper are defined as follows.

Circular cylindrical orifice:

$$\sigma = (P_2 - P_v) \ / \ (P_1 - P_2) \quad \cdots\cdots (1)$$

$$Re_t \ = U_t \cdot d \ / \ \nu \quad \cdots\cdots\cdots (2)$$

Convergent-divergent orifice:

$$\sigma = 2(P - P_v) \ / \ \rho U^2 \quad \cdots\cdots\cdots (3)$$

$$Re_t \ = U_t \cdot H \ / \ \nu \quad \cdots\cdots\cdots (4)$$

P_1 and P_2 are static pressures upstream and downstream of the orifice respectively. P is upstream static pressure of the convergent-divergent channel. ρ, P_v and ν are defined as density, saturated vapor pressure and kinematic viscosity of water. U_t is an average velocity in the contraction division. H and U are throat height of nozzle and upstream average velocity in the convergent-divergent channel respectively. And, temperature and dissolved oxygen of the water are Tw and β respectively, and Fs is framing rate of high-speed video camera.

EXPERIMENTAL RESULTS AND DISCUSSION

Visualization of unsteady cavitation behavior

The cavitation generated inside the cylindrical orifice was visualized using the metal halide light and laser sheet. It was difficult to observe the behavior inside the cavity because the cavity existed circumferentially along the wall surface in the circular cylindrical orifice. Thus, the visualization was done by the laser sheet in respect of the cavity. Cavitation visualization results using the laser sheet and the metal halide lamp are shown in Figs. 5(a) and 5(b) respectively. Though the images of Figs. 5(a) and 5(b) are the results from different experiments, they are almost in the same phase of cavity shedding. The white part in Figs. 5(a) and 5(b) corresponds to cavitating area.

In the visualization by laser sheet shown in Fig. 5(a), only the cavity at the under side is clearly visualized. The cavity behavior can be viewed by enlarging the base of the test section. In comparison with the case of usual lighting, the behavior of the vortex cavity on the shear layer inside is observed clearly. Re-entrant motion in which the cavity collapses to the upstream in the cavity bottom and unsteady shedding behavior of the cavity were confirmed at this time. Figure 5(b) shows the result of the cavity illuminated from the direction of the camera. It is able to obtain clear information for the observation of the general behavior of the cavity using this visualization method. It is confirmed that the cavity almost uniformly exists in the whole cylinder from this visualization result. And, unsteady shedding behavior with re-entrant motion is observed in Figs. 5(a) and 5(b). The unsteady behavior of the cavity is examined on the basis of these visualization observations.

In this case, the average velocity U_r of the re-entrant motion is evaluated with U_r = 11 m/s, and this value is almost equal to the average flow velocity of the orifice throat U_t of 9.6 m/s. There are some micro vortex cavities including the newly cavities generated on the separated shear layer, after the re-entrant motion reaches the leading edge of the cavity (Frame No.16 or 20 in Fig. 5(a)). These vortex cavities are coalescing. They grow and move to the downstream direction. It is noticed that the re-entrant, coalescence, growth and shedding motion of the cavity behave periodically with a self-excited oscillation [9, 10]. The average convection velocity of the shedding cavity is about 10 m/s. Flow velocity U_c in the orifice entrance contraction section with contraction coefficients of 0.62 is 16 m/s. The ratio between convection velocity of the vortex cavity U_v and velocity of the contraction section U_c is 0.6. This value agrees with the result on the convection velocity of the vortex which Kiya et al. [11] showed in the flow around the leading edge of a blunt flat plate.

Behavior of vortex cavity on the separated shear layer in convergent-divergent channel

A cavity behavior on the separated shear layer is observed in a two-dimensional convergent-divergent channel. Figure 6 shows the behavior of vortex cavities close behind the nozzle throat. First, a re-entrant motion which moves from the downstream position of the attached cavity to the leading edge of the cavity is observed (Frame No. -100 to 0). The re-entrant motion, which is indicated by the black arrows in Fig. 6, reaches the leading edge of the attached cavity around Frame No. 0. There are some small vortex cavities on the separated

