Experimental Thermal and Fluid Science 92 (2018) 46–55

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

A novel water hammer device designed to produce controlled bubble collapses

Juan M. Rosselló[a,c,*], Raúl Urteaga[a,d], Fabián J. Bonetto[a,b,c]

[a] Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina
[b] Comisión Nacional de Energía atómica, Centro Atómico Bariloche, Río Negro, Argentina
[c] Laboratorio de Cavitación y Biotecnología, Instituto Balseiro – Universidad Nacional de Cuyo, Río Negro, Argentina
[d] Instituto de Física del Litoral (IFIS – Litoral), Santa Fe, Argentina

ARTICLE INFO

Keywords:
Water hammer
Forced bubble collapse
Magnetic actuator

ABSTRACT

In this work, a novel prototype of a water hammer device designed to produce controlled collapses of a single cavitation bubble is presented. It employs a new driving method in which a laser generated bubble is initially expanded and subsequently compressed using an electromechanical piston. It brings the possibility of reaching high energy concentrations in the collapses and allows the independent control of the most relevant system parameters. In this way, a higher control over the bubble dynamics is obtained compared to the typically reported in acoustically driven systems, laser cavitation or a conventional water hammer. This device constitutes a proof of concept in a series of low energy trials performed using glycerin and phosphoric acid as working liquids. Simulations of the bubble dynamics for prototypical cases were performed in order to extend the experimental results. We found that the most relevant parameter related to collapse strength is the expansion ratio, i.e. the radius of the expanded bubble (before compression) over the equilibrium bubble radius. The results clearly indicate that this driving strategy has a great potential to produce high energy bubble collapses.

1. Introduction

The experimental study of strongly collapsing cavitation bubbles is still a very interesting and challenging subject [1]. Despite recent advances in non linear bubble dynamics related to the amount of energy concentrated on the bubble collapse [2–4], there is still potential to increase the compression ratio in order to achieve a higher temperature plasma (e.g. of hundred thousand degrees).

The use of a focused laser pulse to “seed” bubbles in a fluid has become a standard technique in cavitation studies due to its versatility of application in different types of experimental set ups [3,5–16]. Laser-induced bubbles (LIB) can be generated either in a static pressure liquid environment [7,9,17], immersed in a stationary sound pressure field [19–21], or in a system with transient pressure variations [22]. In the first case, the abrupt expansion of the gas volume induced by the laser pulse heating is followed by a inertial collapse, strong enough to generate luminescence pulses. As described in studies from Ohl, Wolfrum and Li [5,8,15], experiments performed in water showed a strong dependence on intrinsic parameters of LIB bubbles, such as the equilibrium radius (R_0), the maximum radius (R_{max}), the collapse time (t_c), the mechanical energy density and the intensity of the light pulses (I_L), with the static pressure (p_0) and the laser pulse energy.

The shape stability of LIB bubbles is limited in cases with laser pulse energies above a certain threshold. Also, the initial laser pulse anisotropy [23] and the large radius of LIB bubbles influence their shape stability. Under these circumstances, viscosity and surface tension effect is not sufficient to stabilize the interface before collapse, thus surface waves are developed causing bubbles to break during collapse due to the Rayleigh–Taylor instability (RTI) [6,7].

One way to improve bubble collapse intensity was found in a phenomenon known as “water hammer” [24]. In this process, the collapse of one or more bubbles is forced by a sudden increase of the pressure of a liquid column (containing the bubbles), produced by an abrupt arrest of the fluid (Joukowsky’s pressure). When the phenomenon is violent enough, the compressed bubbles can emit high-intensity light pulses. In recent years, devices based on this technique have been studied using different fluids [2,25]. In those where sulfuric acid or phosphoric acid were used, the emitted light intensity was of up to five orders of magnitude higher than when water was used [25]. A relevant aspect of these systems is that the dynamics of the bubbles is governed by the hammer dynamics [26]. This implies that, as it occurs in acoustic-driven bubbles, it is impossible to modify the experimental parameters

