Investigation of the Primary Mechanisms of Cavitation-Induced Damages

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Abstract

Erosion of solid surfaces due to cavitation has been studied for decades. However, it has been a long debate that which mechanism, namely shockwaves, microjets towards the surface, or both, during the cavitation bubble collapse is the primary factor responsible for that erosion. In this project we investigate the small-scale mechanisms of material erosion induced by the collapse of a single cavitation bubble close to a wall. More specifically, our experimental setup includes modification of the initial nucleus size, the maximum bubble radius, the stand-off distance to the wall, the material softness, and the initial flow temperature. We record the evolution of the bubble using high speed cameras as well as the local impacts on the materials. With the help of specifically designed cold-wires, we also measure the temperature in the liquid and in the bubble. Two different methods are used to generate the bubble: (i) an acoustic shockwave of variable intensity, (ii) a YAG laser, which may introduce a high temperature at the start. We also combine the two methods in which the laser initially creates a nucleus, then the shockwave triggers the expansion of the bubble. The objectives of the project are included in this paper, while some first results will be presented at the CAV2018 conference.

Keywords: cavitation; shockwaves; microjets; material erosion; small-scale mechanisms;

1. Introduction

Cavitation occurs in case of a rapid pressure decrease in a liquid. It consists of formation, growth, collapse, and possible rebound of bubbles. The collapse of cavitation bubbles will release both shockwaves (up to 200 MPa) and microjets (up to 280 m/s) in addition to a temperature increase (up to 5000 Kelvin): it is a consensus in the scientific community that these phenomena are generally involved in the erosion of nearby solid surfaces. There are many experiments and computational works that have investigated the fluid dynamics of cavitation bubble collapse near a rigid wall [1-10]. Material deformation caused by cavitation has been also experimentally measured for materials with different hardness [11-13].

However, the transient, two-way interaction between the collapse of the cavitation bubble and the material still remains unclear. On one hand, almost nothing is known about the dynamic response of the material to cavitation-induced loads, such as the magnitude, profile, and propagation of the surface and body (P- and S-) elastic waves, and the effects of these waves on material failure. On the other hand, although a few experimental studies have revealed — using high-speed photography and acoustic measurements — significant impact of the material's Young's modulus on bubble dynamics [14, 15], the detailed reciprocal effects of the acoustic, elastic, and viscoelastic properties of the material on the two-phase bubble/liquid flow field is still unknown. Moreover, the issue of whether cavitation damage is caused by liquid jets, shock waves, or both has been debated for many years. For soft materials, much of the literature supports that the liquid jets play a dominating role. However, for harder materials, there has not been a consensus, or a systematic study that yields a complete theory (e.g. [1, 2, 16, 17]). Table 1 summarizes a number of representative studies which suggest different dominating damage mechanisms.

The analysis of the mechanisms of cavitation erosion has been made essentially by measurements of the pressure wave intensity generated by the bubble collapse, and visualization of the shock wave propagation [1, 18-20]. The impact force on the material has been measured in some cases by the use of PVDF (Polyvinylidene Fluoride) transducer [21]. Abouel-Kasem et al. [17] identified two different types of pits, small pits (of the order of micrometer) that do not change with time, and large ondulations (tens of micrometers) whose size and depth increase with time. The authors claim that the first type is due to microjets, while the second type is the effect of the pressure wave. They also conclude that the large pits are mostly responsible for the erosion process, which is consistent with a fatigue process, according to their observations. Although these explanations make sense, there is no real evidence of their validity, yet, since they are not supported by any direct observation of the respective effects of the microjet and the pressure waves emitted during bubble collapse. Philipp and Lauterbaun [1] show that the damage due to a single bubble collapse depends much on the distance to the wall at the instant of the collapse. According to their observations, only bubbles in contact with the wall generate high speed microjets that can contribute significantly to the wall pitting. They also mention the occurrence of multiple pits in case the bubble adopts a toroidal shape during the collapse. Roy [22] confirms that for bubbles close to the solid surface, both the microjet and the pressure wave impact the wall, with respective intensities that depend on the bubble size, its initial distance to the wall, and the pressure gradient that drives the collapse.

More specifically, the limitations of the current state of the art can be summarized as follows:

- The re-entrant jet velocity has not been characterized yet.
- In most of the previous studies, the bubbles have been generated with a laser. It results in bubbles filled with vapor, which may be significantly different from "real" bubbles, usually partially filled with air.
- Local efforts generated by the bubble collapse on the wall have never been measured.
- The temperature variations induced by the bubble collapse have never been measured.

Authors	**Cause of Bubble Collapse**	**Solid Material**	**H/R**	**Dominating Mechanism**
Tomita and Shima (1986)	Inertial	Epoxy	0.8 – 1.2	Liquid jet
Philipp and Lauterborn (1998)	Inertial	Aluminum	0 – 2	Shock
Shaw et al. (2000)	Inertial	Polymethylmethacrylate (perspex) block	0.65 & 0.54	Shock (0.65) / Jet (0.54)
Sankin and Zhong (2006)	Shock-induced	Rubber	0 – 1	Liquid jet
Tzanakis et al. (2014)	Inertial	Steel		Liquid jet
Abouel-Kasem et al. (2009)	Ultrasound	Aluminum		Shock

Table 1: Representative studies on the dominating mechanism of cavitation damage on solid materials. H: stand-off distance, i.e. distance between bubble and solid material. R: bubble radius before collapse.

