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DEVELOPMENT OF BALLAST WATER TREATMENT TECHNOLOGY BY MECHANOCHEMICAL CAVITATION

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ABSTRACT

In order to solve environmental problems caused by ballast water, which is a serious problem worldwide, ballast water purification using cavitation was investigated. Previously, only the collapse pressure of cavitation was used for the treatment of planktons. In this study, however, processing by cavitation containing a chemical and the mechanical processing of cavitation were applied. A Venturi nozzle and an ejector nozzle were used to inject sodium hypochlorite. It was found that the ejector nozzle had higher processing performance than the Venturi nozzle, and was effective for high flow rates of ballast water. It was clarified that high plankton extinction ratios could be obtained using mechanochemical cavitation provided by ejector nozzles.

INTRODUCTION

Ballast water is seawater pumped aboard a ship that is lightly loaded, usually while in port, in order to provide increased stability at sea. When such a ship loads cargo, ballast water is discharged. When the cargo is offloaded, ballast water is once again pumped aboard. An estimated 12 billion metric tons of ballast water is transported across the world's oceans in a single year. About 300 million mt of such ballast water leaves Japan annually, while an estimated 17 million mt is discharged in Japanese ports and surrounding seas.

Ballast water transportation and discharge results in significant amounts of marine organism movement and the resulting disturbance and destruction of local ecosystems has become a worldwide problem. While there is currently no ballast water treatment technology that satisfies global standards (D-2 standard), various ballast water treatment techniques have been proposed and are being studied.

Recently, water jet (WJ) technology, which utilizes high-pressure water jets to generate cavitation with high collapse pressure, has been used for treating ballast water [1]. Previously, we studied ballast water purification using cavitation created by jet-induced stream condensation [2]. That study showed that while a result that totally satisfied the international standard could not be obtained, it was possible to achieve an extinction rate of about 95% [2] using a swirl flow type nozzle.

In this study, mechanical and the chemical treatments were performed simultaneously with the goal of achieving a plankton extinction rate of 100%. This new ballast water purification technology using cavitation requires less chemicals than other methods.

Global standard and ballast water treatment technology

When an unladen or partially loaded ship sails from port, it often carries seawater (in the form of ballast water) that has been pumped aboard to improve the ship's stability at sea. This water normally contains marine organisms such as animal and botanical plankton. Later, the same ballast water containing these marine organisms is discharged into the port of loading as cargo is brought aboard the ship. In addition to plankton, various other living marine organisms are often found in ballast water. These can include seaweed, starfish, jellyfish, small fish and even toxic microorganisms. As mentioned above, when invasive marine organisms are transported to, and discharged in, stable local ecosystems by means of ballast water, ecological havoc can result [3].

The global convention that governs the water quality of discharged ballast water was concluded at the "International conference on the management of the ballast water for ships" held in London during February 2004. The standard nomenclature of this International Convention is “International Convention for the control and management of Ships' Ballast Water and Sediments, 2004”. To date, a total of 30 countries have ratified the global convention.

At this international conference, the International Maritime Organization (IMO) established the standard for acceptable densities of marine organisms in discharged ballast water, which became known as the D-2 standard. This standard allows 10 pieces of animal plankton per 1 m^3, 10 pieces of botanical plankton per 1 mL, 250 cfu of bacteria per 100 mL, 100 cfu of Enterococcus per 100 mL, and less than 1 cfu of cholera bacteria in 100 mL of ballast water.

Current ballast water sterilization techniques include filtration, ozone, boiling, oxygen elimination, ultraviolet bombardment, chemical injection, and gas implantation, etc. Merits and demerits exist for all of these technologies when examined in terms of processing performance, costs and ease of implementation.

The treatment of ballast water using ultrasonic cavitation has also been investigated. This mechanical method, which utilizes the collapse pressure of cavitation, is based on a simple processing principle and has been found to provide a high extinction ratio when applied to animal plankton.

Water jet cavitation

Conventional water jet cavitation

Water jet technology is based on the use of high-pressure water jets to create collapse pressure in the cavitation generated in the boundary layer with geostationary water. Extreme high pressures of about 1,000 MPa occur when the cavitation collapses on a material surface. Such high collapse pressure+ is sufficient to cause compressive residual stress to metal surface structures. When this method is used, pressure varies depending on the distance between the nozzle and material surface. The first peak and the second peak occur near the nozzle. The collapse pressure of the second peak is higher than that of the first peak. When the collapse pressure of the second peak is used, cavitation is applied to the plankton suspended in the ballast water.

