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Dynamics of shock induced bubble formation at the bottom of a liquid filled tank

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Résumé :

Dans ce travail on montre que la propagation d'une onde de choc induite par l'interaction laser- matière sur la face extérieure d'une plaque d'aluminium au fond d'un récipient remplis d'eau permet l'apparition d'une bulle de cavitation. La bulle augmente en taille rapidement avant s'effondrer par l'action de la pression hydrostatique environnante. Dans certaines conditions, on observe l'apparition d'un jet coplanaire à la parois pendant le processus d'implosion de la bulle et s'en suit la formation d'un dipôle de vorticité qui se propage orthogonalement à la parois, vers la surface libre. Le changement de régime entre les bulles qui génèrent un jet vers la parois et celles qui génèrent un jet en direction opposé est expliqué par l'apparition d'une singularité dans la solution d'écoulement potentiel au niveau de la ligne de contact. Les résultats issus de ce travail révèlent l'existence de deux régimes d'implosion différents en fonction de la forme de la bulle lors du moment de volume maximal.

Abstract :

In this work we investigate the consequences of a laser induced shock wave at the outer face of a liquid filled tank. For sufficiently intense energies we show that the propagation of the shock wave generated by the impact of a laser impulse on an aluminium plate is sufficient to trigger the appearance of a bubble at opposite face. The bubble quickly expands and after reaching a maximum radius, it collapses under the action of the ambient surrounding pressure. Using high speed camera recordings we show the appearance of a re-entrant jet parallel to the wall during the collapse stage that ultimately leads to an unconventional jet directed outwards the wall. In some special circumstances this jet can lead to the formation of a vortex dipole that can travel relatively long distances. These observations can be explained using the impulsive theory to obtain the acceleration of the idealized problem of the collapse of a spherical cap bubble in contact with a wall. The findings reported in this work clearly show that a lased induced shock wave can trigger the appearance of cavitation bubbles. In addition we show that the physical mechanisms induced by collapsing bubbles are remarkably different depending on the effective angle of the bubble at the instant of maximum radius which is a significant advance towards the control and understanding of the mechanical effects induced by the collapse of bubbles in the presence of solid walls.

Mots clefs : Shock wave induced cavitation, bubble nucleation, bubble collapse, water jet.

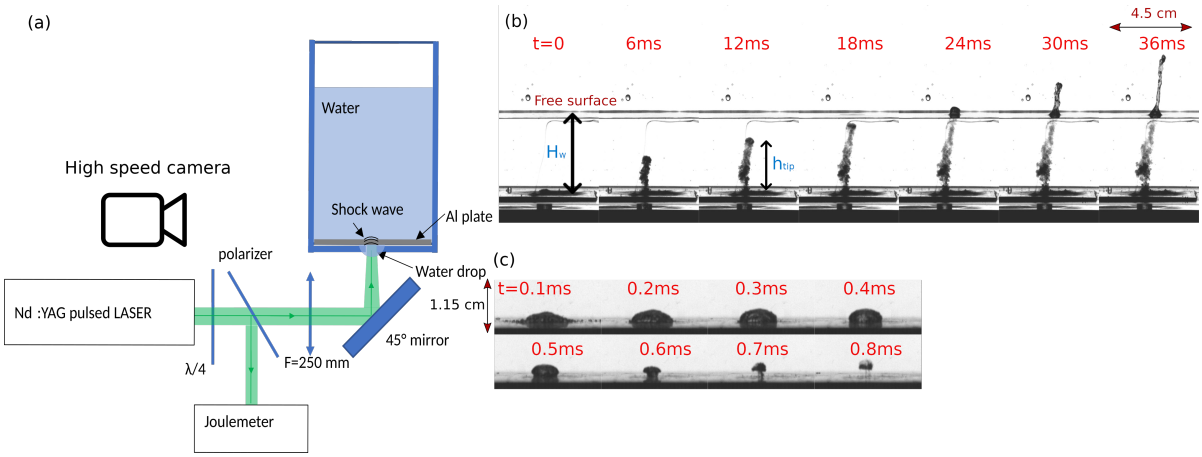

FIGURE 1 – (a) Experimental setup. (b) Evolution of the propagation of the vortex dipole generated by the collapse of a bubble at the bottom of the tank and formation of a jet at the free surface. (c) Formation and collapse of a bubble at the bottom of the water filled tank (zoomed view).