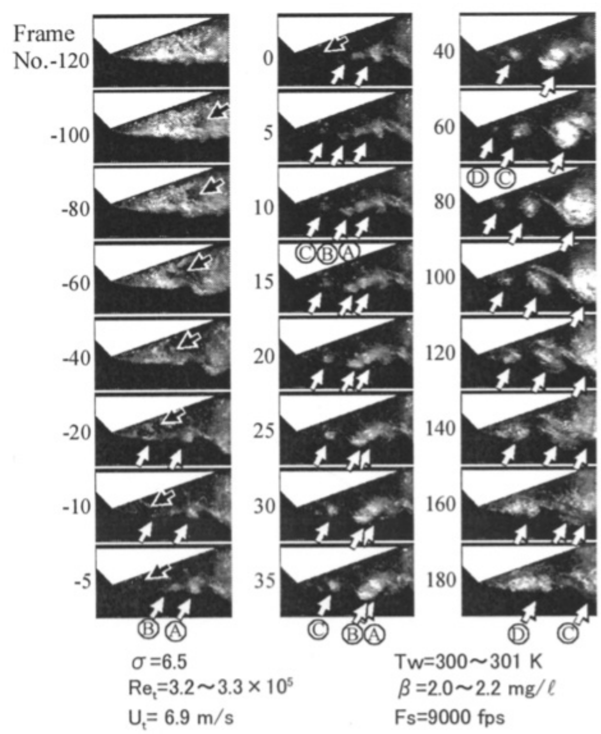


Fig.6 Details of vortex-cavity motion just behind nozzle throat: side-view observation

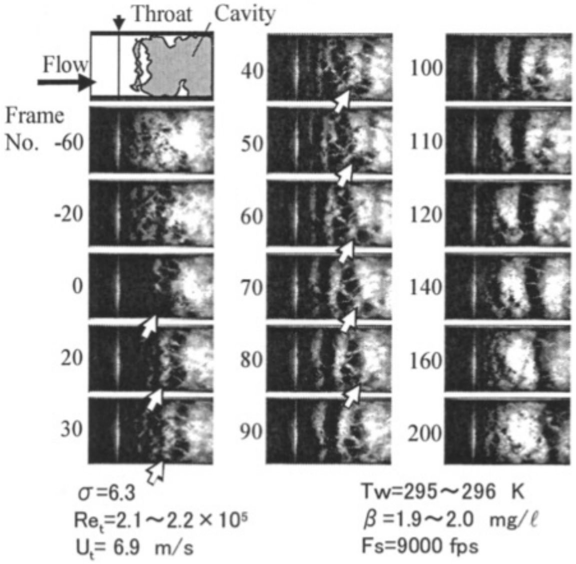


Fig.7 Details of vortex-cavity motion just behind nozzle throat: span-view observation

shear layer at this time (Frame No. -5 to 10). The cavities are denoted by A, B and C in order of occurrence. These small vortex cavities move toward the downstream direction. The cavities A and B show pairing motion (No. 20 to 40) and they coalesce with each other (No. 60 to 80). In addition, the cavity C shows pairing motion and coalesce with the previous cavity. The vortex cavity grows to large scale through such process and is shed downstream. A new vortex cavity D is generated at this time, and it grows to next attached cavity without coalescing into the previous cavity.

Figure 7 shows a cavity behavior on the separated shear layer observed in the span-wise viewpoint. This behavior shown in Fig. 7 is almost the same condition in cavity growing process as in Fig. 6. The left-side transverse line in each photograph corresponds to the nozzle throat. A large cluster-like cavity is observed around Frame No. -60 in Fig. 7. After that, there are some transverse cavities parallel to the line of the nozzle throat at No. 0 to 40. It takes notice to the cavity pointed by the white arrows. The two-dimensional cavity moves toward the downstream direction. The cavity coalesces with the rear cavity around Frame No. 80. In addition, the next cavity coalesces with another cavity (No. 120). It is observed that cavities develop to the new attached cavity. These cavity behaviors are turned over periodically and the periodic shedding of cavitation cloud is caused.

Details in growth process of the cavity

The laser sheet was used on the cavity behavior as shown in the above section, and the observation was carried out in detail. The characteristic result in the case of σ = 1.0 related to sub-cavitation region in cavitation developing process is shown in Fig. 8(a). The result in the case of σ = 0.94 related to the transition cavitation region where the cavity develop into the large scale is shown in Fig. 8(b). It is noticed as the result that the latter condition shows the high impact [8,9]. The vortex cavity behavior is depicted as the image with the sketch as shown in Fig. 8. Characteristic vortex cavity growing on the separated shear layer is clearly observed.

