Proceedings of the 7th International Symposium on Cavitation
CAV2009
August 17-22, 2009, Ann Arbor, Michigan, USA

CAV2009 – Paper No. 64

Evaluation of Incipient Cavitation Erosion for Pipe Wall at Downstream of an Orifice

Yukinori Nagaya
Institute of Nuclear Safety System, Inc
64 Sata, Mihama-cho, Mikata-gun, Fukui, 919-1205 Japan
E-mail: nagaya.yukinori@inss.co.jp

Michio Murase
Institute of Nuclear Safety System, Inc
64 Sata, Mihama-cho, Mikata-gun, Fukui, 919-1205 Japan

Shigeo Mizuyama
The Kansai Electric Power co.inc
1-1 aza Yoshimi 1 Oshima, Oi-cho, Oi-gun, Fukui, 919-2101 Japan

Syuji Hattori
Department of Mechanical Engineering,
University of Fukui
3-9-1Bunkyo, Fukui-shi, Fukui, 910-8507 Japan

ABSTRACT

Cavitation induced vibration and the consequent erosion of pipes are the potential damaging factors in the piping systems. In order to prevent such trouble, it is preferable to develop a detection method for cavitation occurrence. Especially, in power plants, it is necessary to detect cavitation from the outside of the piping during operation. In this paper, in order to evaluate incipience of cavitation erosion, we carried out cavitation erosion experiments using aluminium specimens and we measured impulsive force induced by cavitation bubbles collapse using impact force detectors. In the cavitation erosion experiments, the incipient cavitation numbers, where cavitation erosion pits occured, were 0.8 at 50mm and 75mm downstream from the orifice and 0.7 at 100mm downstream. At those cavitation numbers, the states of cavitation was in a developed state or nearly so. In the measurements of impulsive force, the cavitation number, where impulsive force began to increase, was almost with the same as cavitation numbers at the occurrence of erosion pits.

INTRODUCTION

A local rise in flow velocity in a valve or orifice where the inner pipe diameter decreases causes the fluid pressure to drop, and when the pressure falls below the saturated vapor pressure, cavitation bubbles are generated. With the decrease of flow velocity in the downstream expanded channel section, fluid pressure rises causing the air bubbles to collapse and triggering generation of an impact pressure. This impact pressure brings about the erosion and vibration which are potentially responsible for damage to plant piping systems [1][2]. In 2002, during a valve opening adjustment operation required due to a plant outage, cavitation-triggered vibration occurred in the seal water injection line of a pressurized water reactor (PWR), leading to fatigue cracks in the pipe's welded area. This was the case of trouble in the plant's transient operation stage. In recent years, state monitoring and maintenance have attracted attention in the nuclear power plants, and it is preferable to detect cavitation and cavitation erosion from the outside of the piping during operation. For the power plants which have been operated for a long time, the cavitation erosion increases gradually even if the erosion rate is low. Therefore, it is necessary to detect the locations in pipes where cavitation is occurring, and to evaluate whether cavitation erosion has taken place or not.

Some of authers have investigated detection of cavitation using accelerometers mounted on the outer surface of a piping at upstream and downstream from an orifice, and found that comparison of RMS (root mean square) values at the upstream and downstream positions could possibily be used to detect cavitation in the piping system of an operating plant [3]. However, it is difficult to detect incipient cavitation by this method, and the effectiveness of the method needs confirmation. On the other hand, regarding evaluation of cavitation erosion, the reserch group of the authers has compared the results of erosion tests with copper specimens and RMS values of acceleration on the outer surface at the same locations [4]. Hattori et al.[5] have reported that there was good correlation between integrated values of impulsive force energy obtained using an impact force detector and amounts of cavitation erosion. However, evaluation of incipient cavitation erosion was not reported. In addition, the impact force detector must be attached to the inner surface of the pipe, therefore, it is difficult to measure impulsive force on the inner surface of piping systems in the operated power plants .

In this study, in order to evaluate incipience of cavitation erosion, we carried out cavitation erosion experiments with alminium specimens and impact force detectors.

