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INFLUENCE OF GALVANIC MACRO-CELL CORROSION ON THE CAVITATION EROSION DURABILITY ASSESSMENT OF METALLIC MATERIALS

Akihiro Sakamoto, Hiroshi Funaki and Masanobu Matsumura

Department of Chemical Engineering, Hiroshima University Higashi-Hiroshima,
JAPAN

Abstract: *Cavitation erosion tests were carried out on five metallic materials which are the standard materials of the International Cavitation Erosion Test Program which is coordinated by Dr J. Steller, Institute of Fluid-Flow Machinery, the Polish Academy of Science, Gdańsk, Poland. Three kinds of testing apparatus were used: a vibratory unit, a vibratory unit with a stationary specimen, and a water tunnel. In the two vibratory tests, the ranking order of the materials according to their durability to Cavitation attack showed a complete coincidence with each other. However, the ranking based on the water tunnel test was different from those of the vibratory units. This was because the damage rate of some materials was suddenly accelerated in the middle of water tunnel test.*

It was revealed that the remote cause of the sudden increase in erosion rate is the activation of damaged surface in atomic level, which promotes corrosion only when a macro-cell of corrosion is formed between the cavitation damaged area (anode) and the undamaged area (cathode).

Thus it was pointed out that some undamaged area is some times necessary on laboratory test specimens when an accurate simulation of the Cavitation damage in the field is demanded.

1. INTRODUCTION

An International Cavitation Erosion Test Program started in 1988 under the coordination of Dr. J. Steller, Institute of Fluid-Flow Machinery, The Polish Academy of Science, Gdańsk, Poland. The objectives of this program were (a) to compare the cavitation resistance of selected materials based on test results under different laboratory conditions throughout the world, (b) to determine the dependence of the assessment on the test conditions and (c) to investigate further the basis for standardization of such materials testing.

At the Hiroshima University, one of the participants in the program, Cavitation erosion tests were conducted on the five selected metallic materials, and the test results obtained were sent to Gdańsk, where they are currently under analysis together with the data from the other participating laboratories worldwide. The results of mass loss measurement below are the same as those that have been sent to Gdańsk, but the analysis here is independent.

Various testing methods have been developed thus far to assess the erosion resistance of materials and to examine the mechanism of cavitation erosion. A problem accordingly arose whether the orders of merit of materials tested in different types of experimental setups would coincide, and also agree with their performance in field fluid machines [1]. No synthetic nor quantitative investigation has yet been carried into this problem using various standard materials such as above mentioned Gdańsk program, but field engineers seem to have an understanding that results of materials tested in a laboratory coincide well with their performance in the field [2].

2. TESTING APPARATUS AND MATERIALS

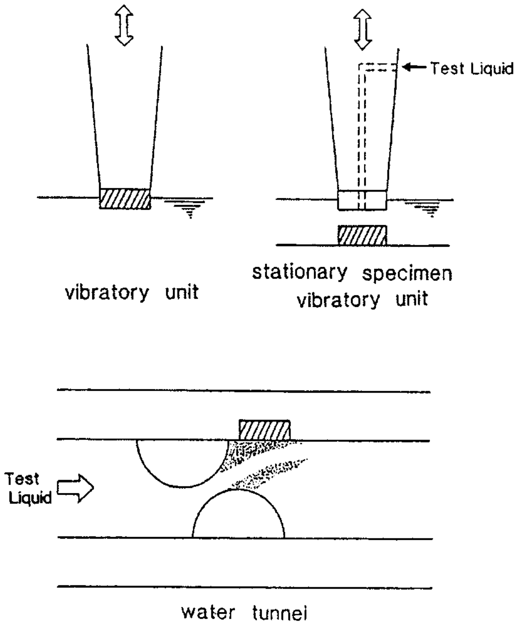

Fig.1 Testing apparatus (a) vibratory unit, (b) stationary specimen vibratory unit, (c) water tunnel.