---

[*] Corresponding author at: Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina.
E-mail address: jrossello@cab.cnea.gov.ar (J.M. Rosselló).

https://doi.org/10.1016/j.expthermflusci.2017.11.016
Received 22 June 2017; Received in revised form 12 October 2017; Accepted 19 November 2017

independently without disrupting the balance that keeps bubbles emitting light. Besides, the shock and rarefaction waves developed in the liquid column induce the appearance of multiple bubbles absorbing a significant part of the available mechanical energy. Also, the fluid movement and the proximity of the bubbles to the tube wall cause a deformation from the spherical shape of the bubbles [11,27] leading to bubble rupture due to the shape instability (RTI). Moreover, in this type of design the displacement of the bubbles together with the hammer tube makes it difficult to acquire the temporal evolution of the bubble radius ($R(t)$). In order to achieve strong collapses and high temperature plasma in liquid hammer-type systems, large accelerations of the liquid column are required, thus its inertia (added to the one of the mechanical device) poses a major technical challenge. Recently, Ramsey et al. [3] produced luminescence from the rapid compression of a bubble in water by means of piezoelectric actuators. In this study, the bubble was compressed to its the minimum radius (R_{min}) from its ambient radius. Considering that the mechanical energy density developed in the collapse is proportional to $(R_{max}/R_{min})^3$, the expansion of the bubble prior to its collapse is a key factor to upscale the energy concentration.

In acoustically driven systems like sonoluminescence (SBSL), the periodic oscillations of the bubbles are commonly affected by a positional instability, which imposes an upper threshold in the applied acoustic pressure, a spatial instability, which produces moving-bubbles in viscous liquids, and a parametric shape instability. These factors impose a limit in the focused energy and also interfere with the measurement process.

In this work we present an alternative approach to the traditional liquid hammer, designed to produce and study controlled bubble collapses, with the potential to overcome the limitations mentioned above. The primary objective of this prototype is to establish a new methodology to achieve strong collapses of a single bubble with a energy concentration higher than those reported so far in SBSL, by independently controlling fundamental bubble parameters, namely R_{max},R_0, the expansion and compression pressures (p_0^{min} and p_0^{max}) and t_c. In what follows, we will refer to as *Single forced bubble collapse* (SFBC) to the particular case in which a bubble is expanded by a negative pressure (traction applied to the liquid) and then suddenly compressed boosting its collapse. In SFBC experiments both the liquid and the bubble remain fixed during a single collapse. The main advantages of this design are the ability to control a significant number of parameters in a completely independent way, and the absence of positional instability and spatial instabilities, features not present in the water hammer devices reported to date.

2. Experimental method

In this section, the design, construction and characterization of the SFBC device are presented. It works in three stages. Initially, a bubble is seeded by laser cavitation into the interior of a expansion/compression chamber. Then it is expanded through the traction generated by a piston acting on the liquid and finally, a sudden compression of the fluid is achieved by hitting the piston with a projectile, inducing the bubble collapse.

2.1. Description of the SFBC prototype

A detailed description of the experimental device is presented in Figs. 1 and 2. The centerpiece consisted of a Pyrex glass tube filled with liquid, sealed by two stainless steel pistons (304L) mounted at both ends of the tube. These pistons could be displaced through the tube to exert a traction or compression force onto the fluid. One of the pistons was fixed to an optical table (from now on the “lower” piston). The second one (“upper” piston), could be moved vertically producing a pressure variation inside the cylindrical vessel. The driving force (~ 80 N) was generated by a electromagnetic actuator and transmitted to the upper piston through a series of permanent magnets (NdFeB) (as shown in Fig. 1). The axial force exerted by the actuator coil could be both attractive or repulsive, and its driving signal of an arbitrary shape. The position of the upper piston was determined by using an infrared photosensor (see Fig. 1 (c)). The magnetic rod (10 cm long, 238 g of mass) had a pattern of grooves designed to avoid the loss of energy by inductive effects. In Fig. 1(a) and (b) and Fig. 2 a detailed view of the device structure is shown. The latter was assembled with four triangular plates of 26 cm in its sides with a circular hole of ~ 6 cm in diameter in their centers (see Fig. 1(b)). The plate holding the actuator coil was made of plywood in order to avoid the formation of eddy currents on it.

