# Contribution of Cavitation Generation to Shock Wave Sterilization Effects in a Narrow Water Chamber

**J. Wang, A. Abe, T. Koita, and M. Sun**

**Abstract** The paper reports on the generation mechanism of cavitation bubbles in a narrow water chamber and the sterilization effects of these cavitation bubbles on marine bacteria. Underwater shock waves are generated by electric discharge. Propagation behaviors of the waves in the water chamber are investigated using an optical method. On the other hand, a bio-experiment with marine bacteria is also carried out to examine sterilization effects. It is found that the shear wave is produced in the wall material of the water chamber by the energy release of underwater electric discharge and results in the tensile stress arising in the water, and thereby cavitation bubbles are induced with the propagation of the shear wave. From the results of the bio-experiments, we confirm a high sterilization effect of the cavitation bubbles.

## 1 Introduction

Cavitation bubbles have been observed in many different fields, and their dynamic behaviors have been studied in detail experimentally, theoretically, and numerically. The phenomenon of the cavitation was first discovered in 1894 when the tests were made to determine why a ship could not reach its design speed during sea trials. The collapse of cavitation was found to reduce the performance of a propeller while also

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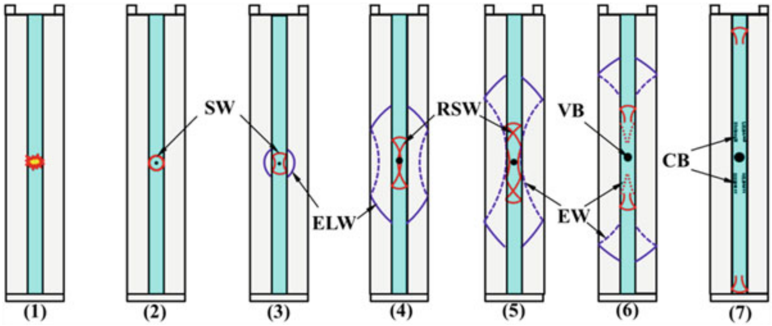


**Fig. 1** Schematic of cavitation bubbles generated behind multiple waves induced by underwater electric discharge in narrow water chamber

giving rise to vibration and erosion. Song et al. [1] applied a high-power laser to the cleaning of the solid surface in liquid and pointed out that a liquid jet and collapse shock wave that were induced by the collapse of the laser-induced cavitation bubble resulted in a high-cleaning efficiency for the removal of particles. In the field of marine sciences, the collapse of microbubble was used to the sterilization of ships' ballast water [2]. When they carried out a bio-experiment to investigate the sterilization effect of the shock wave-microbubble interaction, Wang and Abe [3] found the cavitation bubbles generated behind the concentration of underwater shock waves have a potential to kill marine bacteria. On the other research, Koita et al. [4] observed the generation of cavitation bubbles behind the propagation of multiple waves produced by underwater electric discharge in a narrow water chamber. They thought that the interactions of the waves at the interface between the air and the acrylic wall induced the tensile stress in the water. As shown in Fig. 1, an underwater shock wave (SW) generated by an electrical discharge is reflected partly at the internal wall to form reflected shock waves (RSW) and that part of the SW entering the wall is propagated as an elastic wave (ELW). Expansion waves (EW) are produced by the reflection of the ELW at the interface between the air and the wall and then reenter the water. Cavitation bubbles (CB) are induced by tensile stress resulting from the EW. In addition, as a result of underwater electric discharge, large amounts of energy are released and then probably caused the deformation of the wall material due to the confined space, so that the shear wave propagating in the wall material would be produced and thereby the tensile stress arises in the water. The cavitation bubbles are also produced in this case.

From these backgrounds, considering the sterilizing potential of cavitation bubbles, it is interesting to understand the sterilization effect of the cavitation bubbles generated behind the multiple waves in a narrow water chamber. The paper aims to clarify the generation mechanism of the cavitation bubbles in a narrow water chamber and the sterilization effects of these cavitation bubbles on marine *Vibrio* sp. Propagation behaviors of the multiple waves generated by an underwater electric discharge are observed using an optical method. The sterilization effects are also discussed by the bio-experiments under different conditions.

