Gas removal by a spark-generated bubble in a rigid tube

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Abstract

An experimental investigation of the interactions between a spark-generated bubble and a gas slug in a narrow tube is studied. The growth and collapse of the vapor bubble are recorded with the help of high-speed photography. The behavior of the trapped gas slug is affected by the dynamics of the vapor bubble in the rigid tube. In this paper, the complicated interactions of two bubbles are revealed. It is found that the direction of the post-collapse flow depends on the relative position of the vapor bubble in the tube. Likewise, the velocity of gas removal is associated with the relative positions and sizes of the bubbles. The pressure generated by the collapse of the vapor bubble plays an important role in propelling the gas out. At last the directions of the post-collapse flow are summarized. A brief "Pumping effect" in the narrow tube is discussed, which is useful for gas removal in practice. These results may be beneficial for the cavitation applications.

Keywords: spark-generated bubble; gas slug; tube; jet; post-collapse flow

Introduction

Cavitation bubbles have numerous behaviors near different boundaries such as free surface[1, 2], rigid boundary[3], elastic boundary[4, 5], and so on[6]. When a single bubble collapses near a solid boundary, it will produce a collapsing jet. The shock wave and high-speed collapse jet generated by the collapsing bubble are useful for physical and chemical reactions. Cavitation effect is useful for some applications such as surface cleaning[7, 8], extra-corporeal shock wave lithotripsy(ESWL)[9] and drug delivery[10]. With the development of ultrasound technology, the cavitation will be utilized more and more widely. Now removal of particulate is mostly associated with the cavitation implosion. Obstruction removal is another common application for cavitation bubble. Pavard investigated the particle removal effect reinforced by the bubble collapse[11]. The particle in a vertical or horizontal hole is propelled by the pressure which is associated with the expanding and collapsing of the oscillating bubble. The velocity of the solid particle removal is proportional to the stand-off distance. Xu did the similar work[12].

Nevertheless, there is a lot of gas-liquid slug flow in practical fluid systems, such as chemical equipment and hydraulic devices. The gas mixed in the liquid could induce vibration, noise and energy loss. So the gas removal is an important issue in fluid systems. In this study, the collapse jet induced by the spark-generated bubble is used to remove a trapped gas slug in a rigid tube. The correlation between the removing direction and the position of the spark-generated bubble is discussed.

Experimental Setups

The sketching of experimental setup is illustrated in Fig.1. A transparent plexiglass tank of 400mm×200mm×200mm size with an open-top, which is filled up to about 90% with tap water. The water and environment temperatures are maintained at 16℃ ±3℃, and the ambient pressure is kept at 1 atm. A quartz-glass circular tube with 3mm interior diameter and 100mm length is fixed on a rigid holder, which are all submerged in the tap water. In this work, we only consider this case that one large-size gas bubble filling up the section of the narrow tube. The gas slug attached into the tube keeps stable before the vapor bubble occurs. Just like we did before[13], the low-voltage spark method is used to generate the vapor bubble in our present work. This low-voltage circuit includes three capacitors (one of 3300μF and two of 1000μF), a 1KΩ resistor and a 45V±5V DC power. The charging and discharging of the circuit is controlled by a two-position switch. The ends of the wires are fine copper electrodes with 0.2mm diameter. Moreover, the joint point of the electrodes is adjusted along the centerline of the tube. The gas slug is trapped in the narrow tube before the electrodes are placed near it. In our experiments, we submerged half of the tube into water vertically, then rotated the tube to be horizontal and submerged the entire tube into water, so there is a section of gas bubble trapped

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in the tube. Its length and position are adjusted along the axial direction of the tube too. Specially, the gas slug should be kept away from the tube end. Besides, the vapor bubble should not be too close to the tube end and the gas edge. In our present work, the vapor bubble is kept contactless with the gas slug.

In order to record the transient process, a high-speed video camera (Phantom UHS-12 V2512) with a filming rate of 20,000 frames per second is used, which is fitted with a Nikkor 60-mm microlens. The camera is mounted in front of the tank, and a high-intensity LED lamp is placed at the back of the tank. This lamp covered with an oil paper supplies the backlight during the camera working.