Mechanochemical cavitation jet

Although it did not satisfy the global standard, an extinction rate of about 90% was achieved in ballast water purified by conventional water jet cavitation. With these results in mind, an experiment was then conducted to determine whether a higher extinction effect could be achieved by combining cavitation with sodium hypochlorite. This water-jet produced cavitation containing chemicals is called mechanochemical cavitation. Figure 1 shows a schematic diagram of plankton treatment using mechanochemical cavitation. In this method, the planktons receive simultaneous mechanical and chemical attacks, which has a synergistic effect on the damage that results.

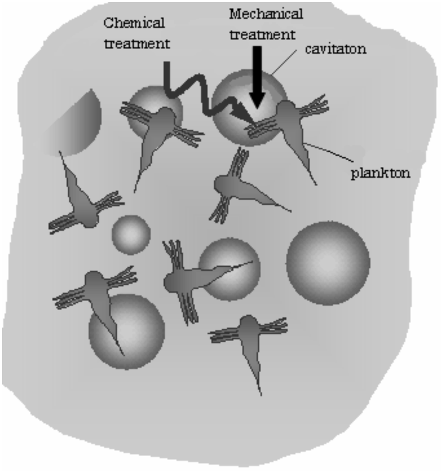

Fig. 1: Plankton treatment using mechanochemical cavitation.

Experimental

Plankton

Larvae produced from hatched tetra brine shrimp eggs, *Artemia salina*, were used as the test plankton. After water was added to a 10 L container and a regulated amount of salt was added, brine shrimp eggs were introduced to the mixture. The mixture ratio used was 10 L water, 200 g salt and 20 g brine shrimp eggs.

Here, the salinity concentration after hatching was 20 PSU. Figure 2 shows an optical microscope photograph taken after the eggs hatched. In order to simulate ballast water before treatment by mechanochemical cavitation, the hatched planktons were inserted into a 500 L tank filled with water with a salinity concentration of 20 PSU.

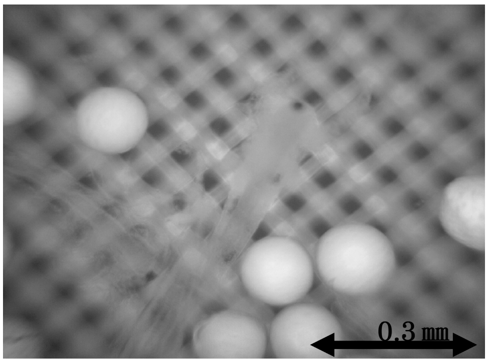

Fig. 2: Optical microscope observation of eggs and plankton.

Following collapse cavitation treatment, plankton were classified as dead, damaged with decreased mobility, and living. In the present study, the planktons were counted visually. Damaged but still living planktons were distinguished from the dead planktons. The survival and extinction rates of the planktons were evaluated using the following expression:

Survival rate = (Number of living planktons after treatment)／(Initial number of live planktons)
Extinction rate = (Initial number of live planktons － Number of living planktons after treatment)／(Initial number of alive planktons)

Effect of chemical injection

The effectiveness of sodium hypochlorite injection to plankton and plankton's egg was studied before the use as mechanochemical cavitation containing sodium hypochlorite. In this stage of the study, plankton and plankton eggs were immersed in a 10-ppm sodium hypochlorite solution for three hours. The results of the experiment are shown in Fig. 3. As can be seen in the figure, large numbers of adult plankton were killed outright or were noticeably weakened. Furthermore, cracks were found to have developed in the eggs of plankton that had been immersed in the sodium hypochlorite solution. This clarified that the addition of sodium hypochlorite was effective in treating eggs as well as hatched plankton in ballast water.

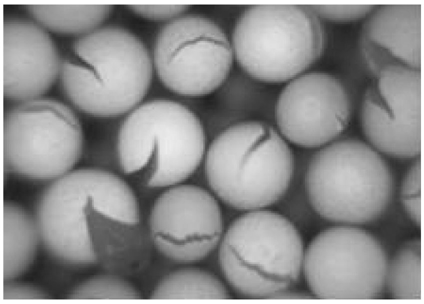

Fig. 3: Effects of sodium hypochlorite on plankton eggs

Equipment

Swirl flow type processor

The individual cavitation produced by the high-pressure water jets generates new cavitation by repeating the process of collapse, generation, and growth. It was thought that plankton would be killed by collapse pressure when this cavitation collapses nearby. It was also considered likely that the center portion of a swirl flow nozzle would develop a low-pressure zone due to the swirl of ballast water, which would provide an increase in the cavitation collapse pressure. In this method, ballast water enters the swirl flow nozzle by an inlet angle of 7º, which is declined against the center of the swirl flow nozzle. A wire disk is located in the outlet of the swirl flow nozzle, which is shown in Fig. 4. Here, the wire disk, which is made of stainless steel, has a gap structure, where the planktons collide.

