Experimental Thermal and Fluid Science 44 (2013) 108–113

Contents lists available at SciVerse ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Interaction of two oscillating bubbles near a rigid boundary

Lup Wai Chew [a], Evert Klaseboer [b], Siew-Wan Ohl [b], Boo Cheong Khoo [a,c,*]

[a] Department of Mechanical Engineering, National University of Singapore, Kent Ridge, Singapore 119260, Singapore
[b] Institute of High Performance Computing, 1 Fusionopolis Way, #16-16 Connexis, Singapore 138632, Singapore
[c] Singapore-MIT Alliance, 4 Engineering Drive 3, Singapore 117576, Singapore

ARTICLE INFO

Article history:
Received 20 December 2011
Received in revised form 15 May 2012
Accepted 6 June 2012
Available online 15 June 2012

Keywords:
Oscillating bubble
Cavitation
Bubble collapse
Liquid jet
Bubble dynamics

ABSTRACT

Oscillating bubbles or non-equilibrium bubbles are known to induce the development of liquid jets in the presence of a nearby rigid boundary. The liquid jets can be useful in many applications such as surface cleaning and drug delivery into biological cells. Single bubble oscillation near a rigid boundary has been studied in detail in the literature. In this paper, we extend the research in this area to a two-bubble system near a rigid boundary using high speed photography. Various measurements on the direction of the (bubble-collapse induced) water jets were performed. We identified the parameter sets where the influence of the adjacent bubble and the rigid boundary is important. The experimental results are summarized in a graph that enables easy prediction of the direction of the water jets induced by bubble collapse near another bubble and a rigid boundary.

1. Introduction

The study of bubble dynamics was pioneered by Lord Rayleigh [1]. Oscillating (non-equilibrium) bubbles, as commonly encountered in many industrial applications, are usually small in size (in the order of millimeters) and have a short oscillation period (in the order of milliseconds). This rendered direct observation of such bubbles difficult in the past. In recent decades, however, the development of high speed photography has allowed the bubble dynamics to be captured and studied in greater detail [2–5].

Literature shows that a single bubble oscillating in a free field (infinite volume of fluid) will expand to a maximum volume before collapsing/contracting spherically [6] provided that gravity effects are negligible. If a free surface such as an air–water interface is introduced nearby, the collapse of the bubble will develop a liquid jet which is directed away from the free surface [7,8]. On the other hand, the collapse of a bubble near a rigid surface will develop a liquid jet which is directed towards the rigid boundary [9,10]. The bubble behavior becomes much more complicated when a second bubble is created near the first bubble as the second bubble will influence the dynamics of the first bubble. Fong et al. [11] summarized the interaction between two similarly sized bubbles while Chew et al. [12] summarized the interaction between two differently sized bubbles in a free field. They reported that the collapse of two bubbles can induce the development of two water jets (one jet from each bubble) which can be directed towards or away from each other. The induced liquid jets have several applications such as surface cleaning [13] and removal of particles from holes [14]. The understanding of bubble behavior is useful in mitigating or preventing cavitation erosion [15].

The complexity of the bubble behavior becomes imminent when two or more bubbles are placed near to a rigid boundary [16], and the induced liquid jet(s), if any, are likely to be dependent on the distance between the two bubbles, as well as the distance from the rigid boundary. This paper aims to study systematically the combined effects of the nearby rigid boundary and the adjacent oscillating bubble on the induced liquid jet(s) and the associated flow dynamics.

2. Experimental setup

Fig. 1 shows the experimental setup which is similar to the setup in Lew et al. [5] and Chew et al. [12], except that the water tank used is larger (30 cm × 30 cm × 30 cm) and the two pairs of electrodes are placed near the acrylic plate to create two bubbles near a rigid boundary. The electrodes used are fine copper wires of 0.2 mm in diameter. To minimize possible interference from the electrodes on the bubble oscillation, the bubbles created are ensured to have a maximum diameter 20 times larger than the electrodes. The main circuit consists of a 60 V power source, a 1 kΩ resistor, capacitors with total capacitance of 5500 μF and a switch. The bubble oscillation is captured using a high speed camera

* Corresponding author at: Department of Mechanical Engineering, National University of Singapore, Kent Ridge, Singapore 119260, Singapore. Tel.: +65 65162889.
E-mail address: mpekbc@nus.edu.sg (B.C. Khoo).