1 Introduction

The formation and later dynamics of bubbles in contact with walls is a topic that remains relatively unexplored. This aspect is fundamental importance as the efficiency of traditional and also more innovative applications based on the use of collapsing bubbles for medical treatment or the dissipation of energy by the formation of bubbles critically depend on the response of the bubbles to pressure pulses. In a previous work [1] we have shown that the propagation of a shock wave from an aluminium plate into water is capable to induce the appearance of a cavitation bubble inside a confined medium. In this work, we explore the consequences of the formation of a cavitation bubble at the bottom of an open water filled tank.

2 Experimental setup

In the experiment proposed we generate a bubble at the bottom of a water filled tank with a high power pulsed laser that induces a shock wave under water-confinement onto the external face of the bottom aluminium wall [2] (see figure 1a). The laser source is a pulsed Nd :YAG laser model Quanta-Ray Pro 350-10 manufactured by Spectra Physics. It provides 3.5 J at maximum energy with gaussian like temporal pulse of duration of 9.2 ns at half maximum. Its wavelength is 1064 nm and it is operated in single shot mode. The laser beam at the laser generator output is about 13 mm of diameter. It goes through a quarter wave plate and polarizer system for acurate energy modulation. Afterwards, the beam is sent through a planoconvex length of focal distance of 250 mm. The focal spot on the aluminium bottom face is about 4 mm of diameter. The energy per shot is measured with a joulemeter, model Maestro, manufactured by Gentec. The temporal energy profile was measured with a fast photodiode model UPD-50-SP from Alphalas and the enegy repartition in the beam was measured with a gentec beam analyser. Once the laser focuses on the aluminium wall, the deposited density of power is high enough for sublimating few micrometers of the aluminium target. This sublimation results in the expansion of a plasma similar to a surfacic explosion. A water droplet is put over the irradiated surface in order to confine the plasma expansion. This method results in a more intense pressure during a longer time. A shock wave is thus induced and propagates through the aluminium bottom wall. Knowing the beam characteristics, it is then

possible determining the laser induced shock wave profile [3]. The formation and later dynamics of the bubble are recorded with a high speed camera (figure 1c). In some experiments, a small layer of ink is deposited at the bottom of the tank prior to the laser impact in order to visualize the flow generated by the bubble at long times (figure 1b).

3 Results

The shock wave generated by the laser-matter interaction propagates through the aluminium bottom and is then transmitted into the water tank eventually leading to the appearance of a high pressure vapor region that quickly expands. The subsequent bubble expansion makes bubble inner pressure to drop generating a spherical cap at low pressure that collapses by the action of the surrounding pressure. The high speed camera recordings shown in figure 1(c) reveal the formation of a relatively flat bubble with an effective contact angle at the instant of maximum volume larger than 90 degrees. The highest velocities during the collapse stage are reached close to the contact line generating a mushroom like structure as a consequence of the re-entrant jet formed. The bubble eventually detaches from the wall and propagates in the direction outwards the wall. This behavior is markedly different from classical bubble collapse experiments where a jet develops from the tip of the bubble towards the wall impinging into the solid surface [4]. The change on the direction of the jet observed in this case with respect to previous studies can be explained using the impulse theory, which uses the fact that the acceleration field during the first instants of the bubble collapse is given by the solution of a Poisson equation in the liquid domain for the pressure. It can be shown that the pressure gradient normal to the interface near the contact line is of the form [5]

$$\frac{\partial p}{\partial n} \propto \frac{\pi}{2\alpha} r_s^{\frac{\pi}{2\alpha}-1}$$

where r_s is the distance of a point to the contact line and α is the effective contact angle between the wall and the interface. This expression shows that for $\alpha > \pi/2$ (e.g. 90 degrees) the acceleration at the contact line becomes infinity, while for $\alpha < \pi/2$ the acceleration at the contact line is zero and increases as we move towards the bubble tip. Thus, the jetting formation process strongly depends on the effective contact angle at the instant of maximum volume.

Figure 1(b) shows camera recording snapshots of the entire liquid filled vessel where we have added a thin layer of ink over the bottom floor. The experimental results reveal the formation of a vortex dipole similar that propagates towards the liquid free surface leading to the generation of a liquid jet. Image treatment and data post-processing techniques are used to obtain the temporal evolution of the vortex dipole tip position (figure 2 left) for various experiments. The vortex dipole velocity at short times tends to $0.5U_c$, with $U_c = \sqrt{p_0/\rho_l}$ being the representative velocity of the Rayleigh collapse problem. The velocity of the plume decays afterwards and eventually the structure distabilizes after some time. Both, the process of vortex formation and the propagation distance of the dipole vary significantly among different experiments under -to the authors knowledge- the same experimental conditions.

