Outcomes following single bubble collapse in a rigid tube

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Abstract. Following the collapse of a vapour bubble inside a rigid tube, various outcomes could be caused by the propagation and reflection of the shock wave. Using high-speed camera system and hydrophone, the secondary cavitation and acoustic pressure curve due to the collapse of single bubble in a rigid tube are studied experimentally. The secondary cavitation has a decisive effect on the pressure pulse sequence, which usually appears at a certain area symmetric to the first bubble. Two particular cases of first bubble generated near the midpoint and the endings of the tube are also investigated, where the strength, position and period of the secondary cavitation show different features. The mechanism behind these results are discussed briefly, which is related to the propagation and reflection of the shock wave.

1. Introduction

When cavitation occurs, the geometrical boundary constraints have a major effect on both the behaviour of cavitation bubbles and the outcomes after the collapse. A round-section rigid tube is a common boundary for cavitation bubbles, referring to lots of fields, such as hydraulic systems, MEMS and dental therapy. The dynamic behaviour of single bubble in a rigid tube has been investigated experimentally and numerically [1, 2], focusing on the deformation, the liquid jet, and the pressure distribution around it. Recently, the interaction phenomena between two vapour bubbles in a rigid tube were also reported [3]. Theoretically, a one-dimensional model was developed by Kornilovitch [4] to describe the inertial pump effect of the collapsing bubble, which produces a final momentum in the tube.

On the other hand, the mechanism of “shock wave-reflection-cavitation” has been widely observed in pipes following water hammer [5] or a manually excited shock wave [6], which could cause various outcomes. In a rigid tube, the collapse of vapor bubble could also emit shock wave, which will propagate along the tube, then be reflected and converge again. The outcomes could be greatly affected by the pressure waves, leading to secondary cavitation and different pressure pulses, similar to the bubble collapse near a free surface [7-9]. However, these outcomes were usually neglected or simply described in one sentence in past works about bubble collapse in rigid tube.

The present work aims to experimentally study the phenomena after the collapse of a single bubble in a rigid tube. Experimental results of the secondary cavitation and acoustic pressure sequence are presented, with a brief discussion on the mechanism behind the outcomes observed.

2. Experimental setup

As shown in figure 1, vapor bubbles are generated by low voltage electric spark method [10], which are named as “first bubble” in the present study. The circuit consists of a 50 V power source, three
capacitors (3300 μF × 1, 1000 μF × 2), a resistance of 1 kΩ, and one pair or two pairs of electrodes (fine copper wires of 0.26 mm). An organic glass tank (400 × 200 × 200 mm³) is used as the container to hold tap water, in which a glass tube is fixed. The liquid and laboratory temperature are maintained at 20°C ± 2°C, and the environment pressure is kept at 101.3 kPa. Before inducing the spark, the contact position of the electrodes is carefully adjusted to be inside the tube and at its radial centerline. The details of the first and secondary cavities are captured with a framing rate of 15,000 frames per second by a high-speed video camera (Photron FASTCAM-ultima APX), which is fitted with a Nikkor 60-mm microlens. Backlight is produced by a high-intensity LED lamp. A hydrophone (Reson TC4013) is employed to record the acoustic pressure curve during the experiments, which is placed at the radial center line, two centimeters away from the tube ending. The hydrophone has a frequency range up to 170 kHz, whose output is recorded by an acquisition board (KEYENCE NR-600).

The tubes employed in the experiments have unified interior diameter of $D_t = 6$ mm, and length of $L_t = 110$ mm. All the first bubbles occupy the entire section of the tube, therefore the problem could be considered one-dimensional. The axial position is scaled by $L_t$ into a non-dimensional coordinate $X$, which ranges from 0 to 1. The collapse position of the first bubble is noted as $X_F$. The equivalent maximum radius of the first bubble is noted as $R_e$, which is calculated by assuming a spherical bubble with a same volume.

The acoustic pressure curve is also shown in figure 2. The first pressure pulse “A” corresponds to the low-voltage spark, while pulse “B” is caused by the collapse of the first bubble, 4.17 ms after pulse “A”. From the time interval of 2.88 ms, the third pulse “C” could be attributed to the collapse of the secondary cavitation. After that, the recorded pressure pulses are quickly weakened.