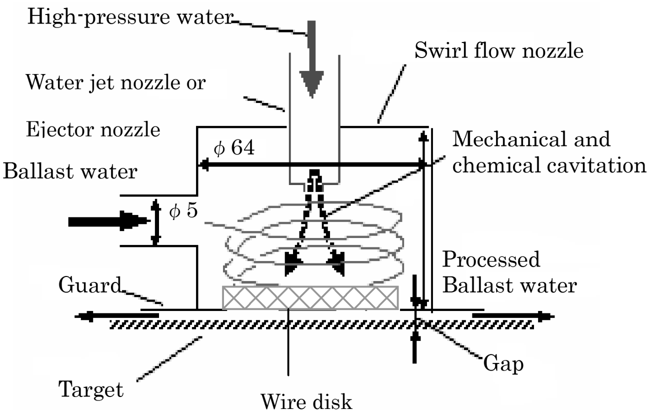

Fig. 4: Schematic illustration of swirl flow processor.

Venturi nozzle

It is also possible to generate mechanochemical cavitation by installing a suction-type (Venturi-type) nozzle on the swirl flow processor. In this method, it is necessary to add sodium hypochlorite to the high-pressure water in order to perform simultaneous mechanical and chemical processing by cavitation. However, directly injecting the chemical into the water jet pump is undesirable from the standpoint of pump safety. Therefore, the Venturi nozzle chemical injection method shown in Fig. 5 was adopted. If the pressure of the suction portion becomes the atmospheric pressure to the chemical water can be introduced into the main current with high-pressure water. The pressure around the suction portion is altered by the dynamic pressure of the main stream, which is determined by the nozzle diameter of high-pressure water. The high-pressure pump used in experiment had an output pressure of 14.7 MPa and a flow rate of 18 L/min.

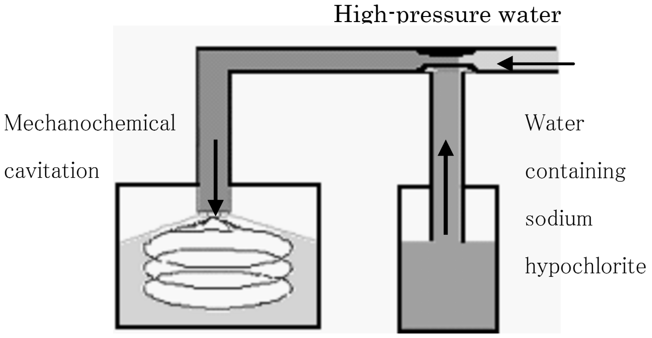

Fig. 5: Venturi nozzle applied to ballast water.

The static pressure around the suction portion becomes higher with a decrease in the nozzle diameter of the main stream. Therefore, in situations where the nozzle diameter was less than φ 3.1 mm, water containing sodium hypochlorite could not be introduced into the high-pressure water.

Because the collapse pressure of cavitation depends on the reduced size of the high-pressure water nozzle diameter, collapse pressure increase possible when a Venturi nozzle is used is restricted.

Ejector nozzle

To solve the Venturi nozzle problem described above, the application of an ejector nozzle (as shown in Fig. 6) was investigated. In an ejector nozzle, the suction of the sub-stream tends to occur in small-sized high-pressure nozzles, because the dynamic pressure of the high-pressure water in the nozzle can increase higher than is possible with a Venturi nozzle. Moreover, the sub-stream containing sodium hypochlorite mixed with high-pressure water, the horn type structure having a various size of angle is adopted.

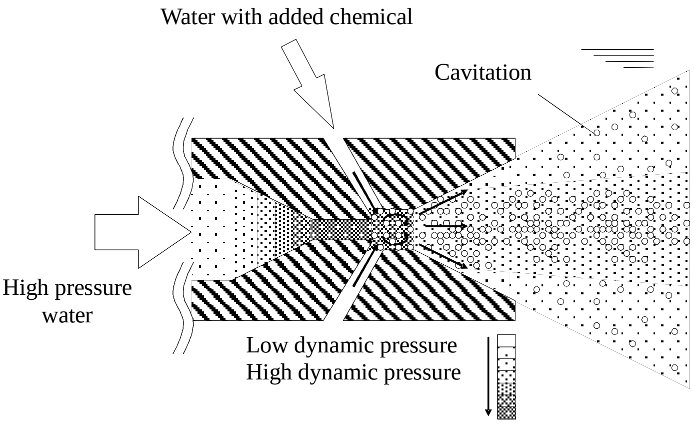

Fig. 6: Configuration of ejector nozzle.

