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Dynamics and acoustic energy dissipation in conical bubble collapse

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ABSTRACT

We follow the dynamics and acoustics of conical bubble collapse (CBC) in a U-tube device, to understand its associated phenomena such as: light emission, turbulence, bubble cloud formation, strong rebound pressures, shock wave emission, and liquid–gas interface behaviour. High-speed video frames linked with the waveforms acquired by piezoelectric transducers and photomultipliers during the collapse are analysed. All of the data acquisition is synchronised to the same timeline. Acoustic energy dissipation is investigated in detail by analysing the piezoelectric waveforms using Fourier transforms and wavelets.

The primary experimental results demonstrate that as the compression proceeds, (a) the liquid meniscus reaches the conical zone in cavitation conditions; (b) the liquid meniscus undergoes a geometric transformation (2D to 3D), it becomes a "bulb with a nozzle", wherein the instabilities are dragged and confined inside it; (c) the nozzle is retained as part of the new meniscus that continues to push the gas pocket; and (d) both structures (bulb and gas pocket) are connected by a neck/nozzle and will eventually form a "slug". Furthermore, during the collapse, the bulb eventually becomes a bubble cloud, and the bubble structures exhibit their own expansion–contraction rate. These phenomena are widely discussed.

A detailed analysis of the acquired signals yields frequencies and scales, which are associated with the onset of shock waves and its propagation, as well as the frequency bands that occur when the energy has dissipated. Good agreement was found between the experimental measurements and two different models for CBC dynamics. From the analysis of the dynamics and acoustics, we consider that various light emission mechanisms are activated during the collapse of a conical bubble, these are: thermal, chemical, and electrical in nature.

Introduction

Cavitation is a phenomenon of considerable practical importance that has been studied since the pioneering work of Rayleigh (1917). This phenomenon involves several phases, namely, the nucleation, growth and collapse of bubbles; in this last phase, a considerable force and localised stress are generated producing noise and high-speed liquid jets, and sometimes it is accompanied by emission light and shock waves into the liquid. In an effort to understand such phenomena, many researchers have focused on studying the dynamics of spherical collapse, considering either an isolated spherical bubble or one bonded in a cluster or clouds, inside high-speed flows in piping lines or circulating in microfluidic systems. Throughout the 20th century, authors such as Rayleigh, 1917; Flynn, 1975; and Holland and Apfel, 1989, among others, associated this type of collapse with the liquid inertia; the term 'inertial cavitation' is subsequently introduced to indicate that in those collapses, the inertial forces are dominant and would consequently be expected to generate energetic effects, such as in single bubble sonoluminescence, or SBSL. Leighton (1994) summarised the theories from which luminescence originates, categorising them into three groups: thermal, mechanic-chemical, and electrical. For an up-to-date summary of experiments and theories in this field, see Young, 2004.

During the growth and collapse of cavitation bubbles, whether induced by laser, spark discharge, ultrasonic energy or the dynamics of a flow field, flow physics is dominated by inertia. Even with the dominance of inertia, other physical effects such as surface tension, viscous forces, compressibility and thermodynamics of the vapour-gas mixture inside the bubble, as well as evaporation and condensation, heating in the thermal boundary layer, and the presence of nearby borders, all contribute to the overall performance (Brennen, 1995).

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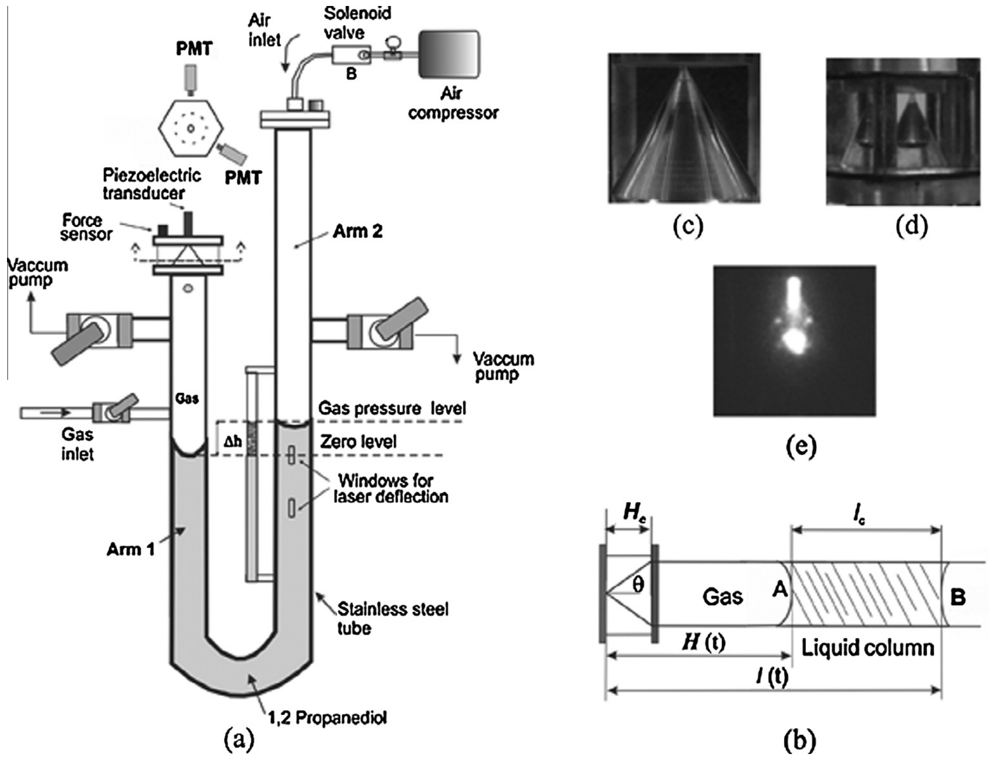