The magnetic actuator coil was powered with a brand *Bosch S455D* battery (Max. curr. CA = 620 A, Energy 55 A h, Volt. 12.6 V_{CC}, Resistance $R_{Batt} \approx 9\,\text{m}\Omega$). This type of energy source has a high discharge velocity, which makes it suitable to generate high current pulses with a short actuator response time (~ 2.5 ms), which is the time it takes for the electromagnet to produce the maximum force over the magnetic rod detached from the piston head. The control hardware was an electronic switch (based on low resistance MOSFET) designed to handle the high currents required by the experiment.

Fig. 1(c) shows the expansion/compression chamber, given by a Pyrex glass tube of 2.5 mm wall thickness, 2.6 cm inner diameter and 10.5 cm long. The entire cylindrical cavity was sealed using four O-rings located in pairs on each piston. The pressure variations inside the cylinder were recorded by a PZT hydrophone (Hyd) mounted on the lower piston. The vertical displacement of the upper piston was determined using an infrared photosensor whose analog (continuous) signal was partially interrupted by the flap mounted on the steel the magnetic rod (see Fig. 1(c)). This tracking method had a spatial resolution of ~ 2 μm and a temporal resolution of 10 μs.

In this experimental device, the bubble collapse is forced with high pressure pulses generated by the impact of a bar (from now on the “impact bar”) propelled through the steel tube described in Fig. 2. This bar was made of nylon polyamide 6 (density $\rho_b = 1.14\ \text{g/cm}^3$) with a mass of 23.5 g (Fig. 1(d)). The bar had a pattern of grooves employed to monitor the temporal evolution of its displacement, velocity (v_b) and acceleration (a_b) using a series of photosensors distributed along the tube (Fig. 2). The impact bar was propelled employing the compressed air injection system shown in Fig. 2(a). The gas flow and the air line pressure (P_{line}) was controlled using an electronic valve and a regulator. In this mechanism, the bar was released with a second electromagnet synchronously with the opening of the gas valve. The bar impact speed could be changed by modifying P_{line}, or by delaying the moment when the gas is released (relative to the time of flight of the bar). Both the control and synchronization systems, as well as the data acquisition from the sensors, were implemented in an Arduino UNO board with a temporal accuracy of ~ 1 μs. Tracking the position of the impact bar allowed the magnetic actuator to be deactivated just before the collision with the piston and optimize the momentum transfer from the bar to the piston.

The bubbles were generated by focusing a high power laser pulse (Nd-YAG Quantel YG980, 9 ns pulse width, $\lambda = 532$ nm) to the center of the compression chamber. The radius R_0 (defined relative to atmospheric pressure) could be set by seeding the bubbles at different instants of the traction/compression cycle or by changing the energy in the laser pulse [8,28,29]. The initial pressure p_0^{min} could be controlled by modifying the force exerted on the piston according to the polarity and intensity of the magnetic pulse in the linear actuator. The latter is the (positive) vacuum absolute pressure which determines R_{max}. Thus, bubbles could be generated by applying vacuum pressure on the system to have low values of R_0 and achieve large expansion rates ($R_{max}(p_0^{min})/R_0$).

The cavitation bubbles were characterized using two methods, one based on video recordings and the other on light scattering. In the laser induced bubble trials, images were captured with a Hitachi KP-F120 video camera, applying a stroboscopic backlighting technique with a