The three different types of experimental devices used in the present study were as follows: (a) a vibratory unit [3] in which a disc-shaped specimen of 16 mm diameter was vibrated vertically in a test liquid at a high frequency of 20 kHz and with a double amplitude of 25 ^m; (b) a vibratory unit with a stationary specimen [4] which was located 0.4 mm from a vibrating nozzle of stainless steel; and (c) a water tunnel developed by Prof. Louis with a rectangular channel (40 X 30 mm) test section with two semi-circular columns by which the fluid flow was accelerated to generated cavitation [5,6] (Fig. l). The surface of the stationary specimen was damaged by the collapse of cavities which were generated by the vibrating nozzle. A test liquid was injected into the gap between the nozzle and the specimen through a bore in the horn. The temperature of horn was accordingly kept constant at that of the test liquid what avoided the heat expansion of horn, and therefore the distance between the nozzle and the specimen was also kept constant leading to an excellent reproducibility of experimental results. The central area of specimen was not damaged as cavitation was not generated at the bore mouth. The mechanism of cavitation generation in the water tunnel resembles that of pumps and valves in the field.

Table 1 Compositions and mechanical properties of materials

		composition	Mechanical parameters		
		(%)	σ_s(MPa)	σ_y(kPa)	H_V
Aluminium	(A)	2.7 Mg	208	169	66
Brass	(C)	63.7Cu-36.3Zn	335	110	115
Armco iron	(F)	0.035C-0.10Mn	380	335	120
Carbon Steel	(S)	0.43C-0.63Hn-0.26Si	419	221	210
Stainless steel	(SUS)	0.40C-17.6Cr-9.40Ni	605	225	420

The test specimen shape was the same for all the three devices. The test liquid was deionized water (conductivity of 0.2 μS cm^{-1}) for the vibratory units and tap water for the water tunnel. Five metals were chosen out of the six standard materials of the above mentioned International Cavitation Erosion Test Program. The mechanical properties and the approximate chemical analysis of the materials are presented in Table 1.

3. RESULTS

Test specimens were exposed to cavitation for a certain duration, and the change in the weight of specimen was determined using an electric balance of accuracy 0.01 mg. The mass loss curves as a function of test duration for all materials examined in each device are resented in Fig. 2. It should be noted that the scale f ordinates (mass loss) of Fig. 2 is common but that of abscissa (exposure duration) is different. In the stationary specimen unit, it took nearly 2.5 times as long, and in the water tunnel 25 times as long to obtain the same mass loss as was gained in the vibratory unit. This is, of course, to be attributed to the fact that each experimental device had its own intensity of cavitation. In spite of this large cavitation intensity variation, the materials tested were ranged in the same order of merit based on the amount of mass loss in the two vibratory cavitation units. In the water tunnel test, however, the order was different and stainless steel (SUS) as well as carbon steel (S) exhibited unusually large amounts of mass loss (Fig.2(c)). Based on these experimental results, it may be concluded that the cavitation erosion durability assessment of metallic materials depends on the testing device used. It may be further noted that the test results obtained in accelerated erosion tests in laboratories such the vibratory cavitation devices do not agree with the performance of the same materials in actual field fluid machines on regarding the water tunnel as a fluid machine.

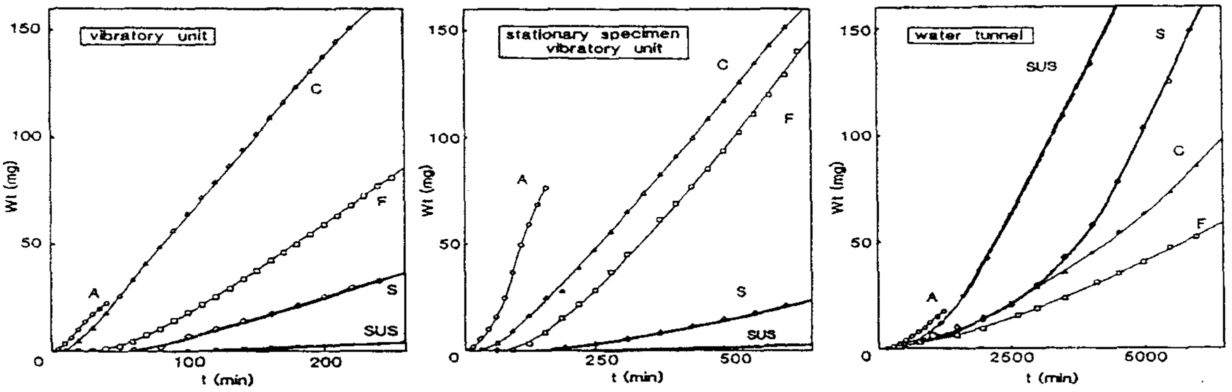

Fig.2 Mass loss vs. exposure duration plots for (a) vibratory unit, (b) stationary specimen unit and (c) water tunnel