The part of the white cluster indicated by the white arrow in the figure is correspondent to the vortex cavity. The observing region is the orifice inlet near the wall. In spite of the cavity circumferentially existing along the wall, vortex cavities which occur on the separated shear layer are clearly observed in a different from the case of usual lighting. There are some vortex cavities, and they move to the downstream. Pairing (Fig. 8(a): Frame No. 4, No. 16, No. 24, Fig. 8(b): Frame No. 8, No. 20, No. 24) and coalescence (Fig. 8(a): Frame No. 8, No. 20, No. 28, Fig. 8(b): Frame No. 12, No. 24, No. 28) behavior of the cavity are also observed at this time. In the case of Fig. 8(b), the frequency of shedding cavity is about 270 Hz, while it is about 830 Hz in the case of Fig. 8(a). The convection velocity of the cavity shed downstream is 9.0 m/s in Fig. 8(a) and it is about 9.4 m/s in the case of Fig. 8(b). The speed is almost similar to each other.

In the case of high cavitation number shown in Fig. 8(a) (the cavitation is in relatively underdeveloped condition), some vortex cavities coalesce with each other in the process from the occurrence to the shedding and then are shed downstream. In the case of low cavitation number where the cavitation develops to the relative large scale as shown in Fig. 8(b), some vortex cavities coalesce with each other on the region of shear layer. They coalesce into the shedding cavity when they shed downstream. After that, one of them grows to the attached type cavity. Since the more vortex cavities coalesce the more cavities grow greatly, the time is taken longer until the cavity sheds. Therefore, there is a difference in the cavity shedding frequency even though the convection velocity of the cavity is the same.

CONCLUSION

The unsteady behavior has been observed in a circular cylindrical orifice. The main results are described as follows.

(1) The cavity can be clearly observed in the cross section of the orifice using a laser sheet.

(2)The unsteady cavity behavior exists in an axisymmetrical internal flow field like a circular cylindrical orifice as well as the flow field around a convergent-divergent nozzle.

(3) The cavitating flow with separated shear layer shows an unsteady periodic shedding behavior and re-entrant motion.

(4) Small vortex cavities on the separated shear layer greatly grow through the pairing and coalescence, and as a result they are shed downstream. The behavior depends on the growth condition of cavitation.

ACKNOWLEDGMENTS

The authors would like to thank Mr. Hirokazu Nakamura who was a graduate student of Kanazawa Institute of technology for his considerable assistance. And the authors also acknowledge the help received from Mr. Loo Ching Nong (Lecturer of Singapore Polytechnic).

REFERENCES

[1]Knapp, R. T., 1955, "Recent Investigations of the Mechanics of Cavitation and Cavitation Damage," Trans. ASME, Vol. 77,

