Generation of thermocavitation bubbles within a droplet

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Abstract

High-speed video imaging was used to study the dynamic behavior of cavitation bubbles induced by a continuous wave (CW) laser into highly absorbing water droplets containing copper nitrate (CuNO$_4$). The droplet lays horizontally on a glass surface and the laser beam ($\lambda$=975 nm) propagates vertically from underneath, across the glass and into the droplet. This beam is focused $z$=400 µm above the glass-liquid interface in order to produce the largest bubble possible. The laser-induced bubble is always in contact with the substrate taking a half-hemisphere shape; it reaches its maximum radius ($R_{\text{max}} \sim 1$mm) and collapses rapidly thereafter, displaying a toroidal shape in the final stage of the collapse. As a consequence of the bubble collapse, a liquid jet is produced at the droplet free interface emerging out at velocities of $\sim 3$ m/s for this case, which allows the formation of secondary droplets due to the breakup of the jet. The dynamics of cavitation bubbles in confined geometries (drops) and the liquid jet formation are composed of multiple and interconnected hydro- and thermodynamic events that occur inside and outside the droplet which we are currently exploring.

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Introduction
Cavitation bubble collapse within droplets has been investigated experimentally in recent years [1-9]. This phenomenon is rich in terms of the multiple and interconnected hydro- and thermodynamic events that occur inside and outside the droplet. Also, its full understanding is crucial to predict and eventually control the many practical applications that could benefit from the effects produced by cavitation bubble collapse. For example, erosion on surfaces is associated with liquid jets and shock waves emitted by collapsing cavitation bubbles [10-11]; in the biomedical area, thermocavitation could be used to ablate soft-matter surfaces (tissue) for more effective drug delivery [12]; and for the generation of finer sprays to improve combustion efficiency [5]. So far, the principal mechanisms of optical cavitation within droplets have been the use of expensive pulsed Nd:YAG lasers [1-5] and CO₂ lasers [6-8]. Other non optical methods have also been explored for cavitation within a droplet, for example, spark discharge between two thin electrodes (8-1000 mJ discharge energy) in a microgravity environment. This mechanism of inducing cavitation works through the electrical breakdown of water molecules (Obreschkow et al. [9]) and requires relatively high energy discharges.

The present paper reports on the collapse of bubbles formed within a droplet through the use of a low power continuous wavelength (CW) laser, offering a cheaper option compared with the cavitation mechanisms mentioned above. The working fluid is a saturated solution of copper nitrate (CuONO₄) dissolved in water, which has a high absorption coefficient (α = 135 cm⁻¹) at the operating wavelength (λ = 975 nm). Using high speed video (at frame rates up to 10⁵ fps), we show the generation of a vapor bubble within a droplet by thermocavitation [11-13], followed by a liquid jet emerging from the droplet produced by the shock wave generated immediately after the bubble collapses.

Experimental set up
A hemispherical droplet (5µL volume) confined by a thin circular plastic washer of 5 mm in diameter and ~100 µm depth rests on a glass microscope slide (1 mm thickness). The CW laser beam (λ = 975 nm) was focused (with a microscope objective sitting under the glass slide) slightly above the glass-liquid interface. The objective could be displaced vertically in order to change the focal point (z) inside the droplet.

Figure 1. Experimental set up for the generation and analysis of vapor bubbles produced by thermocavitation within a droplet.

For these experiments, we fixed the laser power to 275mW (the maximum power available from our laser system) and the maximum bubble radius was controlled by changing the focal point [13]. It was found that placing the laser focus z = 400 µm above the glass-liquid interface led to the largest cavitation bubbles of ~ 1mm radius. In order to record the formation and evolution of the bubble inside the droplet, the droplet was illuminated perpendicular to the laser beam with diffuse backlighting from a white light source to project the bubble’s shadow on a high speed video camera (Phantom V7, Version: 9.1), which recorded images of up to 10⁵ fps. The CW laser beam was blocked by a shutter, which was connected together with the high speed camera to a synchronization trigger, so the camera initiated the recording when the shutter opened.

Results and discussion
Figure 2 shows the formation and evolution of a single cavitation bubble created within a droplet of 5 µL volume. A vapor bubble appeared ~82 ms after the laser began to irradiate the droplet (Fig. 2.A). The bubble had a hemispherical shape and it grew until it reached its maximum radius (Rₘₐₓ ~ 1mm) in ~129 µs (Fig. 2.D), causing a protrusion at the top of the droplet due to the vapor expansion. When the bubble started to collapse, the protrusion ceased growing (Fig. 2.E-F). The vapor bubble took a toroidal ring shape during the final stage of the collapse (Fig. 2.F), caused by the pressure near the pole of the bubble, which is presumably higher than the pressure on the sides during that stage of the collapse, producing a negative curvature over the bubble surface [14]. Lauterborn et. al. [10], using high speed photography and holography, showed that once the toroidal ring collapses, it is divided into several separate collapsing parts, exactly as it occurred in our study,
where we observe a cloud around the toroidal ring (Fig. 2.G). The shock wave produced at the moment of the collapse, produces a crown at the base of the protrusion (Fig. 2 G-H), which emerges out the droplet at velocities about 3 m/s, forming a characteristic jet-and-crown shape, similar to that generated by droplet impact on liquid pools [15-16]. The Figures marked with lowercase letters (2 a-h) are topside views of the corresponding uppercase ones shown above.

The ejected jet-and-crown outside the droplet allows the formation of a liquid column of ~0.5 mm in diameter, which propagates upward until it separates (Fig. 3); forming small droplets (it is not shown due to the frame size). This narrow column is found to reach velocities of 3 m/s. In comparison, past work using pulsed lasers to induce cavitation have measured velocities of 100 to 250 m/s for microjets of 5-50 µm in diameter. Besides the potential use of jet formation for fire/fiber coating, ink-jet printing and secondary atomization, this liquid column has also found some potential use as a temporary liquid waveguide, as was shown by Nicolas Bertin et. al [17] recently.

**Figure 2.** Sequences of images of formation and collapse of vapor bubble into a small droplet. The images with uppercase letters are when the camera was placed almost perpendicular to the laser beam (Fig. 1) and lowercase letters the camera was angled vertically about 45 degrees. The exposure time is 41 µs and the time between each frame is 2 µs.

**Figure 3.** Liquid column formed after the bubble collapse.

**Conclusions**

Using a CW laser focused in a highly absorbent solution we showed that it is possible to generate vapor bubbles within a quiescent droplet by thermocavitation, with the added advantage of a very simple and inexpensive experimental setup relative to other methods used for the same purpose. Furthermore, the mechanism of bubble formation is different from that induced by pulses lasers or electrical discharger inside the droplet, and the liquid jet velocity (~3 m/s) is much smaller compared with the velocities reported with pulsed laser systems (see Ref. 5). However, the jet’s base diameter in our case is much larger (~0.5 mm). The control and stability of these liquid columns and droplet formation due to the breakup of the column could be potentially implemented in many applications, such as liquid jet polishing of optics, wire and fiber coating, ink-jet printing and temporary liquid waveguides.

**Acknowledgements**

The authors acknowledge financial support from CONACyT-Mexico and Omnibus Academic Senate Research Grant, UCR. Also a special thanks to Josue Lopez for laboratory assistance.

**References**