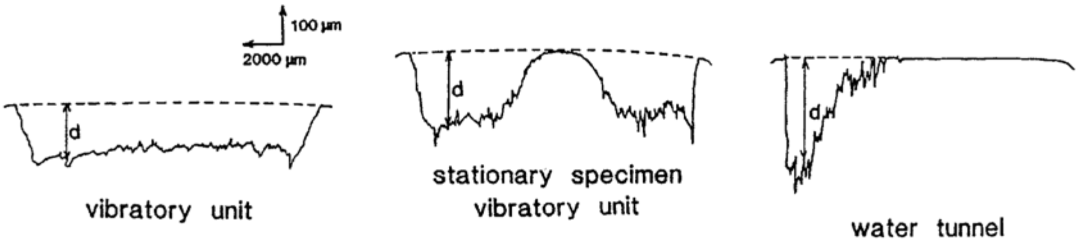

Fig.3 Profiles of damaged surface of Armco iron specimen and definition of damage depth *d*: (a) vibratory unit; (b) stationary specimen vibratory unit; (c) water tunnel

Damage depth *d* (µm) was employed as an alternate of mass loss for the index of cavitation damage. It was determined at a fixed point on a test surface as the distance between the profile of original surface and that of damaged surface (Fig.3), and was measured with a surface roughness meter. Experimental results obtained on the five test materials examined in the three devices are presented in Fig. 4. The most important and favorable feature of these figures was the linear relationship between the depth and testing time even though the straight

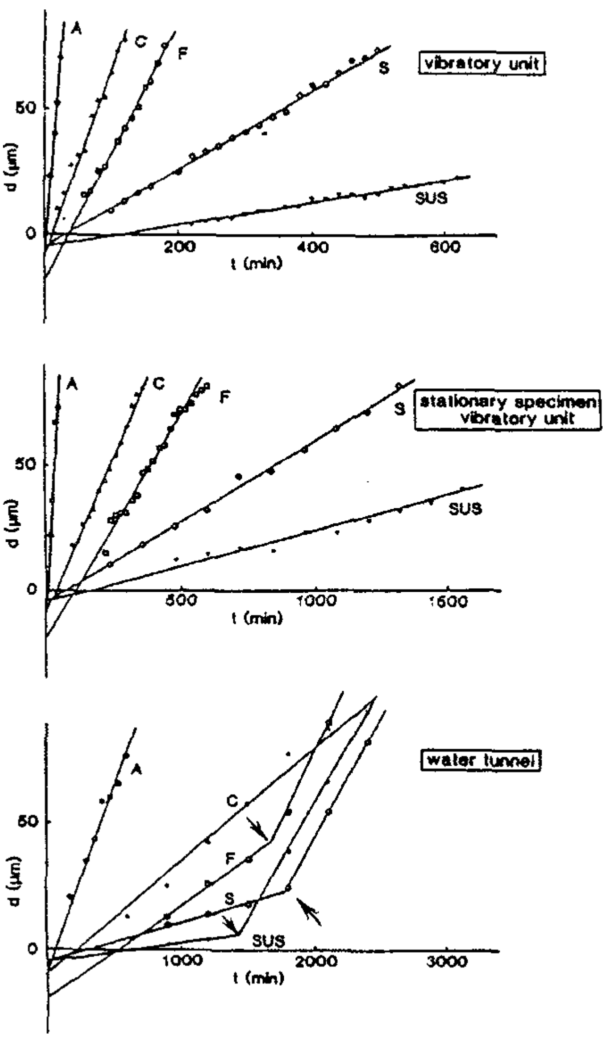

Fig.4 Damage depth vs. exposure duration plots for (a) vibratory unit, (b) stationary specimen vibratory unit and (c) water tunnel

lines did not go through the origin because of the incubation periods. In the water tunnel, the *d* vs. *t* plots of Armco iron (F), stainless steel (SUS) and carbon steel (S) were bent upwards. This may be possibly responsible for the inconsistent assessments. The second feature is that in each figure the materials are ranked in a unified order i.e. A>C>F>S>SUS, based on the slope of the *d* vs. *t* line before the break points which are indicated by the arrows in Fig.4(c). The third is that the extrapolation of *d* vs. / plots back to the beginning of the test crossed the ordinate at a point of certain negative depth, and that this point depended on the material but was independent of test device. The plots were extrapolated by a solid line in order to emphasis the importance of the characteristic point. The meaning of this point was already discussed elsewhere [7].