EXPERIMENTAL SET UP

Experimental loop Figure 1 shows the closed loop for the experiments. It consists of a reservoir, a piping system, a measurement section and a pump. The reservoir is a pressure vessel with a volume of 1.28 m^3 that can be used for tests with a maximum safety valve venting pressure of 3.2 MPa. The reservoir is equipped with an internal heater to heat up the water to desired temperature with an accuracy of ±1°C (150°C maximum). The flow rates are measured with an electromagnetic flow meter inserted upstream from the measurement section. Pressures are measured with pressure gauges installed both the upstream and downstream. Temperatures of the sample fluid are measured with a thermometer mounted in the reservoir. The fluid in loop is pressurized and the fluid pressure is controlled using nitrogen gas from a tank attached to the reservoir. The flow velocity is controlled using the pump speed, which is regulated with an inverter. Service water is employed as the sample fluid. Since the dissolved gas in the sample fluid is considered to influence bubble generation and impulsive forces during bubble collapse, the concentration of dissolved oxygen is measured before and after the experiment to ensure that there is no significant change in the concentration. The range of dissolved oxygen content is about 3-6g/m^3.

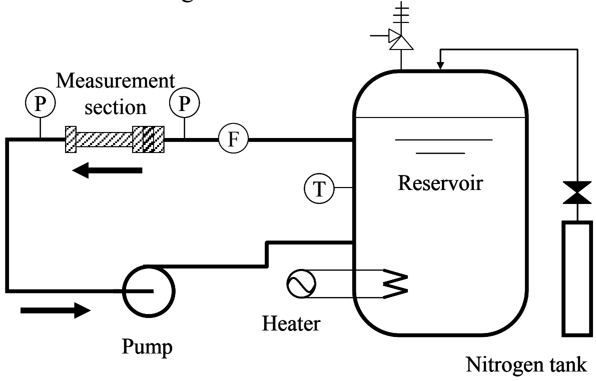


Figure 1: Experimental loop

Measurement section Figure 2 shows the measurement section. Its ends are made of stainless steel with an upstream-end flange forming the orifice. The inside piping diameter *D* is 49.5 mm and the orifice throat is 0.5*D*. The piping section is made of acrylic resin so that the fluid state can be observed visually, its wall is provided with through holes (diameter 5 mm). In erosion experiments, aluminium specimens are inserted into the through holes at 50, 75, and 100 mm downstream from the orifice. In measurements of impulsive force, impact force detectors are inserted into the through holes at the same positions as used for the erosion experimants.

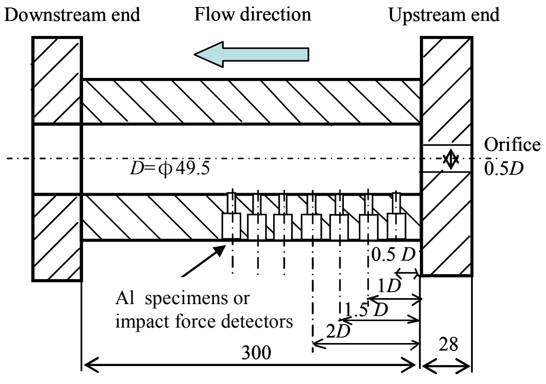


Figure 2: Piping section (Unit: mm)

Figure 3 shows the structure of a specimen. The erosion surface diameter at the specimen tip (exposed plane) is 5 mm. Aluminium is softer than the carbon steel, stainless steel, and other steels which are used for pipes in the power plants, so it is easy to make erosion pits on the spesimens. Therefore, it is suited to evalutating the limits of erosion occurrence by weak cavitation as in incipient cavitaion.

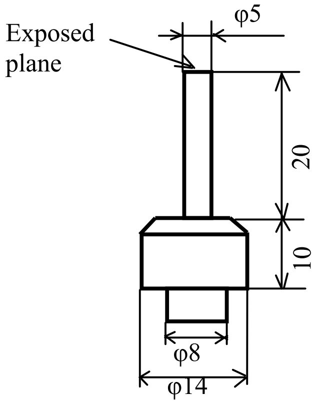


Figure 3: Al specimens (Unit: mm)

Figure 4 shows the structure of the impact force detector. The impact force detector was developed by Prof. Hattori's laboratory at the University of Fukui. The built-in pressure sensor consists of a piezoelectric element, a titanium detection rod and a copper reflection rod. The piezoelectric element is sandwiched between the detection rod and the reflection rod.