# 2 Experiments

## 2.1 *Bio-experiments*

Figure 2 shows a schematic of the bio-experimental setup in a narrow water chamber. The dimensions of the narrow water chamber were 300 mm (H) × 240 mm (W) × 5 mm (D). As shown in Fig. 2, a bag made of a 0.1-mm silicone film was designed in the water chamber and filled with cell suspension of marine *Vibrio* sp. The dimensions of the silicone bag were 120 mm (H) × 100 mm (W) × 5 mm (D). Its acoustic impedance was almost the same as that of water. The discharge point was set up at a distance of about 20 mm from the bottom of the silicone bag in the water chamber. Underwater shock waves were continuously generated by a high-voltage pulse power supply and a pulse generator.

Figure 3 illustrates a considerable sterilization mechanism in the narrow water chamber. The cavitation bubbles generated behind the underwater shock waves interact with the reflected shock waves or the next coming shock wave. Finally, rebound shock waves and free radicals are generated by the collapse of the cavitation bubbles, and the marine bacteria around the bubbles are killed. A photo of the marine *Vibrio* sp. used in the bio-experiments is shown in Fig. 3c.

## 2.2 *Optical Observation*

To further investigate the mechanism whereby the cavitation bubbles were generated in the narrow water chamber, the optical observation was carried out in the box area by the dashed lines as shown in Fig. 4. In Fig. 4a, the water chamber was filled with