2. Objective

The bubble-material interaction problem described above is a challenging multiphysics and multiscale problem involving a strong coupling between the fluid dynamics and the wall deformation. The dynamic process is highly nonlinear, featuring shock waves, high speed flows, large deformation and topological change of liquid-gas interface, and shock-induced fracture. The effects of the bubble size, distance to the wall and characteristic time of the collapse on the effects on the wall are currently an open question. More specifically, the respective impacts of the microjet and the shock waves, according to these different parameters, in terms of local efforts, elastic or plastic deformation, and potential mass loss has to be clarified. Both the effects of a single bubble collapse and the cumulative effects of the collapses are of interest, to eventually determine the primary mechanisms that are responsible for the damages. The final objective is the clarification of the various couplings between the flow dynamics and the material response. The analysis will focus on the characterization of small scale mechanisms induced by the collapse, i.e. the bubble evolution, the microjet propagation, the temperature variations, and the local stresses and deformations in the material.

3. Experimental Setups

The general objective of the experiments is to investigate the microscale mechanisms that govern the collapse of a cavitation bubble and its interaction with a solid surface located close to the bubble. The study is focused on quite large bubbles (the size will be typically varied between 1 and 10 mm), which are characterized by a life time of a few milliseconds.

We will use three techniques to create the bubbles. The first one is laser-induced cavitation. In this setup we use Q-Switched Nd: YAG laser (532 nm), which is commonly used in such tasks, to introduce cavitation bubbles. The laser is expanded by a beam expander, then converged using a focal lens. In the second setup we will use an acoustic method to trigger a single nucleus expansion in the liquid, specifically with a shaker moving up and down to create shockwave. The pressure at a specific height is given by

$$p_h = p_0 + \rho h(\mathrm{g} + \frac{dz(t)^2}{d^2t})$$

where p_h is the pressure at height h of bubble position, p_0 is the pressure above liquid, h is the distance to free surface, ρ is the liquid density, g is gravitational acceleration, and z is the vertical displacement. This setup can generate more realistic cavitation bubbles, partially filled with air, but harder to control. The third option will be to combine the two techniques above to create a single bubble, as an intermediate way to balance the merits of both previous techniques We also want to control p_0 so we will connect a pump to the water tank. We use a high-speed camera (Phantom VEO 410) to record the evolution of cavitation bubbles at a frequency of about 50,000 Hz. A continuous lighting is applied to illuminate the bubbles and appropriate filters are used to cutoff the light induced by the laser. With these experimental setups, we will investigate various sizes, different stand-off distances to the wall, and evaluate the differences between the three techniques of bubble inception.

The experimental setup will provide measurements of the following quantities:

(1) The bubble size and shape at all instants.

(2) The velocity fields in the liquid and vapor phases, based on Particle Image Velocimetry (PIV) with optical means [23].

(3) The temperature inside the bubble and in the liquid will be measured with cold wires. This technique is currently in development in a similar configuration of growth and collapse of a cavitation bubble [24]. Cold wires are homemade sensors composed of an internal fiber that provides the mechanical resistance, a first coating with a high temperature coefficient, and a second external layer of low resistivity, which is applied everywhere but at the sensor location (about 1 mm long). A small current intensity is used to measure the variations of the wire resistance according to the flow temperature.

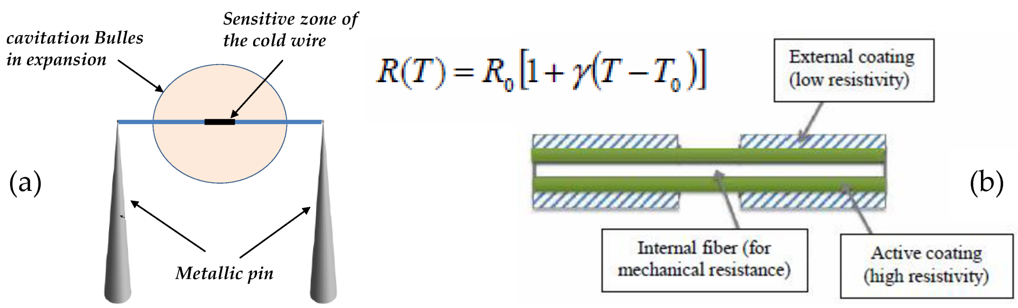

Figure 1: Cold wires for temperature measurements [24]. They are composed of an internal glass fiber and two successive coatings (see Figure 1b). The small diameter of the wires (about 15μm) enables to achieve very short time response (of the order of the microsecond or less) in order to capture the rapid temperature peak expected at the end of the bubble collapse. Using several wires will enable to obtain the temperature distribution inside the bubble and in the surrounding liquid. This device will be used in the present project to characterize the temperature variations during all investigated bubble collapses.

(4) Measurements of local efforts will be performed on the surface of the material, using PVDF (polyvinylidene fluoride) coating on the wall. Previous experiments have used such sensors to monitor at high frequency the global effort variations, while it is planned in this work to manufacture a specific array sensor that will provide the local efforts due to the various impacts related to the bubble collapse. For that purpose, a distributed sensor composed of a segmented electrode etched on a continuous PVDF layer using classical lithography techniques will be manufactured [25].

4. Current Work

We have already prepared all the required components to generate one single bubble using a laser. Currently we have designed most of the experimental setup, such as the tank shape and different optical sets (e.g. beam expander vs concave lens, parabolic lens vs convex lens). We will be evaluating a variety of equipment combinations until we reach the desired performance. In the next months we will start some preliminary tests. By the time of conference, we should be able to present some first results of bubble collapse and related erosion on the wall, for several stand-off distances of the bubble.

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