System for measuring impulsive force Figure 5 shows the system for measuring the impulsive force which causes collapse of cavitation bubbles. In this system, electric signals generated by the impact force detector are transmitted to a pre-processing circuit. Then frequencies below 19.5kHz are removed by the high band pass filter. This system measures the peak forces which are applied to the exposed plane of the detector at the frequency of 600,000 times/ min.

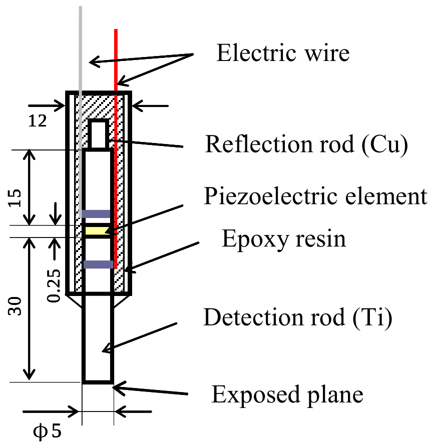


Figure 4: Impact force detector (Unit:mm)

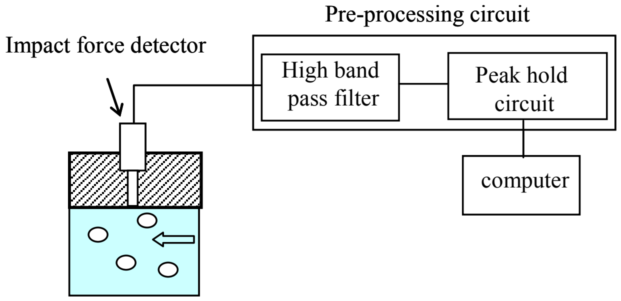


Figure 5: Measurement system

Cavitation number The cavitation number is set as an experimental condition by changing the pressure in the reservoir. In this study, we define the cavitation number as:

$$\sigma = (P - P_v)/(0.5\rho V_o^2),$$

where P represents the downstream pressure of the orifice, P_V denotes the saturated vapor pressure at the experimental water temperature, ρ is the density of water at the test water temperature, and V_o is the average velocity in the orifice.

Experimental conditions In the experiments, the average velocity is kept constant at V_o = 15.0-15.4 m/s and the water temperature is about 20 ℃. To change cavitation number, pressure of the reservoir is controlled by using nitrogen gas and its tank vent valve, while watching a pressure gauge positioned downstream from the measurement section.

RESULTS AND DISCUSION

Erosion experiments Tullis [6] carried out erosion tests using aluminium specimens, and defined the cavitation number, which occured an erosion pit during a minute in a unit area (1inch^2), as the incipience of erosion. We also use this definition of incipience of erosion. In erosion experiments, specimens were exposed to the fluid for 30 min at each state of cavitation. Figure 6 shows enlarge photos of aluminium specimens positioned 50mm downstream from the orifice affter the erosion experiments. We judged whether there were erosion pits or not by taking well-light photos of specimens, and then observing the round hollows where was no reflection on the exposed plane. The erosion pits are circled in figures 6 (a) σ =0.7 and (b) σ=0.8. But in figures 6 (c) σ=0.9 and (d) σ=1.0, no erosion pits are observed in the plane exposed to the fluid.

Table 1 summerizes the results of the erosion experiments. At 50 mm and 75 mm downstream from the orifice, there were erosion pits below σ =0.8, but there are no erosion pits at 100 mm downstream. At 100 mm downstream from the orifice, erosion pits are observed only at σ = 0.7. The locations of aluminium specimens which had erosion pits on the surface differ with the cavitation number.