![Figure 1. Sketch of the experimental setup](image-url)
In the experiments, the location of $X_F$ is found to dramatically affect the outcomes following the collapse of the first bubble, especially in the cases of first bubble generated near the axial midpoint ($X_F \to 0.5$) or near the tube endings ($X_F \to 0$ or $X_F \to 1$). Figure 3 shows a case of midpoint spark, where $X_F = 0.49$ and $R_e = 4.44$ mm. The first bubble experiences symmetric expansion and contraction, then it collapses to its minimum volume at 5.07 ms, which is also much longer than the period of 0.41 ms calculated by Rayleigh equation. The following outcomes have obvious difference with that in figure 2, including both secondary cavitation and the rebound cavity. From 5.07 ms to 9.27 ms in figure 3, a single large cavity could be obtained, which has an anomalous shape. Besides this large rebound cavity, secondary cavitation also occurs. As shown in the picture of 5.33 ms, the secondary cavitation appears soon after the collapse of the first bubble. The secondary cavitation locates close to the rebound cavity, and disappears quickly. A similar oscillation period is obtained after the collapse of rebound cavity at 9.27 ms, where a smaller rebound cavity comes out, together with a weaker secondary cavitation around it. The midpoint spark produces more pressure peaks than those in figure 2. Besides, “C”, “D” and other following pulses in figure 3 are all clearly related to the collapse of rebound cavities instead of secondary cavitation, which is similar to the vapor bubble near a wall [11].

Another particular case is a spark near the tube ending, as shown in figure 4, where $X_F = 0.10$ and
$R_e = 4.15$ mm. The first bubble expands and exceeds the left tube ending, forming a ring shaped bubble outside the tube. The secondary cavitation here is asymmetric with the collapse location of the first bubble, which is different from figure 2. The first two time intervals between acoustic pressure pulses are respectively 2.47 ms and 1.66 ms.

4. Discussion
As shown in figure 2 to figure 4, the preliminary results show that the collapse of single bubble in rigid tube could induce a secondary cavitation, which usually locates symmetric with the collapse position of the first bubble (about the midpoint $X = 0.5$). Based on this position correlation, a mechanism of the secondary cavitation could be deduced as follows. The collapse of the first bubble is the energy source of the secondary cavitation, which emits shock wave towards both endings of the tube. Due to the violent section expansion at the tube endings, part of the energy in each shock wave is reflected as an expansion wave. If the wave speed is assumed unified in the entire tube, the expansion waves reflected from the two endings will meet at a certain position, symmetric to the collapse position of the first bubble. This interaction of two expansion waves causes an extremely low pressure at the symmetric position, where secondary cavitation happens. In the present experiments, the shock waves take most collapse energy of the first bubble, which is released to excite the secondary cavitation. Therefore, the rebounding process is obviously weakened.

When a vapour bubble collapses in free field, the strength of its rebounding cycles could be observed from the pressure pulses. However once the violent secondary cavitation appears, it is no longer appropriate to use the frequency of the pressure pulses to evaluate the size of the rebounding bubble. In this case, more energy dissipation during the collapse could lead to a larger interval between the pressure pulses, because that the pulses following the collapse are dominated by the secondary cavitation. The power of the rebound cavity or the secondary cavitation could be judged from the period ratio, i.e. comparison of the first two time intervals between the pressure pulses. In figure 2~4, the period ratios are respectively 0.69, 0.83 and 0.67. Comparing with the common case of figure 2, the tube ending case (figure 4) seems only to affect the position of secondary cavitation, while the strength of that changes slightly. However, the rebound in figure 3 is much stronger, which relates to the unique wave propagation in the case of $X_e \rightarrow 0.5$. The reflected expansion waves in midpoint cases converges just around $X_e$, so the major energy of the shock wave is transmitted back to the rebounding cavity, which could explain the increase of the rebound strength. The irregular shape of the rebound bubble results from the bubble fission during the last stage of the collapse.

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