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Interactions between two oscillating bubbles in a rigid tube

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ABSTRACT

The interaction phenomena between two oscillating vapor bubbles in a rigid narrow tube is studied using a high-speed video camera. The bubbles are generated by low-voltage electric sparks in water held by glass tubes of various inner diameters (6 mm, 8 mm and 10 mm). The bubbles not only deform greatly during the first oscillation period, but also induce a liquid flow in various directions after their collapse. The interaction phenomena are summarized in two aspects: four kinds of deformation interactions and three different directions of the post-collapse flow. Moreover, the key factors affecting the interaction are discussed in detail. It is found that the deformation phenomena are mostly dependent on the phase difference. The threshold of the blocking effect is also discussed, which has a significant influence on the post-collapse flow's direction. In order to identify the cases of stagnation, a simple momentum model is presented.

1. Introduction

Vapor bubbles formed due to the variation of local pressure or temperature play an important role in many industrial and clinical areas. It has been discovered that the collapse of the bubbles is one of the most important causes of erosion, vibration and noise in turbo machineries and hydraulic systems [1]. Except for the undesirable effects, cavitation bubbles can also be employed for good use in some applications, such as droplet ejector, surface cleaning, clinical therapy and drug/gene delivery [2,3]. Almost all applications of cavitation are closely associated to the collapse behavior of the bubbles, which has been investigated by many researchers for about 100 years. Pioneered by Rayleigh [4], early researchers focused on a single bubble oscillating in a free field, whose expansion and contraction are symmetric. Later investigations benefit from the development of high-speed photography, allowing the bubble dynamics to be observed in detail [5]. The surrounding conditions have been confirmed to be a decisive factor for bubble behaviors. A famous example is a single oscillating bubble near a rigid surface, which is found to develop a liquid jet towards the surface by both experimental and numerical investigations [6].

One of the surrounding boundaries of interest is the narrow tube, which is a common case in oil transportation, marine engineering, micro-fluidics and clinical applications. Yuan [7] numerically studied the inertia-driving growth and collapse of a vapor bubble in a tube, based on potential flow. It was found that the maximum volume and lifetime of the bubble depended on the initial pressure and the channel geometry. Ory [8] developed the calculation using incompressible viscous N–S equation, finding that a net flow developed when the bubble was not located at the midpoint of the tube. Lately, this pumping effect was studied by Yin [9], Torniainen [10] and Kornilovitch [11], focusing on the development of a one-dimensional model to predict the net flow rate. Besides the pumping effect, researchers were also interested in the bubble deformation and the jet produced by the collapse. Shervani-Tabar [12] numerically investigated the dynamics of a discharge-induced vapor bubble in a vertical rigid tube, by a boundary integral method. They depicted that the bubble elongated in the axial direction during the growth phase, and two broad liquid jets directed inward were developed during the collapse. Ni [13] studied the collapse behavior of a bubble in rigid narrow tube by means of both experiment and simulation. Their simulation went on after the jets contacted, which showed that a toroidal bubble formed at the end of the collapse, afterwards a ring-shaped jet was generated pointing towards the tube wall. On the bubble collapse in an elastic tube, a coupled FEM and BEM code for simulation was developed by Miao [14], describing the typical bubble–tube interactions and stresses. Coralic [15] studied shock-induced collapse of a bubble inside a deformable vessel, whose results showed that a 40 MPa shockwave to collapse the bubble generated a vessel wall pressure of almost 450 MPa, inducing an invagination of nearly 50% of the initial vessel radius on a 10 ns timescale. The most recent work on this topic was put out by Farhangmehr [16], who studied the dynamics of a single bubble in a rigid cylinder with compliant coating. Using boundary

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integral simulations, it was found that the confinement of the cylinder greatly increased the lifetime of the bubble and influenced its behavior.

Besides the surrounding boundary condition, the interaction between bubbles in the vicinity also affects the collapse behavior distinctly. The bubble behavior becomes much more complicated when a second bubble is induced nearby. Fong [17] described the interaction between two similarly sized bubbles in a free field, while the case of two differently sized bubble were studied by Chew [18]. In most cases, it was found that two jets were developed by the two bubbles respectively, which could be directed towards or away from each other. Otherwise, the two bubbles might merge into one single bubble, or experience a special collapse process which was named as “catapult” by Chew [18]. The dimensionless separation distance, the phase difference and the ratio of size difference were considered as main factors to determine the behavior of the bubble interaction. Moreover, the bubble–bubble interaction will become more complicated if a nearby boundary is introduced. The cases near an elastic membrane and near a rigid boundary were summarized by Aghdam [19] and Chew [20], respectively. According to their results, the bubbles might develop liquid jets towards each other or towards the nearby surface, while in some cases the jets were oblique. The direction of liquid jets could be affected by the boundary, by the adjacent bubble, or by both.