Figure 7 shows photos of the acrylic section taken during the erosion experiments. From these photos, we see that the numbers of cavitation bubbles increased with decreasing cavitation number. For σ=0.7 and 0.8 at 50 mm downstream from the orifice, there are many bubbles near the piping walls. On the other hand, for σ=0.9 and 1.0, there are comparatively fewer cavitation bubbles than for σ=0.7 and 0.8, and there are dense bubble areas around the center of the piping section at 75 mm downstream from the orifice. For σ=0.8, there are dense bubbles areas near the walls, but there are no erosion pits on the specimens mounted at the same locations.

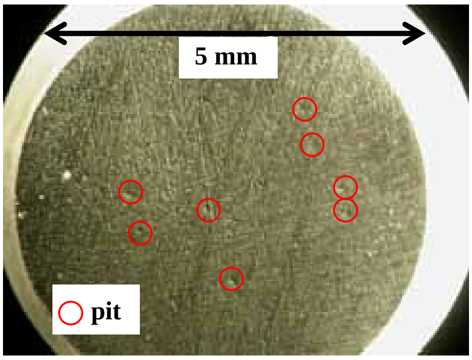
It seems that the difference between locations, as to whether there are erosion pits or not, is caused by the different distribution of collapsed cavitation bubbles near the piping walls as the cavitation state changes, but it is necessary to examine this point further.

Table 1: Cavitation number and location of cavitation erosion pits occurrence

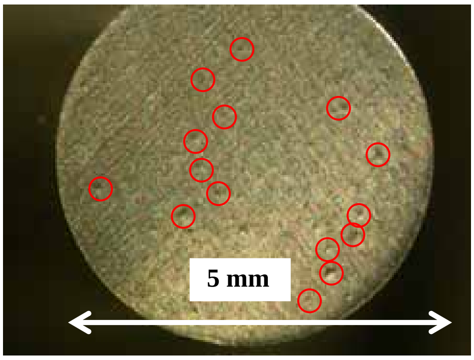
Cavitation number σ	Distance of downstream from orifice (mm)		
	50	75	100
0.7	○	○	○
0.75	○	○	×
0.8	○	○	×
0.9	×	×	×
1.0	×	×	×
1.1	×	×	×
1.2	×	×	×

○: Pits ×: No pits

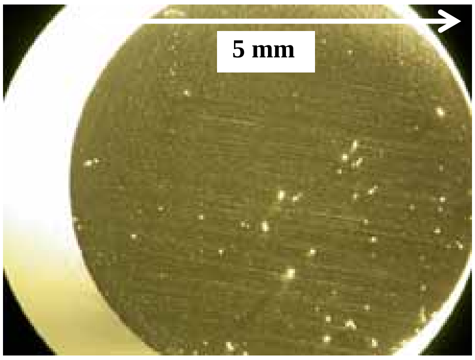
Measurements of impulsive force The impulsive forces were mesured for 1 min continuously three times at each state of cavitation. In addition, these measurements were repeated three times. Figure 8 shows examples of measurements made using impact force detectors. In figure 8 (a), the distributions of the frequencies of impulsive force are similar for the three measurement times, and they are concentrated between 0N and 1N. The impulsive force at the muximum frecqency is about 0.1N. Muximum impulsive forces vary from about 4.7N to 5.8N. This tendency is qualitatively similar to results of