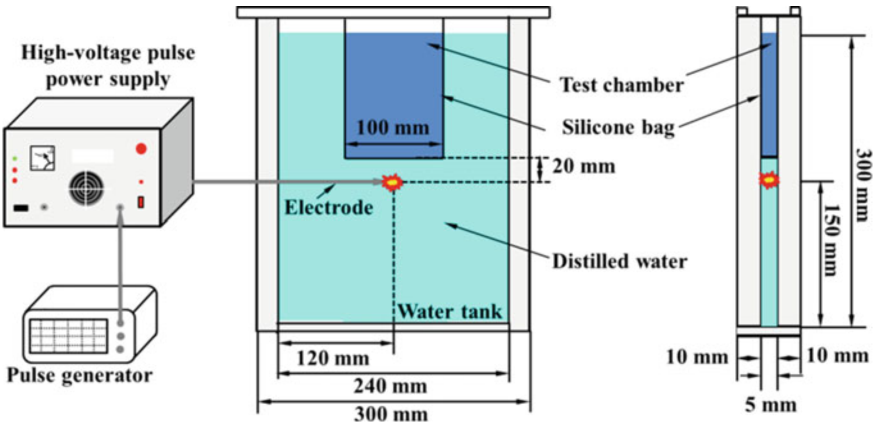


**Fig. 2** Schematic of bio-experimental setup in narrow water chamber

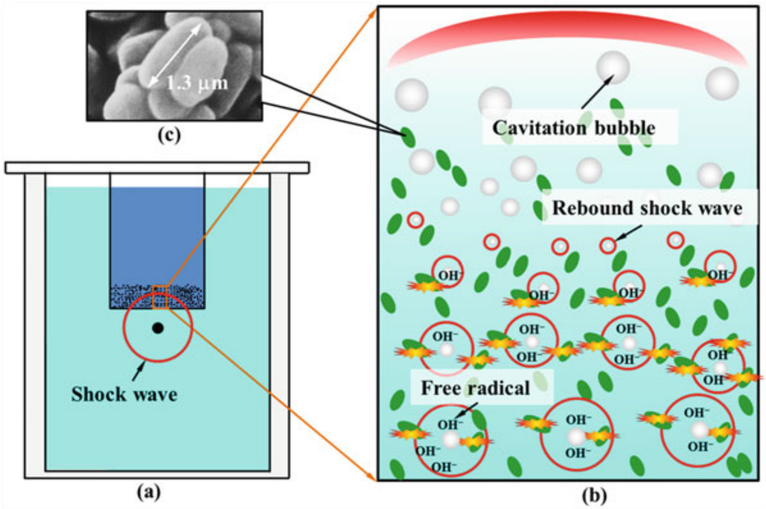


**Fig. 3** Concept of sterilization mechanism using cavitation bubbles behind generated underwater shock waves: (**a**) Schematic of water chamber, (**b**) Collapse of cavitation bubbles and (**c**) A photo of marine *Vibrio* sp.

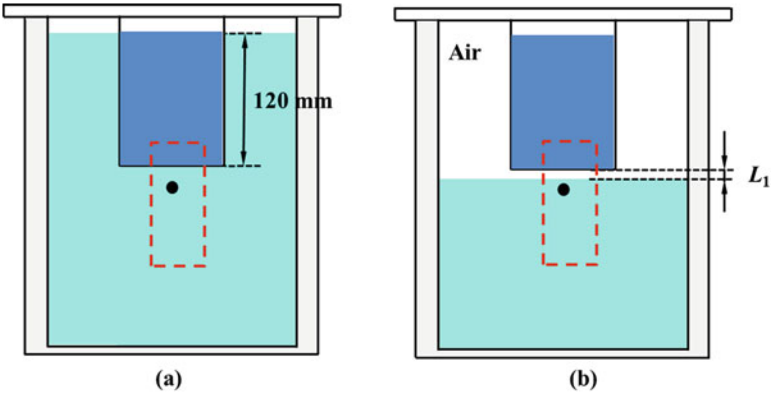


**Fig. 4** Schematic of narrow water chamber used for optical observation: (**a**) Chamber full of distilled water, (**b**) Air layer of $L_1$ between water surface and silicone bag

distilled water, while the silicone bag contained artificial seawater. Figure 4b shows the other setup of the water chamber arranged with an air layer of $L_1$ between the water surface and the bottom of the silicone bag, to prevent underwater shock waves generated by electric discharge directly propagating into the silicone bag.

## 3 Results and Discussion

Figure 5 shows the multiple waves generated by an underwater electric discharge in the narrow water chamber, observed using the schlieren method. The output power of the electric discharge was 28.6 kV. The high-speed camera (i-SPEED 7, Nac Image Technology) captured images at a frame rate of 100 kfps and an exposure time of 300 ns. The resolution of the images was 840 × 216 pixels. In the figure, an ELW propagating in the acrylic wall and the SW generated by the electric discharge are observed in Fig. 5 (1). The SW is thought to be cylindrical due to the thickness of the water chamber. The images indicate that its propagating speed is about 1500 m/s. At 20 μs, the SW is reflected partly at the bottom of the silicone bag, as indicated by RSW 1, and then transmitted through the bag. At 30 μs, the secondary wave (second wave) has passed through the bag, and then its reflected wave (RSW 2) is observed behind the RSW 1. Moreover, the area of cavitation bubbles is found and grows with the passage of the second wave following the SW in the silicone bag. Therefore, we consider that the second wave is an expansion wave. The expansion wave can be caused by the reflection of the ELW at the interface between the air and the wall of the water chamber [4], the propagation of the shear stress propagating in