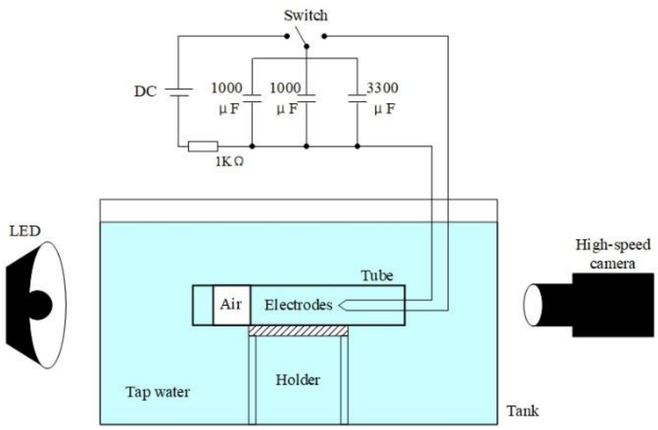

Fig.1 Experimental set-up

The typical schematic diagram of the tube is shown in Fig.2. The gas slug and vapor bubble are all located at the horizontal centerline of the narrow tube. At the moment of the vapor bubble grows to its greatest size, all the gas slug and vapor bubble occupy the cross section of the circular tube. So this case could be considered as one-dimensional motion. In order to evaluate the effect of the positions and shapes of the bubbles, the sketch of parameters is simplified. As shown in Fig.2, L and D represent the length and the interior diameter of the rigid tube respectively. In our experiments, one kind of tube has unified interior diameter of D=3mm, and length of L=100mm. The horizontal length of the gas slug and the vapor bubble are measured as L_A and L_B severally. In order to reduce the effect of the tube end, the gas slug and vapor bubble should be kept away from the tube-endings. We define the leftmost tube center as the origin point. X_A is the distance from the original point to the center of the gas slug. The length between the collapse point of the spark-generated bubble and the original point is noted as X_B. We ignored this slight shift of the collapse point away from the spark point because of the pumping effect and transformation of the gas slug. Because of the tube is horizontal and narrow, so we ignored the gravity.

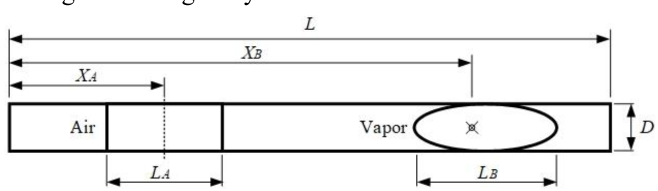

Fig.2 Sketch and parameters

Results

Obviously, the growth and collapse of the vapor bubble could induce the deformation of the gas slug. Fig.3 shows two typical sequences of the interactions between a vapor bubble and a gas slug in a rigid tube. The vapor bubble is generated at T=0ms when the capacitor voltage is applied to the electrodes. In Fig.3(a), it reaches its maximum size at 1.15ms, and then it collapses at 2.3ms. During the course of the expansion of the vapor bubble, the gas slug contracts until the vapor bubble stops expanding. The axial length of the gas slug decreases from 27.3mm to 25.7mm approximately. Conversely, the gas slug expands in the course of the contraction of the vapor bubble. The secondary cavitation occurs at 2.35ms following the collapse of the vapor bubble. The results show that the multiple oscillations of the vapor bubble induce the expansion and contraction of the gas slug repeatedly. At last the post-collapse flow moves to left from 3.6ms to 61.5ms in Fig3(a). The average velocity of the post-collapse flow is about 0.41m/s.