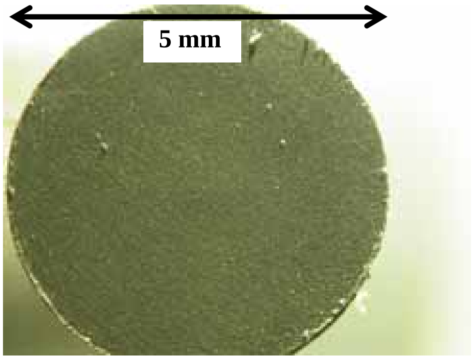
(a) σ=0.7



(b) σ=0.8

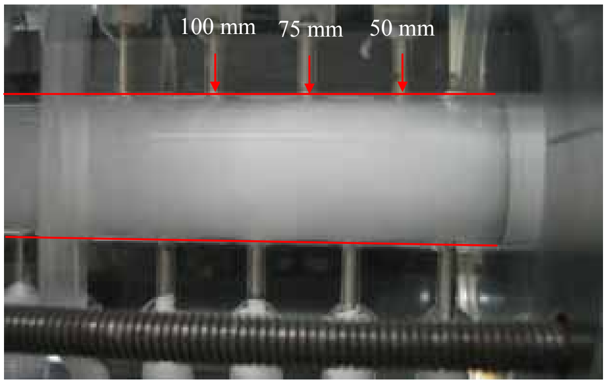


(c) σ=0.9

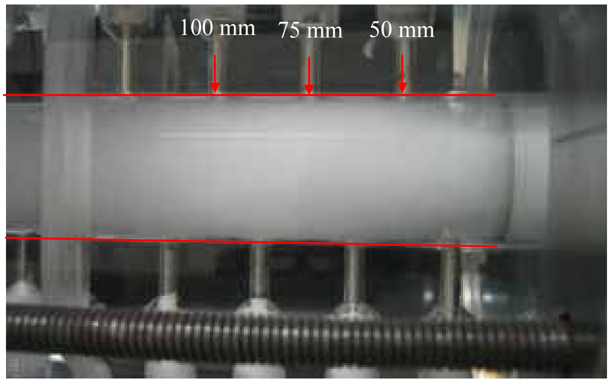


(d) σ=1.0

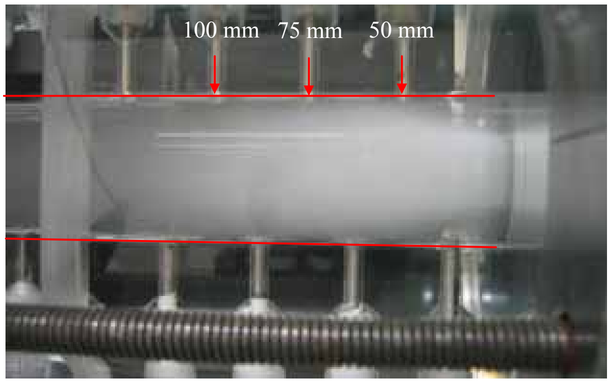
Figure 6: Erosion pits on aluminium specimens positioned 50mm downstream from the orifice