Fig. 1. (a) Schematic of experimental apparatus, showing U-tube device and connections used to follow the dynamics from CBC; (b) simplified schematic for modelling CBC. Cone details: (c) finished polycarbonate cone; (d) cone assembly with liquid shows the meniscus; and (e) image of the luminescence in CBC taken from an ICCD camera operating at 125 fps.

Nevertheless, the inertia of the liquid and motion and the gas–liquid interface are not typically accessible to control or measure. In most cases, the complexity of the experimental conditions excludes a strict comparison between experimental data and theoretical treatments. To observe such inaccessible parameters experimentally and allow critical testing against theories for inertial collapses, Leighton et al. (between 1995 and 2000) designed and instrumented an apparatus with a well-U-type geometry in which it is easy to determine and control these parameters. With this apparatus, they simulated both the expansion (through a reduction in static pressure) and compression (by means of a liquid piston) of a gas pocket. The collapse is specifically designed to be unstable; the bubble undergoes fragmentation after the first rebound. Thus, the process of collapsing a gas pocket at the apex of a cone by pushing a liquid piston has arisen and is called conical bubble collapse, CBC.

Leighton et al. (1998) also developed an analytical model for the dynamics of a conical bubble, adapting the formulations of Rayleigh (1917) and Noltingk and Neppiras (1950 and 1951) to conical geometry. Moreover, using experimental measurements of gas pressures generated by the collapse, they compared the bubble wall speeds and collapse times using high-speed photography, pressure records, and measurements of luminescence. They found good agreement between theory and experimental data using water as a liquid piston and air as a gas pocket.

The use of a U-tube with conical termination was pioneered by Henwood and contributors Kosky (1968), Kosky and Henwood (1969) and Hawtin et al. (1970), who proposed a new technique to emulate the condensation and collapse of vapour bubble in conical cavities. Their analogue apparatus consists of a U tube with conical termination to one limb. A liquid piston, driven by the pressure difference between two surfaces of the liquid, is used to collapse the vapour bubble. As recording instruments, they used high-speed tape photography and several pressure transducers located along one limb. Additionally, in 1970, these authors derived and used a mathematical model to predict the rate of collapse of a vapour cavity under a pressure gradient by considering the geometry of the analogue apparatus. Their theory is based on incompressible hydrodynamics and a boundary layer that is introduced to describe the resistance to heat transfer in the liquid phase as well as in the solid wall. They found good agreement between theory and experimental data using water at temperatures between 20° and 85 °C.

The developed theory and experimental runs reported by both groups, however, have different objectives; the former emulates the expansion, compression and rebounds of the bubble, while the latter examines only the compression phase and rebounds of the vapour bubbles. In both cases, a pressure difference exerted at the opposite ends of the water column drives the motion.

Recently, other studies using a similar apparatus (see Fig. 1a as an example) including those of Chen et al. (2005) and Jing et al. (2008), as well as Navarrete et al. (2011), and Godínez et al. (2012), focused their studies on the spectroscopic features of the luminescence and pulse width of the light emission to determine the mechanisms that produce it. These researchers found that the intensity and shape of the emitted light and the spectrum depend on the type of gas, its temperature and pressure, and the physicochemical properties of the liquid piston and substances dissolved in it, as well as the boundary conditions. Moreover, some authors realise that the collapse time is three orders higher than those found in SBL or MBSL. They explain qualitatively that the larger and brighter light pulse from CBC in comparison with those from SBSL and MBSL is due to several mechanisms that are activated by the meniscus dynamics during its long-time collapse.

In summary, the collapse of the conical bubble (CBC) is a procedure that can emulate luminescent cavitation (inertial cavitation) in all of its phases. This procedure allows us to control the site of