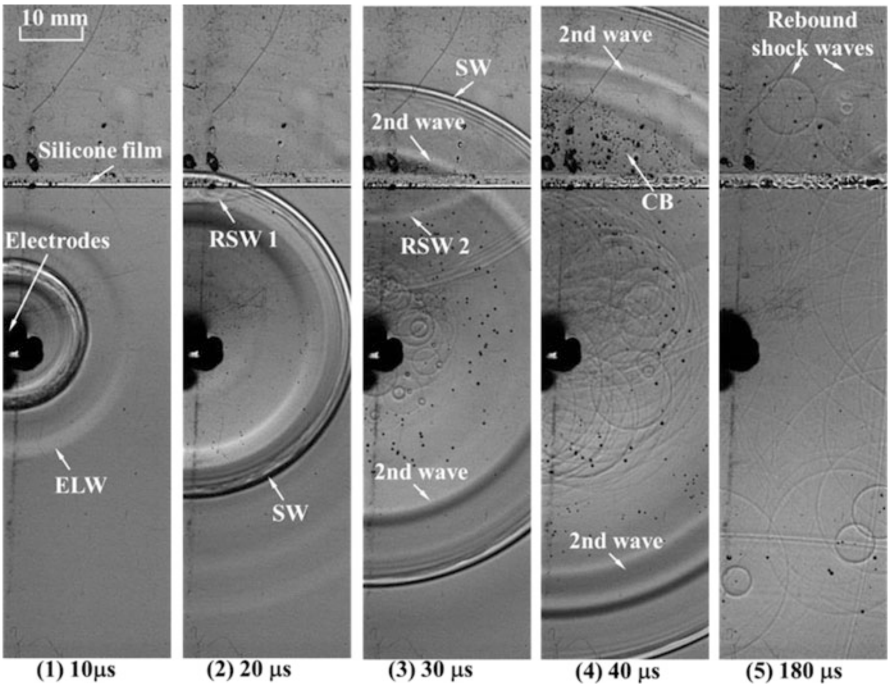


**Fig. 5** Observation of multiple waves generated by underwater electric discharge in narrow water chamber using schlieren method

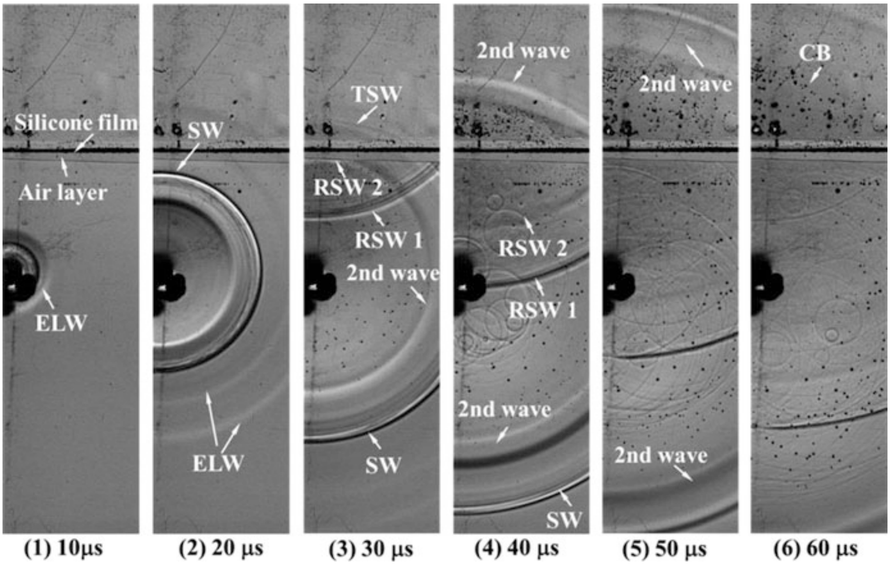


**Fig. 6** Observation of multiple waves generated by underwater electric discharge with a 2-mm air layer

the wall material, or the concentration of underwater shock waves [3]. At 180 μs, the rebound shock waves generated by collapses of the cavitation bubbles are captured in the silicone bag. These results suggest that the cavitation bubble behind the expansion wave following SW is potentially capable of killing marine bacteria.

