Experimental Thermal and Fluid Science 60 (2015) 299–307

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Experimental study on the dynamics of an oscillating bubble in a vertical rigid tube

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ARTICLE INFO

Article history:
Received 26 April 2013
Received in revised form 5 June 2014
Accepted 29 September 2014
Available online 14 October 2014

Keywords:
Oscillating bubble
Rigid tube
Toroidal bubble
Jet
Eccentricity

ABSTRACT

In this experimental investigation, the spark-generated bubble dynamics inside a vertical rigid tube (cylinder) filled with water is studied using high-speed photography. It is observed that, for all cases, the bubble behavior is influenced to some extent by the proximity of the tube walls. The presence of the tube greatly increases the bubble lifetime and the buoyancy plays an important role. The bubble center moves upwards at the first stage of the growth phase due to the buoyancy. The buoyancy also leads to the formation of an initially upward (first) jet originating from the bottom part of the bubble. The first stage of bubble contraction or collapse phase depicts the flattening of the top part of the bubble. A (second) jet is then initiated and it develops downwards; the bubble becomes toroidal and impacts on the bubble's bottom surface. As the two jets develop respectively in the growing and collapsing phases of the bubble evolution, the absolute velocity of the rising jet is higher than that of the downward jet. We also consider the change in the bubble dynamics when it is placed off the center of the tube (with eccentricity).

1. Introduction

In hydrodynamic cavitation, bubbles or cavities, which are filled with vapor, gas or a mixture of both, may emerge in the initially homogeneous liquid as the surrounding pressure is reduced below the saturated vapor pressure. This kind of cavitation has been known as one of the most important causes of erosion, efficiency reduction, generation of excessive vibration, noise and other mechanical damages in the hydraulic machineries. Many scientific works have been done to investigate these undesirable effects [2]. The bubble usually contracts or collapses asymmetrically because of the proximity to rigid boundaries or a free surface. The collapse is accompanied by a high-speed jet. The jet originates on the bubble boundary, which is farthest away from the rigid surface and penetrates the bubble and impacts on the bubble surface closest to the rigid surface. Destructive effects of cavitation aside, this phenomenon can also be harnessed for good use in some industrial applications such as supercavitating flow for the reduction of hydrodynamic drag [13] and surface cleaning [25]. The collapsing bubbles are also useful in biomedical applications such as kidney stone shock wave lithotripsy [14,5], in drug and gene delivery into biological cells by enhancing the permeability of the cell membrane [26], and tumor and cancer therapy [27]. In the cardiovascular treatment, the dynamics of ultrasonically excited bubble in a blood vessel is critical [6,7,4]. This motivates our much simplified study of a single oscillating bubble in a rigid tube because some of the underlying physics are relevant.

A number of works were on the effect of viscoelasticity on a rising gas bubble [19,28]. Lind and Philips [19] predict that the dynamics of bubbles rising in a viscoelastic liquid are characterized by three phenomena: the trailing edge cusp, negative wake, and the rise velocity jump discontinuity.

While the dynamic evolution of a bubble in an infinite fluid domain in the vicinity of rigid, free, and flexible surfaces has been widely studied numerically and experimentally [17,31,32,16,11,12], the dynamic behavior of a bubble in the bounded fluid domain, for example, a tube is comparatively less investigated in the literature [20,21,23]. The dynamics of a laser-generated vapor bubble inside microtubes was studied both experimentally using a high-speed image recording technique, and theoretically via comparison of two theoretical models (one pure inertia-driven model neglecting the thermal effects based on a discontinuous time dependence of vapor pressure inside the bubble and another based on heat transfer in addition to inertia and viscous friction) by Sun et al. [29]. They found that due to important role of thermal effects on the bubble behavior, the second model is more effective in capturing its evolution. The natural and forced frequencies of the

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http://dx.doi.org/10.1016/j.expthermflusci.2014.09.017
0894-1777/