According to the behavior before the break point, the assessment of material resistance against cavitation erosion is the same regardless of test device and also the test results of materials in laboratories agree well with their performance in the field.

4. DISCUSSION

The experimental result that the mass loss vs. time plot gives different orders of merit for the materials examined depending on the test device used appears to be closely related to the occurrence of break point in the *d* vs. *t* plots of F, S and SUS in Fig.4. This clue was firstly followed up: the surface profiles of Armco iron (F) specimen damaged in the each of three devices are shown in Fig.3. The specimen examined in the water tunnel shows the break point in the *d* vs. *t* plot, and bears the localized damage with relatively large area undamaged. In order to reproduce this state, an Armco iron specimen was tested in the vibratory unit with the stationary specimen off position (Fig.5(b)), which depicts a large undamaged area on the surface and a break point on the *d* vs. *t* at a test duration of 330 min or at the damage depth of 40 µm (Fig.6).

The close relationship between the appearance of the break point and relatively large undamaged area indicates the formation of a macro-cell of galvanic corrosion, consisting of an anode of damage area and a cathode of undamaged area. An auxiliary electrode of the same materials was electrically connected with a test specimen and the galvanic current was measured with a zero shunt ammeter which was set between them as shown in Fig.5(c). At the beginning of cavitation erosion test, the current of ca. 10 μm flowed from the specimen to the electrode, but at the time when the break point appeared on the *d* vs. *t* plot, it changed the flowing direction, that is from the electrode to the specimen. The amount of current was 3μA. This may be interpreted as follows: in the early stage of cavitation erosion, the cathode reaction of the specimen is more active than that of the auxiliary electrode. On the other hand, these anode reactions assume nearly same activity. Therefore, the galvanic current flows from the. specimen to the electrode. In the advanced. stage, the state of the auxiliary electrode hardly changes, but that of the specimen changes so that the anode reaction is more active due to the change in fracture mechanism, which must result in the change of flow direction.

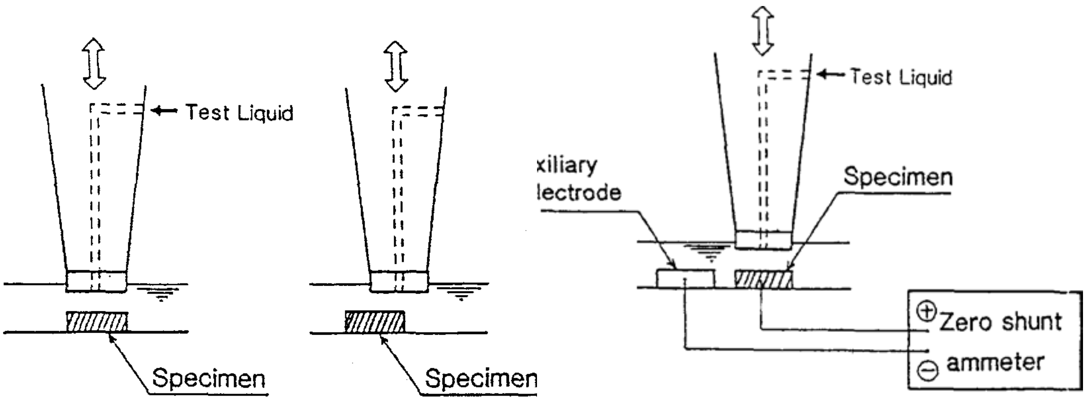

Fig.5 Vibratory cavitation erosion devices. (a) With a stationary specimen in position. (b) With a stationary specimen off position. (c) With a stationary specimen and an auxiliary electrode electrically connected together with a zero shunt ammeter

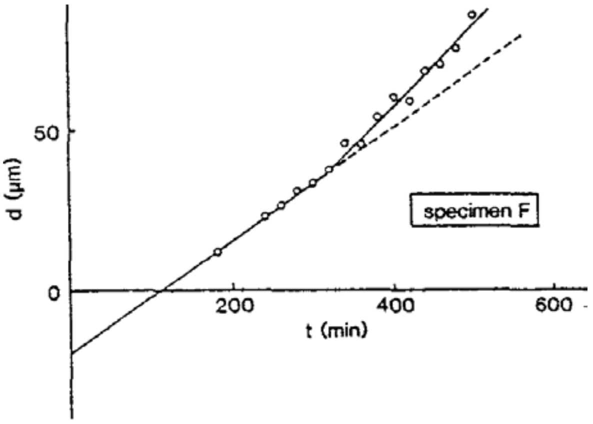

Fig.6 Break point identification in the damage depth vs. exposure duration plot in the vibratory unit with a stationary specimen of Armco iron