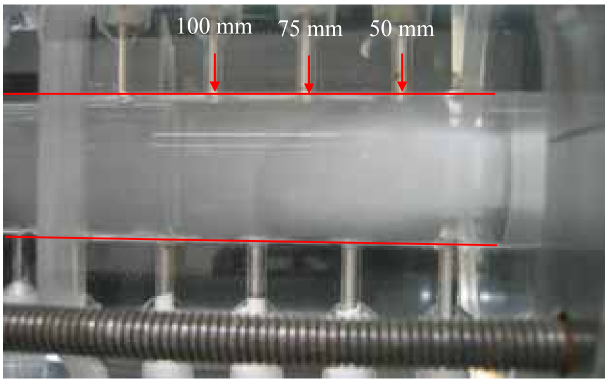
(a) σ=0.7



(b) σ=0.8



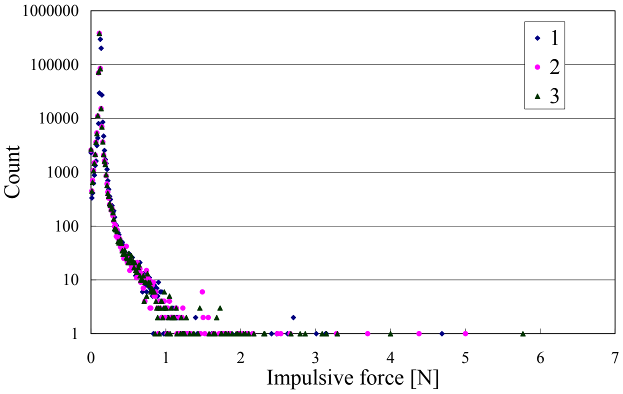
(c) σ=0.9



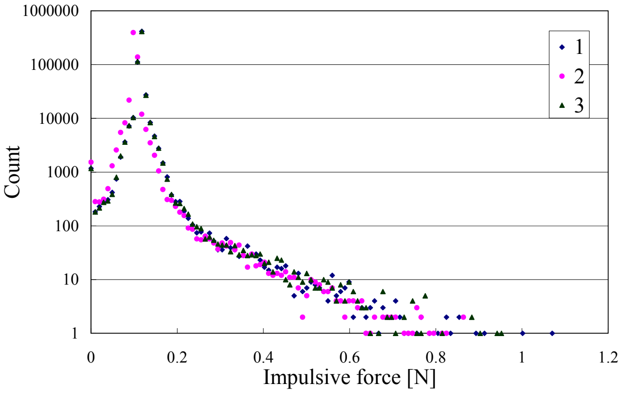
(d) σ=1.0

Figure 7: Visualization of cavitation state downstream from the orifice

measurements at other locations or cavitation numbers, such as figure 8 (b).



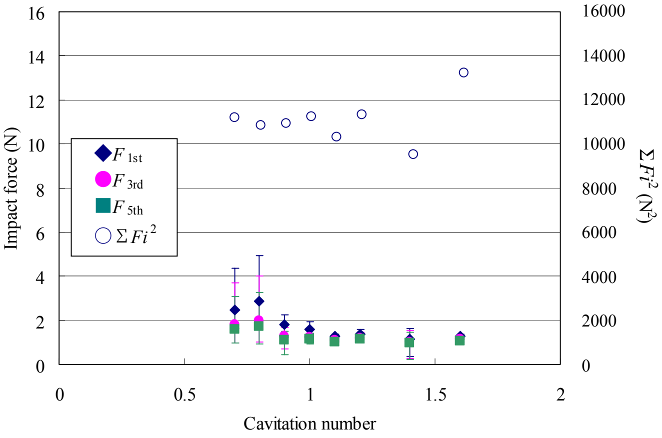
(a) σ=0.7, at 50 mm downstream from the orifice



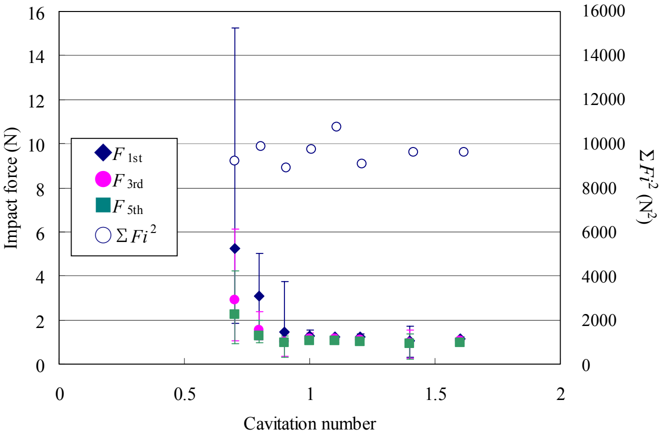
(b) σ=1.6, at 100 mm downstream from the orifice

