Study on application of shock waves generated by micro bubbles to the treatment of ships' ballast water

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Summary. This paper reports the fundamental study for development of a ships' ballast water clarifying treatment technology using shock pressures generated by the collapse of micro bubbles. From the microscopic observation, it was confirmed that micro bubbles less than 65 μm in diameter became small in size and disappeared, and the shock wave generation by their collapse was observed by optical visualization method and pressure sheets. The bio-experiments using a marine *Vibrio* sp. were carried out under the three conditions: (1) only use of micro bubbles, (2) only use of 20 kHz ultrasonic waves, and (3) simultaneous use of them. The number of survival cells was investigated under the respective conditions for 12 hours. The inactivation effect on the marine *Vibrio* sp. by simultaneous use of micro bubbles and ultrasonic waves indicated better inactivation than that by the only use of micro bubbles or ultrasonic waves.

1 Introduction

It has been pointed out that ships' ballast water is one of causes of divergence of the marine ecosystem [4]. The development of ballast water clarifying treatment system is an important assignment in the field of maritime sciences. Recently, extensive studies on the treatment of ships' ballast water have been carried out (for example, see [6]). In order to solve the issue of the marine environmental preservation, the authors proposed a new treatment technique of ship's ballast water as a mechanical technology for the inactivation of marine bacteria. The concept of the clarifying treatment method is to use the pressure of shock waves generated by collapse of micro bubbles. They considered that several hundreds MPa of shock pressure generated by collapse of micro bubbles can inactivate marine bacteria at the local micro space around bubbles [3]. If the shock pressure is effective to the inactivation of marine bacteria, it enables us to treat large amounts of ships' ballast water effectively. In general, application of micro bubbles has been studying in the fields of engineering, biology, medicine, etc (for example, see [1,5,7]). However, no reports on the inactivation of marine bacteria directly using micro bubbles were found. In addition, the characteristics of micro bubbles have not been understood well enough. In this study, in order to examine a possibility of inactivation of marine bacteria by micro bubbles, change in size and collapse phenomena of micro bubbles, shock wave generation, and the inactive effects on marine bacteria were investigated experimentally.

2 Experimental

The experimental device consists of an ultrasonic generator (UIP500, Dr. Hielscher), a micro bubble generator using a swirling flow (M2-LM/SCS, Nanoplanet), a radiator

(CCA-1100, Tokyo Rikakikai) and a centrifugal pump (25SCD, Ebara) (see Figure 1). This experimental water channel has a 10 l capacity.

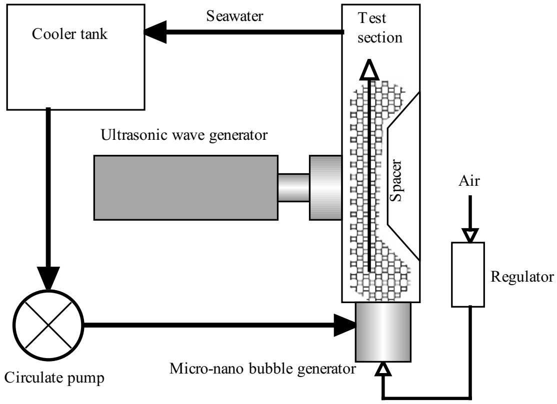


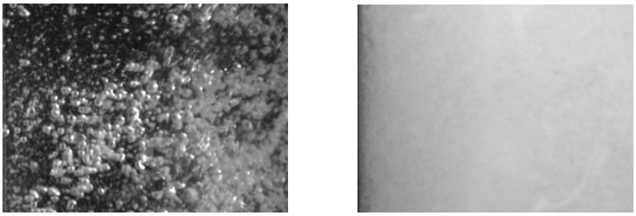
Fig. 1. Illustration of experimental apparatus

It has been well-known that micro bubbles make themselves small and exist in relatively long time after the bubble generation. In order to obtain higher capability for the inactivation of marine bacteria, it is important to understand the behavior of micro bubbles in the water channel. Therefore, micro bubbles were caught using two slide glass plates with a distance of 300 μm near the exit of the micro bubble generator, and the time change of the diameter of micro bubbles were observed by an optical microscope (CX41, Olympus). The collapse of micro bubbles by ultrasonic waves and the generation of shock waves were confirmed by the schlieren visualization method. In addition, shock wave pressures generated by micro jets from micro bubbles were measured with pressure sheets (Prescale, Fujifilm Inc.).