Figure 6 shows the observation of multiple waves generated by an underwater electric discharge with a 2-mm air layer. The experimental and high-speed-camera conditions were the same as those for Fig. 5. In this figure, we can see ELW in Fig. 6 (1) and (2). The RSW 1 is clearly captured when the SW is reflected by the air layer at 30 μs. Moreover, the second wave is being reflected from the air layer. The RSW 2 behind the RSW 1 is thought to be a compression wave. Although the propagation of an underwater shock wave is intercepted well by the air layer, we still find a transmitted shock wave (TSW) in the silicone bag. At 40 μs, the second wave is propagating in the silicone bag regardless of the air layer, and CB are generated behind the second wave. Therefore, the second wave could not be induced by the concentration of underwater shock waves. On the other hand, as shown in Fig. 1 (6), the EW propagating in wall material is in front of the SW so that the second wave is also not from the reflection of the ELW. From the images, it is found that the propagation speed of the wave is about 1469 m/s. Referring to the propagation velocity of shear wave in PMMA material, 1430 m/s, we argue that the second wave causing the generation of the CB is a shear wave travelling in the window material as a result of the release of large energy at the discharge point.

Figure 7 shows estimates of the number of viable cells for an electric discharges of 28.6 kV. The plots shown in this figure are of the averages for six sets of

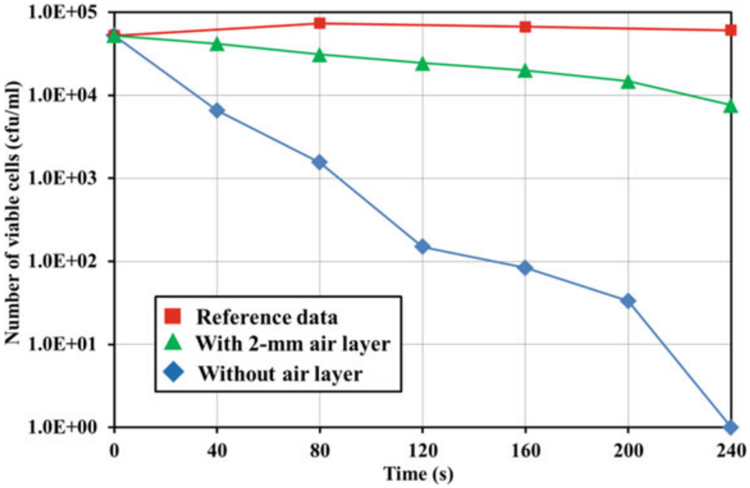


**Fig. 7** Estimation of sterilization effect obtained with 28.6-kV electric discharges: ■ reference data, ▲ with 2-mm air layer, and ♦ without air layer

bio-experimental data. The solid squares are the reference data obtained from the solution of the marine bacteria without the action of any shock waves. The number of viable cells hardly changes throughout the course of the experiment. The solid triangles and diamonds represent the results of the bio-experiments obtained using an electric discharge of 28.6 kV with and without air layer between the water surface and the bottom of the silicone bag, respectively. The figure shows that after 4 min, all the marine bacteria are completely killed without air layer, while only one order of the number of marine bacteria are killed with a 2-mm air layer because of weak underwater shock waves in the silicone bag. Consequently, we can confirm that the cavitation bubbles generated in the water chamber contribute to inactivating marine bacteria. Furthermore, a shock wave inducing collapse of bubble plays an important role in the shock wave sterilization.

## 4 Conclusions

In the paper, we investigated the cause of cavitation bubbles in a narrow water chamber and also the contribution of these bubbles to the inactivation of marine bacteria. A bio-experiment with marine *Vibrio* sp. was carried out in a silicone bag that was set up in the narrow water chamber. Underwater shock waves were generated by electric discharges. To prevent the underwater shock waves propagating into the silicone bag, an air layer was introduced between the bag and the water surface of the chamber. The optical observation exhibited that the generation of the cavitation bubbles was induced by the tensile stress arising in the water due to the propagation of the shear wave in the wall material of the water chamber. The shear waves were produced owing to the deformation of the wall material when large amounts of energy was instantly released by the electric discharge. From the results of the bio-experiments, it was confirmed that the collapse of cavitation bubbles contributes to the inactivation of marine bacteria.

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