Figure 8: Examples of measurements using impact force detectors

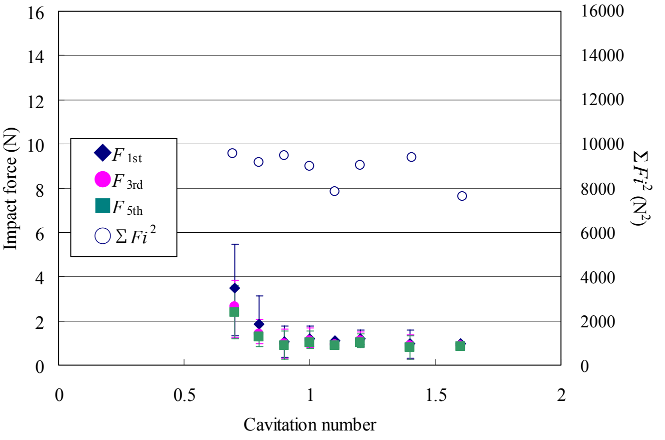
Figure 9 shows the relation between cavitation number and impulsive force at 50, 75, 100 mm downstream from the orifice. The circles are the sammations of squares of impact load which is equivalent to the impact energy (ΣFi^2 = frequency × impulsive force^2) . Hattori et al. [5] reported that a linear relationship was obtained between this parameter and the maximum mean depth erosion rate (MDERmax). The Painted symbols are the maximum force, the third largest force and the fifth largest force during measurements, which are expressed by F_{1st}, F_{3rd}, and F_{5th}, respectivity. ΣFi^2 is almost changeless for different cavitation numbers. Moreover, there is not so much difference between locations for the ΣFi^2. This is attributed to that the distribution of the frequencies of impulsive force being concentrated at small values of impulsive force. By comparison to the experimental results of Hattori et al. [5], these results are three or four orders of magnitude smaller. F_{1st}, F_{3rd} and F_{5th} increase rapidly in the region of $\sigma \leq 0.8$ at 50 mm downstream from the orifice. This tendency is similar to that at the other locations, at 75 and 100 mm downstream from the orifice. However, the result at 100 mm downstream from the orifice is low overall compared with other locations. These results agree with observations of erosion pits listed in Table 1.



(a) At 50 mm downstream from the orifice



(b) At 75 mm downstream from the orifice



(c) At 100 mm downstream from the orifice

Figure 9: Relation between cavitation number and impulsive force

CONCLUSIONS

In order to evaluate incipience of cavitation erosion, we carried out cavitation erosion experiments and measurements of impulsive force and obtained the following conclusions.

(1) In the cavitation erosion experiments, the incipient cavitation numbers, where cavitation erosion pits occurred, were 0.8 at 50mm and 75mm downstream from the orifice and 0.7 at 100mm. At those cavitation numbers, the state of cavitation was a developed state or nearly so.

(2) In the measurements of impulsive force, the cavitation number at which impulsive force began to increase was almost the same as the cavitation numbers at the occurrence of erosion pits.

ACKNOWLEDGMENT

The authors wish to express their sincere gratitude for support from members of Prof. Hattori's laboratory at University of Fukui, who helped to measure impulsive force and to judge erosion pits.

NOMENCLATURE

σ: cavitation number
p: the downstream pressure of the orifice
p_v: the saturated vapor pressure at the test water temperature
ρ: the density of water at the test water temperature
V_o : the average velocity in the orifice.

REFERENCES

[1] Ozol, J., Kim, J. H., Healzer, J. 1994, "Cavitaion Experience with Control Valves in Nuclear Power Plants," *ASME-FED*, 190, 291-297.

[2] Moussou, P., Cambier, S. Lachene, D. et al., 2001, "Vibration Investigation of a French PWR Power Plant Piping System Caused by Cavitating Butterfly Valves," *ASME PVP*, 420(2), 99-109.

[3] Mizuyama, S., Murase, M., Fujii, Y. and Yagi, Y. 2008, "Detection of Cavitation with Accelerometer Mounted on Outer Surface of Piping," *Transactions of the Japan Society of Mechanical Engineers*, Series C, 74(743), 1681-1687. (in Japanese)

[4] Yagi, Y., Murase, M., Sato, K, and Saito, Y. 2003. "Preliminary Study of Detecting the Occurrence of Cavitation and Evaluating Its Influence by a Pipe-Mounted Accelerometer," *Proccedings of the 5th International Symposium on Cavitation (Cav2003)*, Osaka, Japan.

[5] Hattori, S., Fukuyama, T., Goto, Y. et al. 2005, "Influence of Flow Velocity and Cavitation Number on Erosion Rate by Cavitating Liquid Jet Method Specified in ASTM Standard," *Transactions of the Japan Society of Mechanical Engineers*,, Series A, 71(709), 1276-1282. (in Japanese)

[6] Tullis, J. P. 1993, "Cavitation Guide for Control Valves," *NRC NUREG/CR-6031*.