RESULTS AND DISCUSSION

Extinction rate of Venturi nozzle

Initially, the amount of the ballast water current was fixed at 70 L/min. Figure 7 shows the extinction ratio obtained when the concentration of sodium hypochlorite was set from 0 to 50 ppm. When the concentration of sodium hypochlorite was 0 ppm, that is, when only conventional cavitation was used, the measured extinction rates ranged from 75% to 92%, with an average value of about 83%. It should be noted that the extinction ratio increases up to 95% when the concentration of sodium hypochlorite reaches 10 ppm. However, at concentrations higher than 10 ppm, the extinction ratio becomes the constant value of 95%.

Here, the concentration of sodium hypochlorite is defined as the relationship between the concentration of the sub-stream and the amount of ballast water treated. This indicates that the increase to the extinction ratio caused by the addition of sodium hypochlorite is due to the chemical effect.

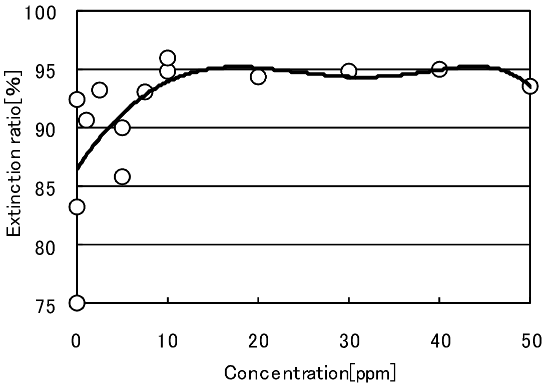

Fig. 7: Relationship between extinction ratio and sodium hypochlorite concentration using Venturi nozzle (flow rate: 70 L/min).

On the other hand, when the flow rate is set to 30 L/min, the extinction ratio increases to more than 97% and no difference between the extinction rates for mechanical and mechanochemical cavitation can be observed. An extinction ratio of 100% is achieved when the sodium hypochlorite density reaches 50 ppm, as shown in Fig. 8.

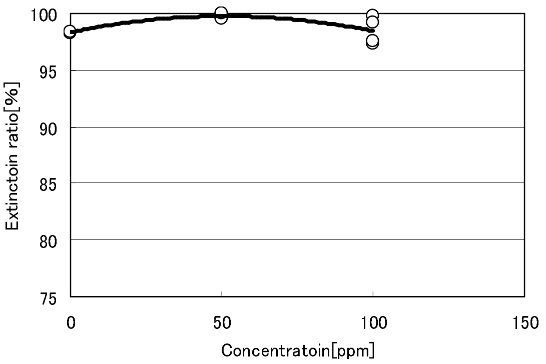

Fig. 8: Relationship between extinction ratio and sodium hypochlorite concentration using Venturi nozzle. (flow rate: 30 L/min).

Ejector nozzle

Suction characteristic

The suction characteristics of various ejector nozzles types were investigated as the experimental parameters of the horn angle (a), the high-pressure nozzle diameter (b), and the sub-stream nozzle diameter (c). Here the main current pressure is 6 MPa. The results of sub-stream suction are summarized in Table 1. In only the nozzle with horn angle less than 40º, the suction of a sub-stream with the atmospheric pressure occurred. In conditions where the horn angle is 60º, the static pressure around the sub-stream increased due to a decrease in the dynamic pressure. This indicates that this increment of statistic pressure may become an obstacle to sub-stream suction.

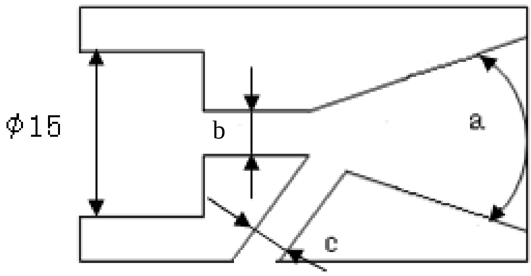

Fig. 9: Ejector nozzle experimental parameters.

Table 1: Results of basic ejector nozzle experiments.