Literature shows that both a rigid tube and the bubble–bubble interaction have unique influence on the bubble behavior, while few work reported the dynamics of two nearby bubbles in a narrow cylinder space. The present experimental work aims to study systematically the interaction between two vapor bubbles in a rigid tube. We intent to characterize the phenomena of liquid jet during the contraction process and after the disappearance of the bubbles, respectively. The combined effects of the cylinder wall and the bubble–bubble interaction are discussed, while the key factors are found to be the nondimentional distance between the bubbles, the phase difference of collapse, the axial positional relationship of the bubbles, and the relative interior diameter of the tube.

2. Experimental setup

The schematic representation of the experimental setup is shown in Fig. 1. The bubbles are generated by low-voltage electric spark method, which is proposed by Turangan [21]. The circuit used to produce spark consists of a 50 V power source (SAKO SK1761SL2A), two pairs of electrodes (fine copper wires of 0.26 mm), three capacitors (3300 μF × 1, 1000 μF × 2) and a resistance of 1 kΩ. The electrodes are placed in a glass tube, which is fixed in a rectangular plexiglass tank ($400 \times 200 \times 200\ \text{mm}^3$) holding tap water. The liquid and laboratory temperature are maintained at 25 °C ± 2 °C, and the environment pressure is kept at 101.3 kPa. In order to capture the details of the collapse, a high-speed photography system is used, which is similar to the apparatus applied in our past work [22]. The pictures are captured by a high-speed video camera (Photron FASTCAM-ultima APX), fitted with a Nikkor 60-mm microlens. Backlight is produced by a high-intensity LED lamp. The oscillation of the bubbles is captured with a framing rate of 15,000 frames per second.

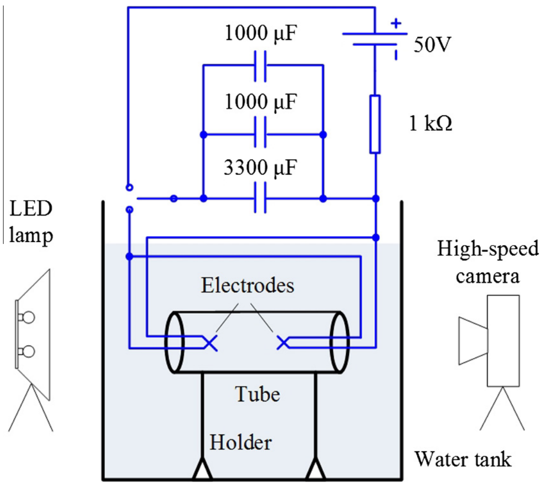

Fig. 1. Experimental setup.

In the present study, the two pairs of electrodes are separately placed in the left and right half of the tube. The contact positions of the electrodes are carefully adjusted to be at the radial centerline of the tube. Three different tubes are employed in the experiments, whose interior diameters D_t are 6, 8 and 10 mm, with lengths of $L_t = 80$, 120, 120 mm respectively. The key parameters in the experiments are shown in Fig. 2. The bubble generated first is named as bubble 1, while the other one is bubble 2. In the cases where the sparks are generated simultaneously, the bubble collapses first is bubble 1. The maximum axial length is used to represent the size of the two bubbles, respectively marked as $L_{\max1}$ and $L_{\max2}$. The initial positions of the two sparks in the tube could be obtained from the parameters of L_1, L_2 and S, as shown in Fig. 2(a). The length parameters are measured from the pictures of high-speed photography, with a maximum uncertainty estimated as 0.02 mm. As shown in Fig. 2(b), t_{s1} and t_{s2} represent the timing when the two sparks are generated, while t_{c1} and t_{c2} are the timing when the two bubbles collapse to the minimum volume.

3. Interaction phenomena of two bubbles in a tube

As reported by Chew [18], the most obvious bubble–bubble interaction is the liquid jets developed in various directions, which is also the key phenomenon which we focus on here. The typical interaction phenomena are depicted in this section, as shown in Figs. 3–7. The initial time $t = 0$ ms is set to represent the appearance of the first electric spark in all the figures. Moving black particles can be observed after the collapse of the bubbles, which are the remnants of the burnt copper electrodes and small bubbles. The particles could help the flow visualization, while they have minimal influence on the bubble behavior because of the negligible weight.

Fig. 3 shows the coalescence of two bubbles in a tube. The initial positions of the sparks are demonstrated in the picture of 0 ms. Two sparks are generated at the same time with a small distance. During the following expansion, the left bubble develops into an ellipsoid shape, while the right bubble is contorted due to the extrusion from the left side, forming a rightward jet as shown in the picture of 1.00 ms. The right bubble reaches its maximum volume at 1.60 ms, when it is absorbed into the left bubble. The left bubble begins to contract from 2.60 ms, and coalesces with the right bubble at the same time. Two broad liquid jets are developed during the collapse of the merged bubble, as shown at 3.53 ms. The first oscillation period of the merged bubble ends at 4.33 ms, then a rebound is observed in the form of a gathered cluster of cavities, which collapses again at 7.87 ms. This case shows that, the behavior of the merged bubble after the coalescence is similar with a single bubble in a tube.

Fig. 4 shows a case where the distance between the bubbles is larger. Both two bubbles are generated at 0 ms, expanding to their maximum size at 1.80 ms. The bubbles contract firstly from the