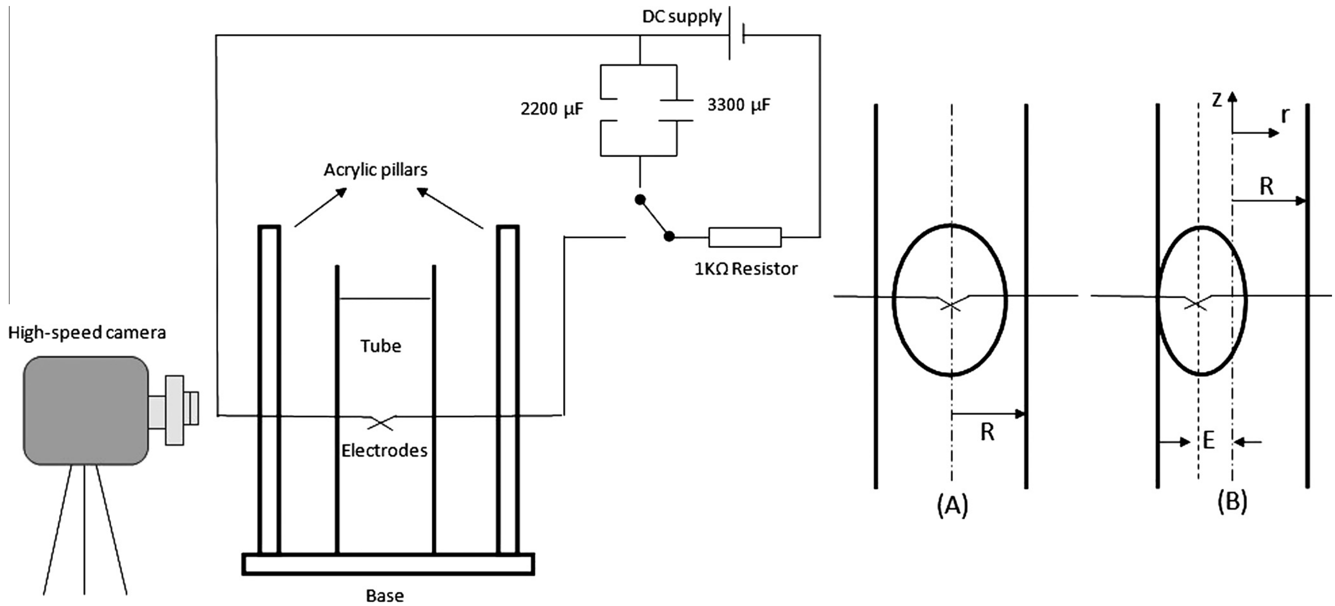

Fig. 1. Schematic representation of the experimental set-up. A rigid tube of 180 mm height and 7.87 mm is filled with tap water to a height of 170 mm measured from the bottom of the tube and used in experiments. The high-speed camera operates at the filming rate of 25,000 frames per second. Two parallel capacitors are charged with a DC power source. Using a two-way switch, the capacitors are then short circuited through a pair of electrodes to create a bubble at the height of 90 mm above the tube bottom. The bubble is generated (A) at the center of tube and (B) off the center of tube. R, R_{max} and E are the tube radius, the maximum radius of bubble and the bubble eccentricity. z and r are the axial and radial directions.

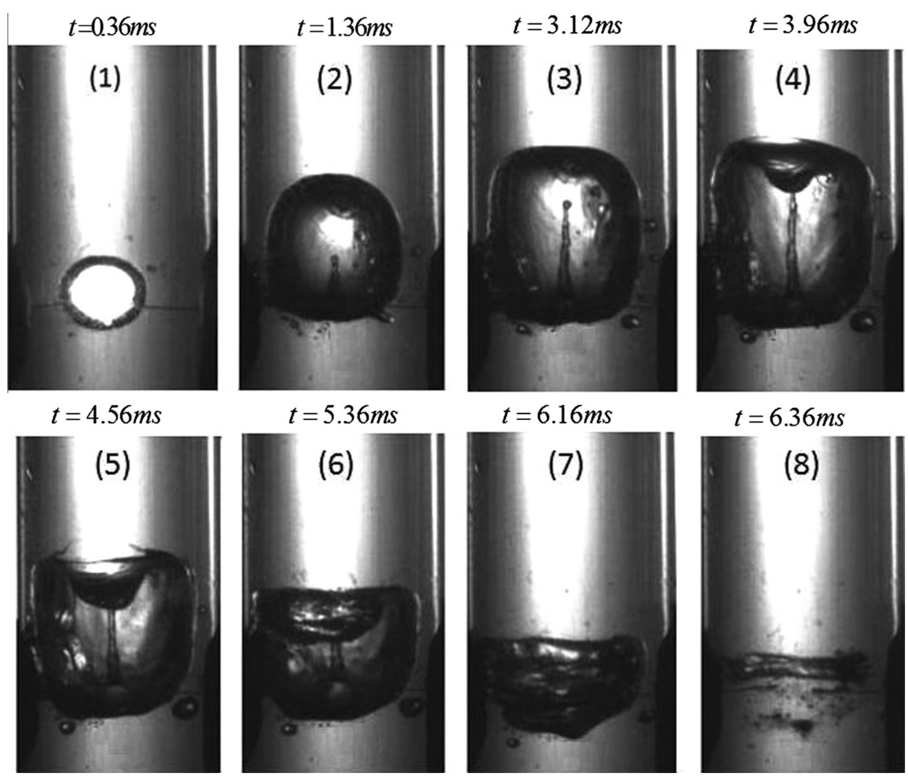

Fig. 2i. Bubble dynamics inside a vertical rigid tube without the eccentricity for λ = 1.17. The bubble grows and collapses axisymmetrically. Growth phase: frames (1)–(4) and collapse phase: frames (5)–(8).

volume oscillations of gas bubbles in viscous and inviscid fluid-filled tubes were studied experimentally and numerically by Oguz and Prosperetti [24] and Geng et al. [10]. Miao et al. [22] simulated the response of an acoustically excited bubble centered within a deformable microtube using an axisymmetric finite element code coupled to a boundary element code to explore potential damage mechanisms. Koita et al. [15] studied experimentally the behavior of a bubble generated by high voltage electronic discharge in a rectangular tube and its interaction with water free surface considering the effects of the voltage and the depth of the discharge.

However in all these previous experimental works due to the very small size of bubbles employed in the microtubes, the surface