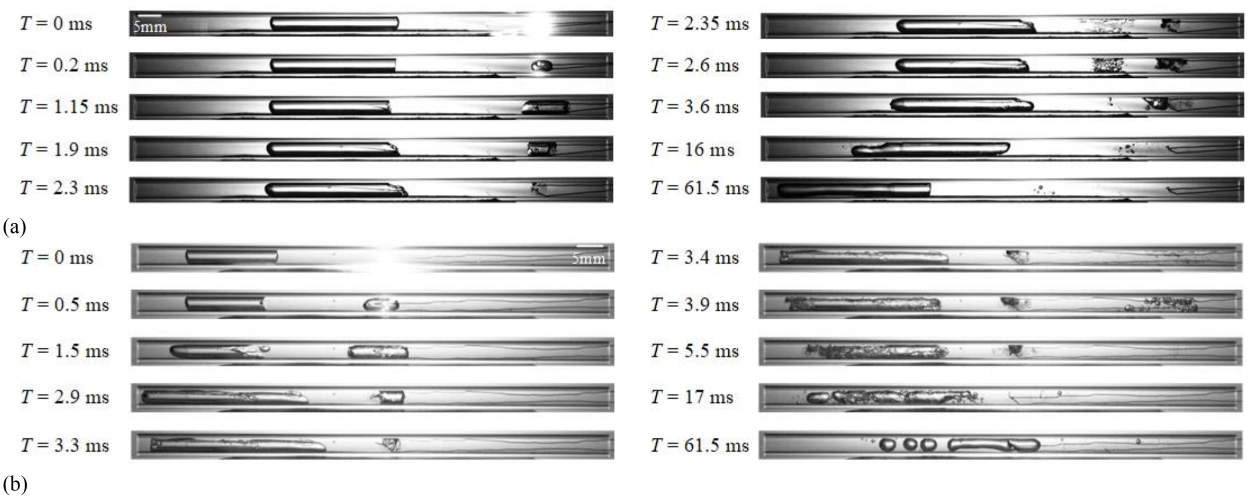

Fig.3 Gas removal by an oscillating bubble in a rigid tube. (a. The whole liquid moves towards left. b. The whole liquid moves towards right.)

Fig.3(b) shows another case where the electrodes are placed at the center of the tube. The spark-generated bubble grows to its maximum size at 1.5ms. Afterwards its left side contracts faster because of the expansion of the gas slug. Its two sides impact each other at 3.3ms. Then the gas slug expands to its maximum size at the time of the vapor bubble collapsing. Whereafter, the secondary cavitation also occurs at the same symmetric position in the tube at 3.4ms. At last the whole liquid in the tube moves rightwards after the vapor bubble collapsed. We measured that the speed of the gas removal is about 0.42m/s.

In conclusion, just like one spark-generated bubble in a rigid tube[13], secondary cavitation occurs at the same symmetric position. The gas slug edge and tube end form the new boundaries where the water-hammer shock wave is reflected. There are three types of the direction of the post-collapse flow in the tube. The three directions are moving leftwards, moving rightwards and stagnation respectively.

Discussion and Conclusion

The experimental results show that the growth and collapse of a single spark-generated bubble could induce post-collapse flow and secondary cavitation in a rigid tube. Obviously, the secondary cavitation is caused by the propagation of the pressure wave just like the results in our previous work[13, 14]. In particular, the gas slug edge and tube end form the two reflection boundaries. One-dimensional model[15, 16] is used to explain the dynamics of the cavitation bubble and gas slug. After the collapse of the spark-generated bubble, the post-collapse flow direction is based on the collapse position of the oscillating bubble. Fig.4 shows the flow directions after the oscillating bubble collapsed. The red circle represents the case of flowing towards the right, and the black square means that the flow direction is from right to left. There is a stagnated flow between moving leftwards and rightwards. The blue triangle representing the flow stagnation is between the two conditions. The blue dash line ($X_R = 0.6\,X_L$) is the fitted line. In order to distinguish the different flow directions, we define two non-dimensional parameters $X_L = \frac{X_B - L_A}{L}$ and $X_R = \frac{L - X_B}{L}$. The length of the gas column is subtracted when calculating the liquid impacting. As shown in Fig.4, the post-collapse flow moves to the right when $X_R > 0.6\,X_L$. Inversely, it will move to left in the case of $X_R < 0.6\,X_L$. Note that there is a large size of the gas slug in the case of $X_L \to 0$.

The gas removal in a rigid tube is induced by the pumping effect. Torniainen[17] studied the characteristics of the net flow induced by the vapor bubble. We will reference the similar method to study the dynamics of spark-generated bubble.

When a bubble collapses in a tube filled with a gas slug, the collapse pressure could impel the net flow. As a method of gas removal, cavitation bubble is useful and efficiently.

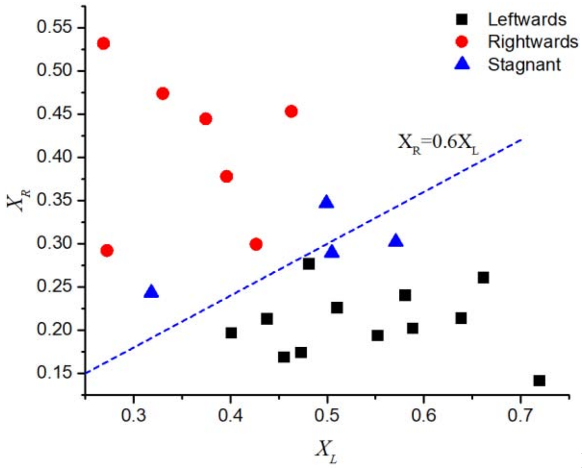

Fig.4 Flow direction after the collapse of the spark-generated bubble

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