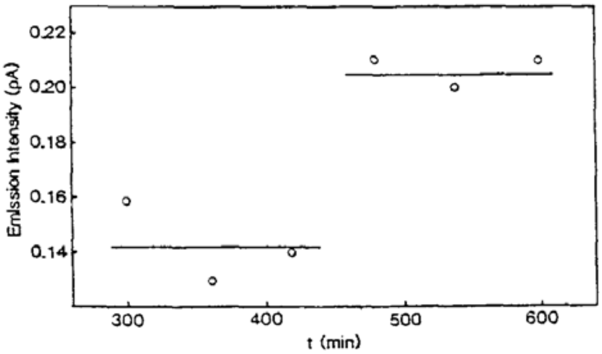

Fig.7 Exo-electron emission intensity as function of time

In order to clarify the reason as to the anode reaction enhancement, the damaged surface and the cross-section were observed with an optical microscope and a scanning electronic microscope. It was observed that the cracks or the appearance of damaged surface before and after the occurrence of break point in the *d* vs. *t* plot showed no significant difference. Further studies were carried out by measuring the exo-electron emission, which is usually radiated from the metal surface newly created by machining, and of which amount is a good index of the activity of the damaged surface at atomic level [8]. The emission intensity increased about 30% just after the appearance of break point (Fig.7).

Lastly, specimen polarization curves were measured which were damaged before and after the break point: an Armco iron specimen was damaged in the vibratory unit for 300 min without an auxiliary electrode, then it was put into the usual measurement cell which was composed of a working electrode of the specimen and the counter electrode of platinum with tap water to measure anodic as well as cathodic polarization curves. The same procedure was repeated for the Armco iron specimen which was damaged for 600 min. Those curves are given in Fig.8. No difference was recognized for the cathodic polarization curves, but the anodic curve exhibits the passivation at 300 min and the active dissolution at 600 min.

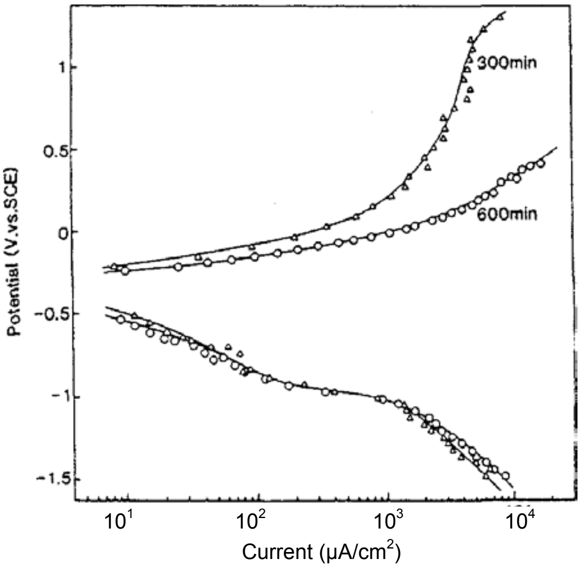

Fig.8 Polarization curves of Armco iron specimen determined before (300 min) and after (600 min) the break point appearance

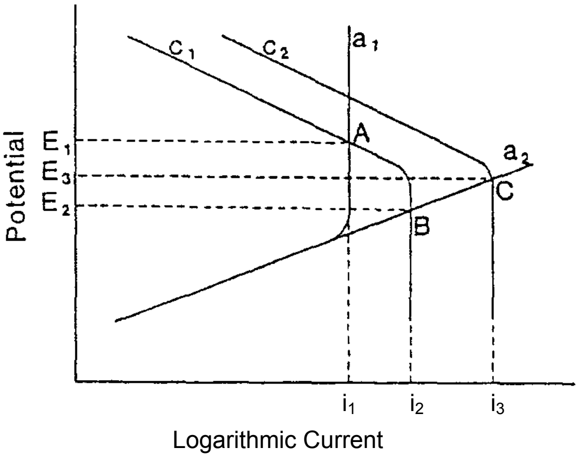

Fig.9. Schematic sketch of internal polarization curves of Armco iron before and after the break point appearance

