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Experimental Study on Interaction of Multiple Cylindrical Bubbles with Underwater Shock Wave

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Abstract

The present paper reports on an experimental investigation of the behaviors of multiple cylindrical bubbles induced by underwater shock wave. The bubbles are formed in a narrow water chamber by an injection to observe conveniently their internal flow. In this way, the number, size, and position of the bubbles are controlled. As observed by using the schlieren method, cavitation bubbles are produced behind a shear waves followed with expansion regions. The life times of these cavitation bubbles are short so that the motion of the cylindrical bubble is hardly affected. For a single bubble, the liquid jet is formed during the bubble expansion and points towards the propagation direction of shock wave. In the case of the multiple bubbles, the direction of the jet depends on the combination of the shock wave-induced action and interaction forces between the bubbles. Here, the generation of a counter jet is used to determine whether or not the interaction forces work. It is suggested that the strength of the bubble motion is a main factor related to the magnitude of the interaction force besides the inter-bubble space.

Keywords: cylindrical bubbles; underwater shock wave; liquid jet; counter jet; interaction force

Introduction

The interaction of shock waves with gas bubbles has been observed in a variety of fields such as shock wave lithotripsy, food engineering, and the treatment of the wastewater. The bubble dynamic behaviors have been studied in detail experimentally, theoretically, and numerically. To the best of the authors' knowledge, understanding of non-spherical collapse begins from the study by Kornfeld and Suvorov [1]. They suggested that cavities could collapse asymmetrically and produce a liquid jet. The jet is generated on the side of high pressure, points towards the low-pressure side, and penetrates the far surface of the bubble. After that, non-spherical collapse is characterized by the formation of a main transverse jet. In order to observe the internal processes of the cavities such as jet motion, Dear et al. [2] proposed a liquid/gel two-dimensional method to produce cylindrical bubbles. They conducted many experiments studying the collapse of a single bubble and multiple bubbles induced by shock wave. It was observed that high-speed jets were generated in the direction of the travelling shock waves. They also found the collapse took place layer by layer because of the shielding effect in the case of the clustered arrays of cavities [3]. However, the gelatin layer liquefied as soon as the shock wave went through it such that the observation was influenced by the liquefaction shadow. On the other research, Chen et al. [4] used a focused laser to generate two-dimensional bubbles in a micro gap filled with blue ink. They investigated the interaction dynamics of an existing stable microbubble and another laser-induced microbubble. They found that the strong interaction can merge the bubbles with complicated asymmetric intermediated patterns. Quinto-su and Ohl [5] recorded the dynamics of two laser-induced bubbles created at different distances in a two-dimensional geometry, and suggested that the interaction forces are inversely proportional to the inter-bubble separation.

In the present paper, an experiment is carried out to observe the behaviors of multiple cylindrical bubbles induced by a spark-induced shock wave. The cylindrical bubbles are produced by an injection in a narrow water chamber composed of two acrylic plates. Compared with the method of generating two-dimensional bubble proposed by Dear et al. [2], it is convenient to simultaneously apply various visualization methods such as the combination of an optical method with PIV or PTV technique which is not presented in the paper, for the way to use a narrow water chamber. In the experiments, the observation is carried out using the schlieren method. We discuss the jet direction and speed in the case of a single bubble and multiple bubbles after the passage of a shock wave.

Experimental Setup

Figure 1 shows a schematic of experimental setup for observing the interaction between cylindrical bubbles and shock waves. In the experiment, underwater shock waves were generated by a high-voltage pulse power supply (HPS 18K-A. Tamaoki Electronics Co., Ltd.). As shown in the figure, the narrow water chamber was composed of two acrylic

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plates of 150 mm (L) ×150 mm (W) × 20 mm (D), and the width of the gap was 1-mm. In the narrow chamber, it is possible to produce the bubble of arbitrary diameters and to put them at required positions using an injection. The chamber was set horizontally to avoid the influence of the gravity on the motion of the bubbles, so that two optical mirrors were placed over and under the water chamber to introduce the observation light into the chamber. The optical observation was carried out by a high-speed camera (MEMRECAM HX-3, Nac Image Technology) with a light source (LS-M350, SUMITA optical glass Inc.). In the experiments, the electrodes were tungsten and the spark gap of the electrodes was 4 mm. The output power of the power supply was 50.0 kV.