A marine *Vibrio* sp. was used in this study. The marine *Vibrio* sp. belongs to the same generic group of cholera that is one of the bacteria restricted by the international convention regarding the ballast water management. The artificial seawater 10 l, in which NaCl (0.4 M), KCl (10 mM), $CaCl_2 \cdot 2H_2O$ (10 mM), $MgCl_2$ (53 mM), and Na_2SO_4 (28 mM) were dissolved, was used for the experiment. After 10 ml suspension including the 10^8 cfu/ml marine *Vibrio* sp. had been put into the 10 l artificial seawater and stirred enough, seawater was poured into the experimental water channel. The experiment was continued for 12 hours. Samples were taken 10 ml after 1 hour and after then every 2 hours, and they were spread onto an agar plate to check a number of colony after 1/10000 dilution. The number of active bacteria was measured by a colony counting method [2].

3 Observation of micro bubbles in artificial seawater

Figures 2 show micro bubbles produced in freshwater or artificial seawater. The micro bubble generator requires 1.0 l/min air for the best operation. In the case of freshwater, most of air bubbles were not micro size, and the number of bubbles was small. On the other hand, in the case of artificial seawater, micro size air bubbles were generated like a

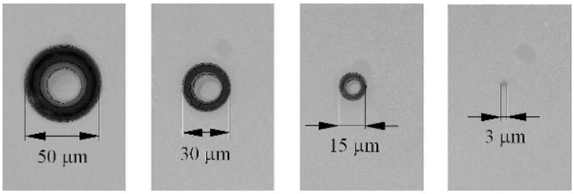


(a) (b)

Fig. 2. Generation of micro bubbles in freshwater (a) and artificial seawater (b)

dense fog in the test section. The reason why a large amount of micro bubbles was easily generated in artificial seawater was considered that the surface tension of seawater was smaller than that of freshwater.

Figures 3 show a time series of the diameter change in artificial seawater. These photos indicate that the bubble diameter decreases from 50 to 3 μm in 650 seconds. It was suggested that the lifetime of a micro bubble was enough long in the test section. Such a slow change in diameter is one of the characteristics of micro bubbles produced by the swirling flow type generator.

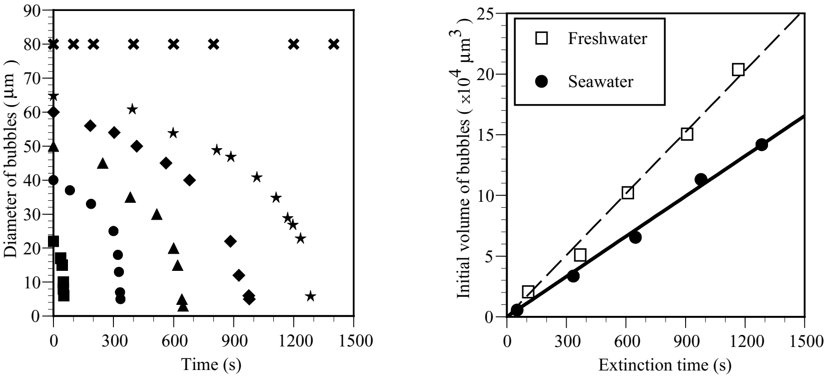


(a) 0 s (b) 500 s (c) 600 s (d) 650 s

Fig. 3. Time change of the size of a micro bubble 50 μm in diameter

Figure 4(a) shows time change in the diameter of micro bubbles in artificial seawater. This figure indicates that the extinction time increases with increasing the diameter of bubble. It is found that the micro bubbles less than 65 μm in diameter became small size and disappeared, but the 80 μm bubble held its size constant. In addition, it took about sixty seconds for the 20 μm bubble to disappear, and the reducing rate of bubble diameter seemed to be accelerated after the bubble diameter had become 20 μm.

Figure 4(b) shows the relations between the initial volume of micro bubble and the extinction time in freshwater and seawater. In both cases, the initial volumes are positively proportional to the extinction time. From a comparison between them, it was found that the lifetime of micro bubbles in seawater was longer than that in freshwater. The average decreasing rate of volume of micro bubbles in seawater was estimated about 110 μm^3/s. It seemed that there was similarity between the motion of micro bubbles and that of vapor bubbles.

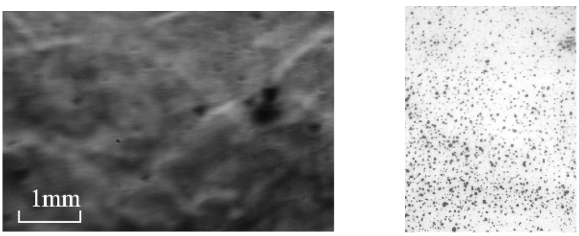


(a) (b)

Fig. 4. Time change in the diameters of micro bubble (a), and relation between the initial volume of micro bubble and extinction time in fresh and seawater (b)

4 Results and discussions

Figure 5(a) shows a photograph obtained by schlieren method, and the density changes in flow field with micro bubbles and ultrasonic waves were visualized. Although there was density non-uniformity in the background, a lot of small circular shadows were shown. We considered that the bright circles around those circular shadows of micro bubbles shows the existence of shock waves generated by collapse of micro bubbles. In addition, as shown in figure 5(b), we obtained a lot of dots on a pressure sheet. They were appeared due to the water jets generated by collapse of micro bubbles.