With experimental results in Figs 6-8 and schematic polarization curves in Fig.9, we can interpret the reason as to why the break point appeared in the *d* vs. *t* plots of Armco iron (F), carbon steel (S) and stainless steel (SUS) of water tunnel tests as follows. The electrochemical state of specimen before the appearance of break point must be at the point A in Fig.9, which is determined by the crossing of the cathodic polarization curve c_1 and anodic one a_1 , the potential being E_1 and the corrosion current ii. In this state, the specimen surface is still covered with an oxide film, which .keeps it in the state of passivation though plastic deformation is brought about to the surface by the repeated attack of cavitation impulsive high pressure. When the cavitation damage of surface proceeds to the extent that the damage mechanism is changed and the surface is activated in atomic level, the anodic polarization curve will change from a_1 to a_2 which shifts the electrochemical state of the specimen from A to B where the potential is E_2 and the current i_2. Certainly i_2 is larger than ii, but it is not so large enough to affect the cavitation erosion rate. This corresponds to *d* vs. *t* plot obtained in the vibratory devices (Fig.4(a) and (b)). In the case of a water tunnel specimen, on the other hand, relatively large area of specimen surface, remains undamaged which acts as' cathode. Even under a limited cathodic current density (the limiting current density for oxygen reduction), the larger the extent of cathode area, the larger the net cathodic current. The cathodic polarization curve for a water tunnel specimen is not c_1 but c_2 because the axis of abscissa is not current density but current. Under the condition of cathodic polarization curve c_2, the shift of anodic polarization curve from a_1 to a_2 puts the electrochemical state of the water tunnel' specimen from A to C, which increases the corrosion current from i_1 to i_3. This big increase in corrosion current accelerates the cavitation erosion rate, which brings about a break in the *d* vs. *t* plot.

Though the corrosion potential of test specimen during cavitation test was not monitored, those of specimens damaged before and after the occurrence at break point are given in Fig.8: more negative after the break point, which clearly supports the preceding interpretation.

The reason as to why no break appeared on the *d* vs. *t* plot for brass (C) and aluminium (A) in the water tunnel test, is as follows: both materials have exhibited poor cavitation erosion resistance and the whole of each specimen surface was completely damaged, resulting in a large anode area and extremely small cathode area just similar to one examined in vibratory units. This was proved by the appearance of a break point on the d vs. t plot for the stationary specimen of brass (C) off position in the vibratory unit. But no break point was appeared for aluminium (A) specimen even under the condition of specimen off position. This was accordingly attributed to the lack of surface activating process at atomic level.

5. CONCLUSIONS

Cavitation erosion tests were conducted on five metallic materials viz., aluminium, brass, Armco iron, carbon steel and stainless steel, by using three different devices, two vibratory units and a water tunnel. The following are major conclusions:

(1) In the early stage of test, materials are exhibited unified order of merit to cavitation erosion irrespective of test device and the order further coincides well with that of their performance in the field. In the advanced stage, however, the orders of merit of materials are not necessarily so depending experimental and field conditions. The cause of such result is the sudden increase in the damage rate occurring during the test depending on the test conditions.

(2) The root cause of the sudden increase in erosion rate must be some change in damage mechanism followed by the activation of the damaged surface, which is further , enhanced by galvanic macro-cell corrosion only in the case that a certain extent of undamaged area on the specimen surface is maintained. It acts as the cathode of the macro-cell.

Those conclusions may be usefully utilized for the forthcoming standardization of cavitation erosion test method in the following respects.

(1) Undamaged area on test specimen surface should be minimized in order to avoid the effect of macro-cell galvanic corrosion.

(2) On the contrary, an enough extent of undamaged area should be maintained in the case that the effect of corrosion on the cavitation erosion is to be examined.

(3) The duration of erosion test has to be cautioned as quite different orders of merit might be obtained in the case that, for example, effect of corrosion inhibitor are examined even if the same material is used and all other test conditions were kept constant,

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Author

Prof. Masanobu Matsumura
Dept of Chem. Eng.
Hiroshima University
1-4-1 Kagamiyama
Higashi-Hiroshima
739-8527 Japan