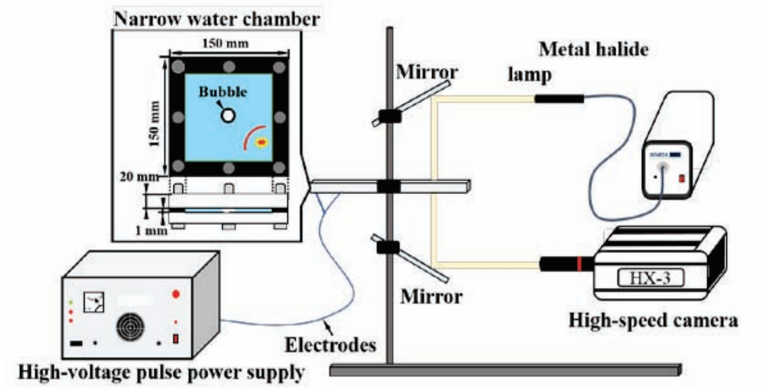

Fig. 1 Schematic of experimental setup for interaction of cylindrical bubbles with underwater shock waves

Results and Discussion

Figure 2 shows the schlieren images of the propagation of the incident shock wave and the generation of cavitation bubble in the narrow water chamber. In the following figures, the yellow arrows indicate the propagation direction of incident shock wave. The cylindrical incident shock wave (SW) passes through during the first and second frames, however there is no deformation of the quasi-cylindrical bubble. In the second frame, it is observed that another wave (EW) also passes through the cylindrical bubble. A lot of small cavitation bubbles (CB) are found behind it. The study of Wang et al. [6] suggested that the second wave is a shear wave travelling in the window material, so that expansion regions are induced in water. The shear wave is caused by the deformation of the window material as a result of the release of large energy when the electric discharge is triggered. Therefore, there are no cavitation bubbles around the cylindrical bubble.

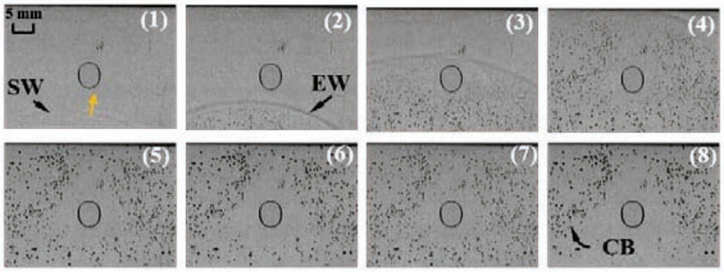

Fig. 2 Schlieren images of propagation of incident shock wave and generation of cavitation bubbles in narrow water chamber. The interval time is 10 μs. The cylindrical bubble with 5.2 mm in minor axis and 6.0 mm in major axis is placed at 50 mm from the discharge point.

Figure 3 shows the sequential images of the motion of a single bubble after the passage of the shock wave. Compared with the frame 1, change of the bubble interface is recognizable slightly after the cavitation bubbles generated by a shear wave disappear in the frame 2. Furthermore, the clear contraction starts in the frame 4. Hence, it is suggested that cavitation bubbles hardly affect the behaviors of the cylindrical bubble. Next, the liquid jet pointing towards the propagation direction of the shock wave is generated, travels inside the bubble, and impacts the far surface during the bubble contraction in the frames 5-11. Before penetrating the bubble surface, the velocity of the jet is about 10 m/s. After that, the bubble is broken up into three bubbles with its re-contraction motion. During this process, the internal flows of the bubble are not observed because the two-dimensional characteristics are not maintained for these small bubbles owing to respectively large width of the gap. On the other hand, we also investigated the correlation between the angles of the shock wave and the jets for a single bubble, as shown in Fig. 4. The results show that the liquid jet is always pointing towards the propagation direction of a shock wave when the shape of a single bubble is close to circle.

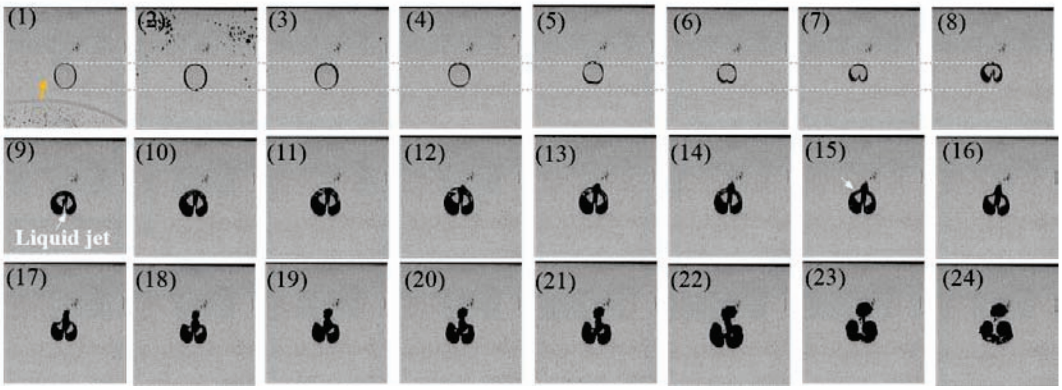

Fig. 3 Sequential images of motion of single bubble after passage of shock wave. The interval time is 100 μs. The cylindrical bubble with 5.2 mm in minor axis and 6.0 mm in major axis is placed at 50 mm from the discharge point.