In some experiments the vortex interacts with the free surface and ultimately produces a strong outward jet that generates large amplitude perturbations that appears with a significant delay with respect to the instant of the bubble collapse (for the example shown the jet appears 24 ms later). This process then

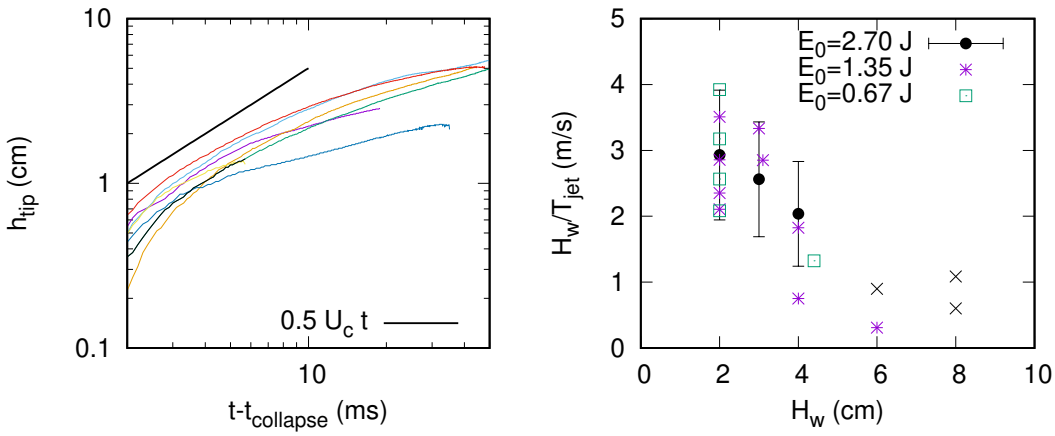

FIGURE 2 – (Left) Temporal evolution of the tip vortex dipole position for various experiments at $E_0 = 2.7$ J. (Right) Averaged velocity of the vortex dipole for different liquid heights and three different laser input energies.

leads to disturbances at time scales significantly larger than those caused by shock wave propagation in underwater explosion experiments (the characteristic time scale of the process of wave propagation in this experiment are of the order of $H_w/c_l = 0.026$ ms). Figure 2(right) shows the results of the averaged velocity obtained as the ratio between the liquid height (H_w) and the time at which the jet at the free surface becomes visible (T_{jet}). We represent with errorbars the dispersion of the results for a large number of realizations at three different energies ($E_0 = 2.7, 1.35, 0.67$ J) and different water heights up to 4 cm. For larger values of H_w is still possible to observe jets at the free surface as rare events marked with black crosses. The laser input energy strongly impacts the probability to observe the phenomenon described, but its influence on the averaged velocity is not significant. This seems to point out about the importance of the bubble shape at the instant of maximum volume on the observed phenomenon, which in the current experiment is difficult to control introducing an uncertainty on the probability to observe the phenomenon described. The probability to observe a free surface jet also decreases with the water height (H_w). We explain that as follows : The vortex formation process during the bubble jetting process shares similarities to the process of liquid injection in a still flow, where a vortex dipole forms and, consistent with the experimental observations at short times, it is known to be able to propagate over long distances at half the injection velocity. In the present experiments, the formation process is influenced by the multiphasic nature of the flow and most importantly the formation time condition is not full-filled. Thus, the vortex dipole formed are not fully formed and may be singificantly perturbed by the turbulence generated during the collapse process. This ultimately leads to a relatively large dispersion on the results observed in terms of distance over which the dipole propagates.

4 Conclusions

We have shown that the impact of a laser on the outer face of an aluminium plate placed at the bottom of a liquid filled tank can be used to investigate the dynamics of cavitation bubbles attached to walls. Relatively flat bubbles are formed, leading to the appearance of a re-entrant jet during the collapse that ultimately leads to the appearance of an unconventional vortex dipole that propagates in the direction outwards the bottom. This vortex dipole can travel relatively long distances and induce the appearance

of jets at the free surface with a significant delay with respect to the instant of the bubble implossion.

We believe that this mechanism is universal and can play some role on mixing process in the deep ocean and, as in this case, on the perturbation of the free surface.

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