Horn angle a[deg]	Nozzle diameter of high puressure b [mm]	Nozzle diameter of sub current c [mm]	Puressure of main current [Mpa]	Injection of atmospheric puressure
60°	ϕ1	ϕ1	6	×
60°	ϕ2	ϕ2	6	×
60°	ϕ2	ϕ4	6	×
40°	ϕ2	ϕ2	6	○
30°	ϕ2	ϕ2	6	○
20°	ϕ2	ϕ2	6	○

Observation of mechanochemical cavitation

At that stage of the experiment, it was not clear whether the increased collapse pressure of the cavitation or the chemical injection has the most influence on improvements to the extinction ratio. In order to confirm the change in the cavitation by the chemical injection, direct observation was performed using an underwater camera. However, the remarkable change of cavitation could not be recognized in the chemical injection.

Extinction rate of ejector nozzle

Fig. 10: shows the relationship between the extinction ratio and the concentration of sodium hypochlorite achieved by the ejector nozzle. Here, the ballast water flow rate was 70 L/min (○) and 90 L/min (●), the main current pressure 6 MPa, the diameter of the high-pressure nozzle was φ 2 mm and the diameter of the sub-current nozzle was φ 2 mm. At 70 L/min, mechanical cavitation without sodium hypochlorite injection provided an extinction rate of more than 95%, which is higher than the 80% level of a Venturi nozzle. This indicates that the extinction rate rises with the increase of collapse pressure caused by reductions in the nozzle diameter of the ejector nozzle.

On the other hand, at 90 L/min, the mechanochemical effect is recognized to be equivalent to the Venturi nozzle. The ejector nozzle has higher ballast water treatment performance than the Venturi nozzle because the ejector nozzle, when set at 90 L/min, provides the same extinction ratio as the 70 L/min the Venturi nozzle is capable of. This clarifies that the ejector nozzle would be more effective than the Venturi nozzle for treatment of ballast water.

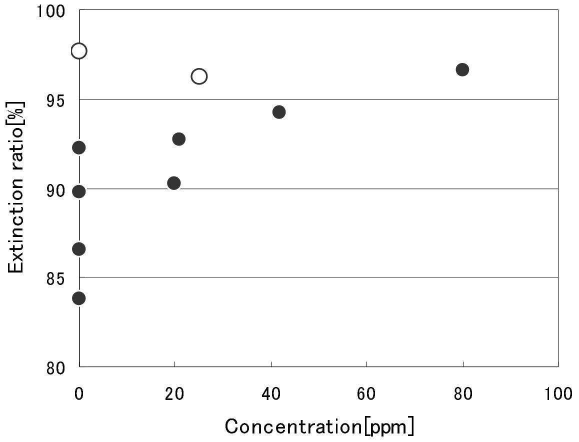

Fig. 10: Relationship between extinction ratio and sodium hypochlorite concentration by ejector nozzle.

Application of mechanochemical cavitation

Mechanochemical cavitation is a new type of cavitation that combines mechanical and chemical effects. The use of mechanochemical cavitation appears to be applicable to a number of other fields other than ballast water processing. These include medical treatments, biotechnology, corrosion resistance, and other surface treatments. In the near future, mechanochemical cavitation is expected to be applied to other industrial fields as well.

CONCLUSIONS

Ballast water treatments were carried out using water jet cavitation containing sodium hypochlorite. As a result of these experiments, the following points were clarified:

(1) A ballast water treatment technology with high processing performance that utilizes an ejector nozzle has been developed.

(2) When treatments were performed using a 3.1-mm-diameter nozzle, a 30 L/min flow rate and a sodium hypochlorite density of 5 ppm, a ballast water extinction ratio of 100% was achieved.

(3) Mechanochemical cavitation can be produced by both ejector and Venturi nozzles.

(4) The plankton extinction rate of the ejector nozzle was higher than that of the Venturi nozzle.

(5) Mechanochemical cavitation is effective for plankton treatment of ballast water.

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REFERENCES

[1] T. Yoshimura, K. Hosokawa, K. Sato, and Y. Taguchi, The Water Jet Technology Society of Japan, Journal of Jet Flow Engineering, Vol. 22, No. 1 (2005) pp. 4-8.

[2] T. Yoshimura, Y. Hashiwata, T. Kanbara, K. Sato and N. Takarayama, The Water Jet Technology Society of Japan, Journal of Jet Flow Engineering, Vol. 23 No. 3 (2006) pp. 4-13.

[3] H. Imai, Japan Marine Equipment Association, Haku, No. 221 (2004) p. 32.