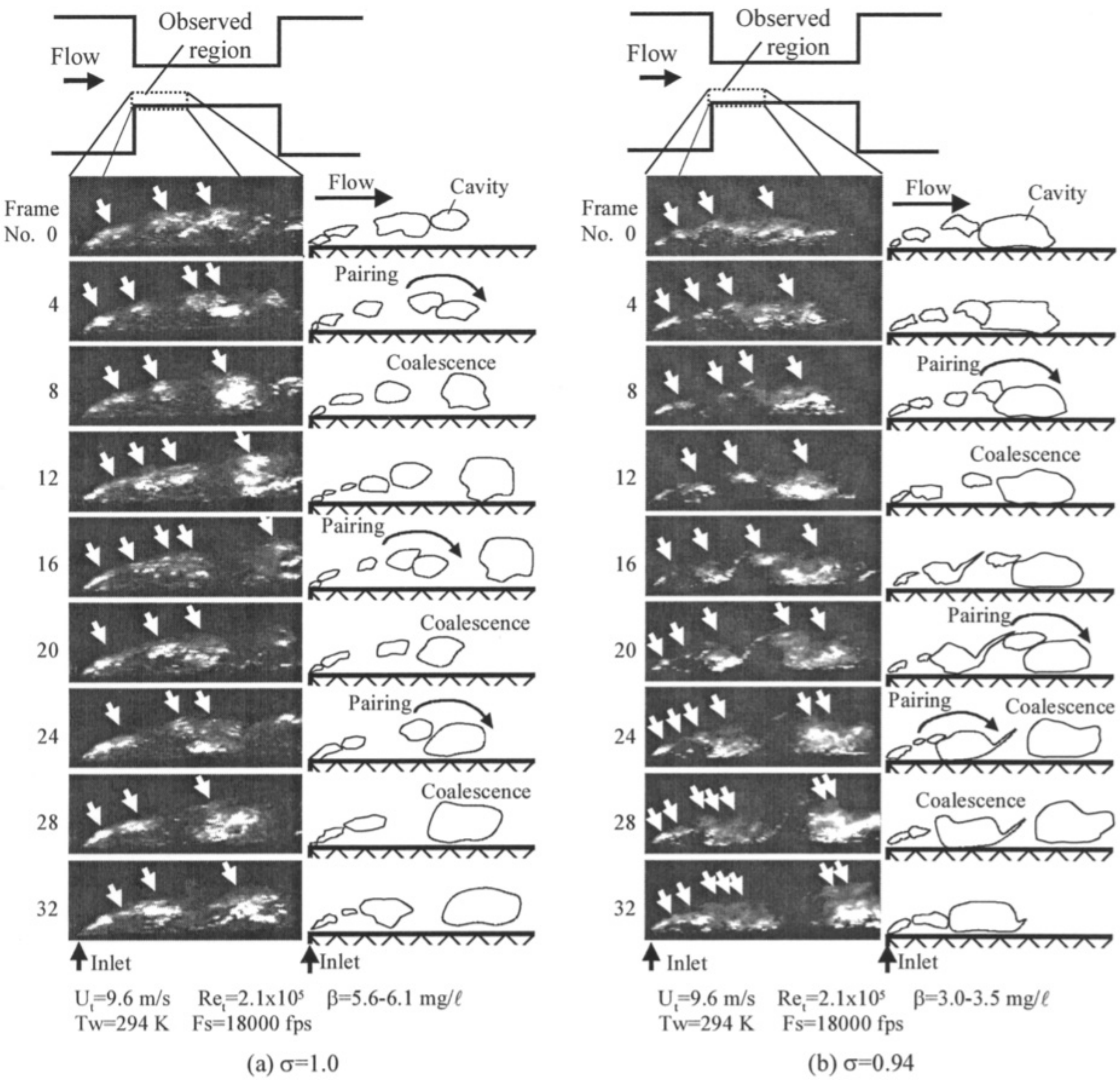


Fig.8 Observation of cavity coalescence using laser sheet method

pp. 1045-1054.
[2] Ivany, R. D., et al., 1966, "Cavitation Bubble Collapse Observation in a Venturi," ASME, J. Basic Eng., pp. 649-657.
[3]Ceccio, S. L., and Brennen, C. E., 1991, "Observation of the Dynamics and Acoustics of Travelling Bubble Cavitation," J. Fluid Mech., vol.233, pp. 633-660.
[4]Sato, K., and Ogawa, N., 1995, "Collapsing Behavior of Vortex Cavitation Bubbles in the Wake of Circular Cylinder," Proc. Cavitation and gas-liquid flow in fluid machinery devices, ASME, FED-Vol.226, pp. 119-125.
[5]Sato, K., and Kondo, S., 1996, "Collapsing Behavior of Vortex Cavitation Bubble near Solid Wall: Spanwise-view Study," Proc. Cavitation and multiphase flow-1996, ASME, FED-Vol.236, pp. 485-490.
[6]Ohba, K., et al., 1995, "High-Speed Observations on Highly Erosive Vortex Cavitation Using Image Processing," Journal of Flow Visualization and Image Processing, Vol.2, pp. 161-172.
[7]Laberteaux, K. R., et al., 1998, "High Speed Digital Imaging of Cavitating Vortices," Experiments in Fluids, 24, pp. 489-498.
[8]Sato, K., et al., 2000, "Impulsive Behavior of Cavitation bubbles in a Circular-Cylindrical Orifice Flow," Cavitation and multiphase flow forum, ASME, FED-251, 11023, pp. 1-8.
[9]Sato, K., and Saito, Y., 2002, "Unstable Cavitation Behavior in a Circular-Cylindrical Orifice Flow," JSME International Journal, Ser.B, Vol.45, No.3, pp. 638-645.
[10]Sato, K., et al., 2001, "Observation of Unsteady Separated - Type Cavitation in Convergent - Divergent Channel," the Third International Symposium on Measurement Techniques for Multiphase Flow, Fukui, pp. 203-210.
[11]Kiya, M., and Sasaki, K., 1983, "Structure of a Turbulent Separation Bubble," J. Fluid Mech., vol.137, pp.83-113.