(a) (b)

Fig. 5. Schlieren photograph (a), and reaction of pressure sheet (b)

The bio-experiments using the test section with widths of 5 mm and 20 mm were carried out under the following three conditions: (1) only use of micro bubbles, (2) only use of ultrasonic waves, or (3) simultaneous use of micro bubbles and ultrasonic waves. Figures 6 show the time change of the inactivation ratio of a marine *Vibrio* sp. In these figures, the ordinate axis is represented by -log(N/N_0)C where N is the number of survival bacteria and N_0 means the initial value, and the abscissa is time (hour). In the case of only use of micro bubbles, the inactivation ratio showed slightly increase without relation

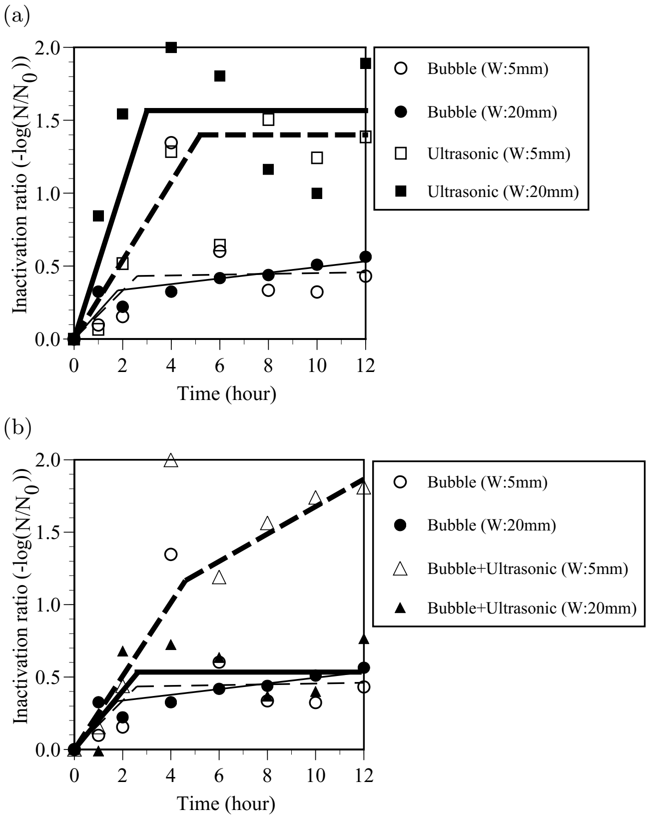


Fig. 6. Time change of the inactivation ratio of a marine *Vibrio* sp.: the results obtained by only use of bubbles and only use of ultrasonic waves in the water channel with widths of 5 mm and 20 mm (a), and the results obtained by only use of bubbles and simultaneous use of bubbles and ultrasonic waves in the water channel with widths of 5 mm and 20 mm (b)

to the width of test section. Figure 6(a) represents the comparison between the result obtained by only use of micro bubbles and that by only use of ultrasonic waves. It is found that the inactivation effect appeared within about early four hours, and after then, the inactivation ratios are approximately constant. In this case, the width of the test section does not relate with the inactivation ratio.

Figure 6(b) shows the result by simultaneous use of micro bubbles and ultrasonic waves. Then, the amount of air introduced into the micro bubble generator was 1.0 l/min that was recommended by the product company as an appropriate value. The experimental result using 20 mm width of test section was similar to the result of only use of micro bubbles. A large amount of micro bubbles probably obstructed the propagation of ultrasonic waves in the test section. In contrast, the result using 5 mm width of the test section increased with increasing time. Therefore, we considered that the ultrasonic waves and their reflection at the surface of spacer in the test section made micro bubbles collapse effectively, and then the marine bacteria were inactivated. From above-mentioned results, it is concluded that the efficient collapse of micro bubbles is important for obtaining higher inactivation ratio. In the present experiment, it is necessary to decide the appreciate conditions about setting of an ultrasonic transducer, volume of air introduced into the micro bubble generator, and flow velocity through the test section.

5 Conclusions

In the present study, it was shown that micro bubbles less than 65 μm in diameter existed long time in artificial seawater, and shock waves and water jets were generated by collapse of micro bubbles exposed to ultrasonic waves. In addition, the inactivation effect on the marine *Vibrio* sp. by simultaneous use of micro bubbles and ultrasonic waves indicated better inactivation than that by the only use of micro bubbles or ultrasonic waves. These experimental results showed that it is important for inactivation of the marine *Vibrio* sp. to induce the collapse of micro bubbles efficiently. Therefore, it is necessary to examine conditions for the efficient collapse of micro bubbles in order to establish the effective treatment technique of a large amount of ships' ballast water using micro bubbles.

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