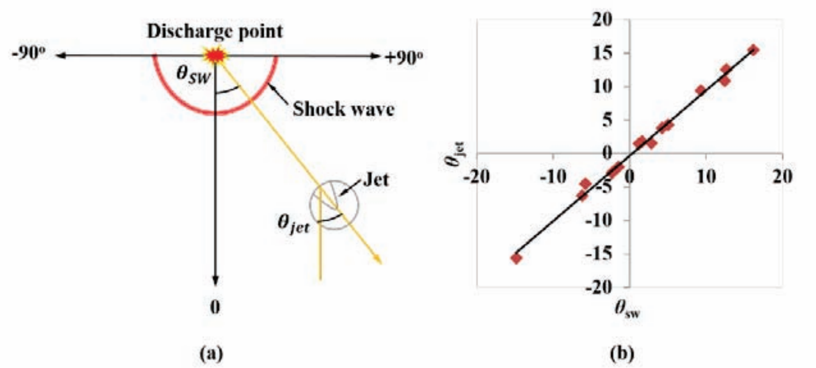

Fig. 4 Schematic of the incident angle of shock wave θ_{sw} and jet angle θ_{jet} (a), and correlation between two angles for single bubble (b).

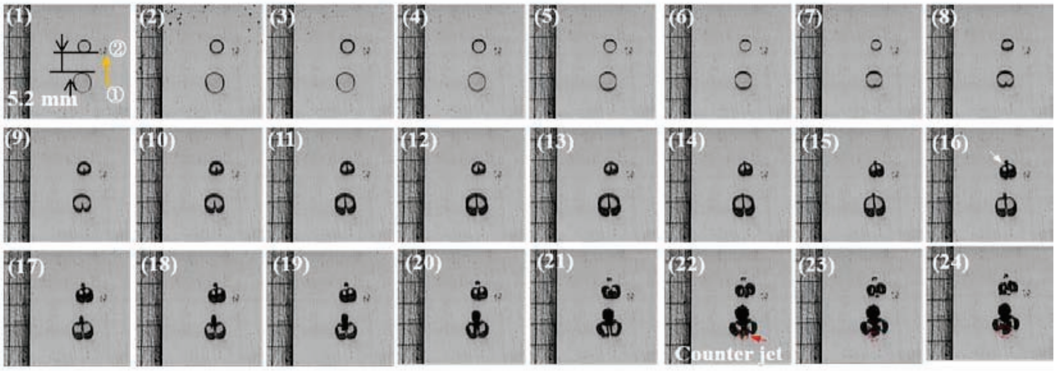

Fig. 5 Behaviors of two bubbles with 5.2-mm separation after passage of shock wave. The time interval is 100 μs. The dimensions of the bubbles are 5.2 mm in major axis and 4.6 in minor axis for ① and 3.4 mm in diameter for ②. The separation between the bubble surfaces is 5.2 mm. The distance from the discharge point to the lower surface of the bubble ① is 35 mm.

Figure 5 shows the behaviors of two bubbles after the passage of the shock wave. In the frames 1-14, it can be seen that the motions of the bubble ① and ② do not affect each other because of a large separation until the generated liquid jets penetrate the opposite bubble surfaces. During this process, the velocity of the liquid jet is 14.7 m/s for the bubble ① and 8.7 m/s for the bubble ②. Furthermore, both of them are pointing towards the propagation direction of the shock wave. After that, both of them begin to shrink. For the bubble ②, the upper surface contracts while the lower surface is stretched by the contraction of the bubble ①. Finally, the liquid jet is separated from the main bubble ② in the frame 19. For the bubble ①, the contraction motion seems not to be affected by the interaction force from the bubble ② before the fame 21. However, a counter-jet is generated in the opposite direction to the liquid jet in the frame 22, which is not captured in the case of a single bubble in Fig. 3. It suggests that the interaction force indeed works on the bubble ①. Here, a dimensionless distance γ is used to estimate the magnitude of the interaction force, i.e., the ratio of the inter-bubble separation to the bubble radius. For the bubble ①, the interaction force from the bubble ② is related to the dimensionless distance $\gamma = 3.06$. The study by Quinto-su and Ohl [5] suggests that the smaller γ is, the stronger the interaction force becomes. Besides, the generation of a counter jet can be used to judge that whether or not the interaction forces affect the bubble behaviors.