0894-1777/$ - see front matter © 2012 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.expthermflusci.2012.06.003

Nomenclature

t	time (ms)	$\gamma_{s,i}$	dimensionless distance bubble i and the rigid boundary
d	distance between two bubbles (mm)	$R_{\max,i}$	maximum radius of bubble i (mm)
d_s	distance between a bubble and the rigid boundary (mm)		
γ	dimensionless distance between two bubbles		

(Photron Fastcam SA1.1, framing rate 20,000 frames per second). The setup is illuminated from the back (backlighting) using a 250 W metal halide light source (Iwasaki Electric) diffused through a piece of translucent paper. The medium used is tap water at room temperature and the rigid boundary is an acrylic plate (10 mm in thickness) fixed to the bottom of a water tank. The spark discharge approach is used to create bubbles in the water with the electrodes touching each other. In this work, two bubbles are generated simultaneously, and the sizes of the bubbles are independent of each other. The spark discharge method has the advantage to precisely control the bubble nucleation spot but the maximum size of the bubbles cannot be controlled accurately. We have repeated our experiments to generate sufficient number of data points to cover a wide range of bubble sizes. Fig. 2 shows the orientation of the bubbles with respect to the rigid boundary. The bubbles generated have maximum radii, $R_{\max,1}$ and $R_{\max,2}$, which are between 2.0 mm and 6.2 mm. The separation distance between the two bubbles, d, and the separation distance between the bubbles and the rigid boundary, d_s, are varied. The line connecting the centers of the bubbles is parallel to the rigid boundary. Within a range of inter-bubble and bubble-wall distances, the two bubbles will induce two water jets upon their collapses.

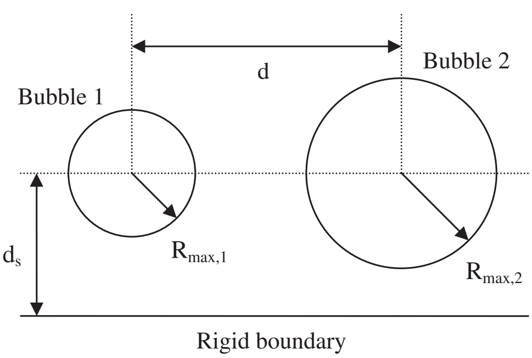

Fig. 2. Schematic showing the definition of the distance between two bubbles, d, and the distance between the bubbles and the rigid boundary, d_s. Both bubbles are aligned with the (flat) stationary rigid boundary.

3. Interaction of two bubbles near a rigid boundary

This section depicts selected experimental results with different jetting phenomena in Figs. 3–7. Fig. 3 shows the oscillations of a pair of bubbles where both water jets are directed towards the rigid boundary. The rigid boundary (acrylic plate) is located 4.42 mm below the bubbles. Although it is not shown clearly as it is out of the focal plane of the high speed camera, the rigid boundary can still be located as the plane where the water jets impact after hitting the boundary. Time, t, in each experiment is set to $t = 0$ at the first appearance of the bright sparks from the discharge of electrical energy from the main circuit. The surface of the bubbles can be clearly distinguished as dark spheres against the brighter background. Both bubbles then expand as shown at $t = 0.25$ ms until the left bubble reaches its maximum volume at $t = 0.60$ ms. It then starts to shrink in size and finally collapses at $t = 0.95$ ms. The remnants of the bubble and the burnt electrodes serve as black particles that aid flow visualization. The collapse of the left bubble develops a water jet directed vertically downward to the rigid boundary. The right bubble at a distance 16.68 mm away seems to have no influence on the direction of the water jet of the left bubble. The right bubble reaches its maximum size at $t = 0.95$ ms and eventually collapses at = 1.60 ms. The water jet developed is also directed vertically downward to the rigid boundary. Hence, in this case, both bubbles are considered to be affected only

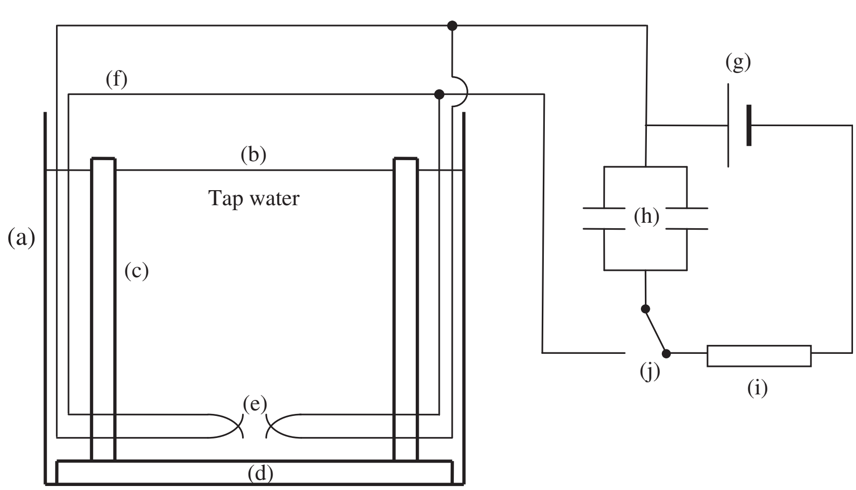

Fig. 1. The experimental setup. The 30 cm × 30 cm × 30 cm acrylic water tank (a) is 80% filled with tap water (b). The acrylic pillars (c) are supported by an acrylic plate (d) which is fixed to the bottom of the water tank. The electrodes (e) used to generate bubbles are connected to the main circuit through insulated wires (f). The main circuit consists of a 60 V voltage source (g), capacitors in parallel with total capacitance 5500 μF (h), a 1 kΩ resistor (i) and a two-way switch (j).