Figure 6 shows the behaviors of three bubbles after the passage of a shock wave. In the frame 1, the cavitation bubbles are captured as indicated in the red ellipse. Similarly as that in Fig. 5, the three bubbles deform successively and form the respective liquid jets. For the bubble ①, the direction of the liquid jet is the same as the propagation of the shock wave and its velocity is 13.9 m/s. It suggests that the motion of the bubble ① is not affected by the interaction forces since a counter jet is not induced, as observed in Fig. 5. However, the dimensionless distance, $\gamma = 2.83$ of the bubble ②, smaller than 3.04 in Fig. 5. Hence, the factors such as the pressure of the incident shock wave also influence the magnitude of the interaction force. In the case of the bubbles ② and ③, the jets tend to point towards each other under the combination of the interaction forces and shock wave-induced action. The velocity of the liquid jet is 14.8 m/s for the bubble ② and 14.6 m/s for the bubble ③. According to the direction angles of jets and shock wave, the magnitudes of the two forces are almost the same.

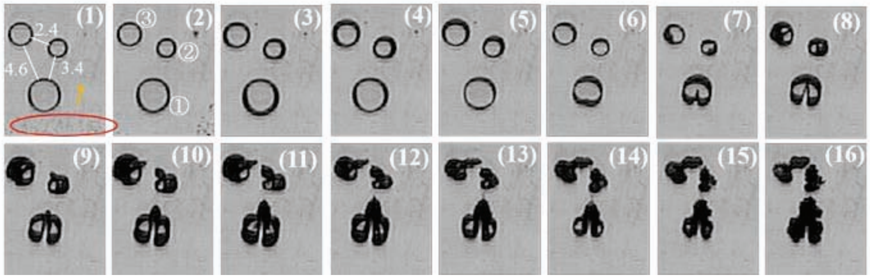

Fig. 6 Behaviors of three bubbles after passage of shock wave. The time interval is 100 μs. The dimensions of the bubbles are 4.1 mm in major axis and 4.0 in minor axis for ①, 2.4 mm in diameter for ②, and 3.4 mm in diameter for ③. The separations are 3.4 mm between ① and ②, 4.6 mm between ① and ③, and 2.4 mm between ② and ③. The distance from the discharge point to the lower surface of the bubble ① is 55 mm.

Conclusion

The paper presented an experiment to observe the behaviors of multiple cylindrical bubbles with a shock wave produced by underwater electric discharge. The cylindrical bubbles were produced by an injection in a narrow water chamber composed of two acrylic plates. In this way, the number, size, and position of the bubbles were controlled. The observation is carried out using the schlieren method. The visualization results showed the cavitation bubbles were produced due to the deformation of the window material as a result of the release of large energy at the discharge point. However, the life times of these cavitation bubbles were short so that they did not affect the subsequent motion of the cylindrical bubbles. For a single bubble, the liquid jet was formed during the bubble expansion and pointed towards the propagation direction of the shock wave. In the case of the multiple bubbles, the direction of the jet depended on the combination of the shock wave-induced action and interaction forces. Here, the generation of a counter jet was used to determine whether or not the interaction forces worked. Beside the separation between the bubbles, the strength of the bubble motion is expected to be a main factor related to the magnitude of the interaction force. A strong interaction forces requires high pressure of incident shock wave.

References

[1]Kornfeld, M., Suvorov, L. (1944) On the destructive action of cavitation. Journal of Applied Physics. 15.
[2]Dear, J. P., Field, J. E., Walton, A. J. (1988). Gas compression and jet formation in cavities collapsed by a shock wave. Nature. 332 (7).
[3] Dear, J. P., Field, J. E. (1988) A study of the collapse of arrays of cavities. Journal of Fluid Mechanics. 190.
[4] Chen, Y., Chu, H., I, L. (2006) Interaction and fragmentation of pulsed laser induced microbubbles in a narrow gap. Physical Review Letters. 96.
[5] Quinto-su, P., Ohl, C. D. (2009) Interaction between two laser-induced cavitation bubbles in a quasi-two-dimensional geometry. Journal of Fluid Mechanics. 2009.
[6] Wang, J., Abe, A., Koita, T., Sun, M. (2017) Contribution of Cavitation Generation to Shock Wave Sterilization Effects in a Narrow Water Chamber. The proceeding of 31th International Symposium on Shock Waves, in press.