Experimental Thermal and Fluid Science 93 (2018) 285–291

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Laser-induced bubble formation on a micro gold particle levitated in water under ultrasonic field

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ARTICLE INFO

Keywords:
Micro gold particle
Levitation
Ultrasound
Laser-induced cavitation
Shock wave

ABSTRACT

Laser-induced bubble formation on a micro gold particle with a radius of 5 μm, levitated at the center of a spherical flask filled with water under ultrasound, was investigated experimentally and theoretically. Bubble formation and subsequent growth and collapse were visualized by a high-speed camera. The strength of shock emitted during the expansion of the bubble formed on the gold particle was measured by a needle hydrophone at various positions from the center of the flask. In the theoretical study, the time-dependent radius of the laser-induced bubble with/without gold particle was obtained using solutions of the Navier-Stokes equations for the vapor inside the bubble and the liquid adjacent to the bubble wall. The shock strengths at various points were also obtained using the Kirkwood-Bethe hypothesis with the obtained time-dependent bubble radius and the pressure at the bubble wall. Calculation results provided the correct homologous behavior of bubble motion and shock strengths at various points from the bubble center. The mass increase due to evaporation near the bubble collapse crucially affected the bouncing motion after the first bubble collapse.

1. Introduction

It is well known that a high-power laser could breakdown liquid [1,2]. Laser-induced breakdown of liquids is characterized by fast plasma formation after evaporation of the liquid and subsequent vapor expansion accompanied by shock wave emission [2]. The bubble wall velocity after the shock departure has been found to be sufficiently high to produce emission of light at the collapse point [3]. The shock waves dealt with here are not the ones emitted at the bubble collapse [4]. Recently, bubble formation on the surface of gold nanoparticles irradiated by a high-power laser in water [5,6] has been studied for medical applications such as cancer diagnosis and possible therapy [6]. However, it is very hard to perform these experiments and to obtain good data from the bubble formation on the surface of laser-irradiated nanoparticles because the nanoparticles dispersed in liquid cannot be controlled properly. To overcome the control problem of particle, a micro gold particle was tried to be levitated at the center of a spherical flask filled with water under ultrasound in this study. Successful levitation of a micro gold particle at the center by ultrasound for the first time enabled to perform experimental work on laser-induced bubble formation on the gold particle (G-bubble) precisely. The measured results such as time dependent radius and shock strength from the expanding of evaporated liquid are compared with the results for laser cavitation without the gold particle, i.e., typical laser-induced cavitation (L-bubble), and the experimental results are also compared with the theoretical results.

2. Experimental setup, procedures and test conditions

Fig. 1a shows a schematic of the experimental setup used to investigate the laser-induced bubble formation on a micro gold particle levitated under ultrasound. A similar experimental apparatus [7] was used to study sonoluminescence, a phenomenon of light emission associated with collapse of oscillating micro-size bubble trapped under ultrasound [8,9]. Two disk-type lead zirconate titanate (PZT) transducers (Channel Industries Inc.; 15 mm in diameter and 5.0 mm in thickness) attached to the side of the wall of the spherical Pyrex flask produced a velocity node near the center of the flask. The flask volume is 100 ml and the corresponding diameter (d) is approximately 57.6 mm. The driving frequency of the PZT transducers was approximately 27.0 kHz which was close to the resonance frequency of the LRC circuit and the acoustic resonance frequency (f_o) of c/d in the water filled flask. The PZTs behave as capacitor, which must be compensated by inductor. The employed ultrasound frequency of 27.0 kHz and amplitude of 1.2 atm could control a levitated bubble whose size ranges from 5 to 7 μm in water [8]. A drop of water containing gold particles

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https://doi.org/10.1016/j.expthermflusci.2018.01.002
Received 18 November 2016; Received in revised form 16 November 2017; Accepted 5 January 2018
Available online 06 January 2018

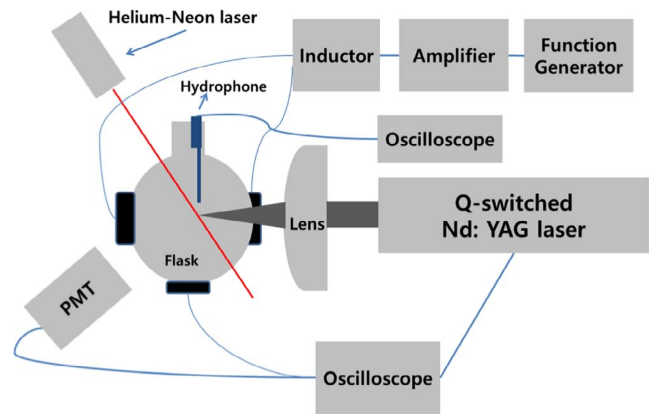

Fig. 1a. Schematic of the experimental apparatus.

with an average diameter of 10 μm was injected by a syringe into the spherical flask filled with degassed water. This procedure was repeated for every experiment. When the gravitational and buoyant forces of a gold particle are equal to the acoustic radiation force [10], the particle will stay near the velocity node, i.e., the center of the flask. The ultrasound amplitude used for levitation of the gold particle is approximately 0.4–0.6 atm, which is one thirds of amplitude needed for trapping a microbubble in sonoluminescence experiment. The levitation of a gold particle at the center of the flask was also confirmed by passing light from a 5-mW He-Ne laser through the particle as shown in Fig. 1b. When a gold particle levitates at the center of the flask, a bulge is created around the gold particle along the light path of the He-Ne laser, which was visualized by a camera (Cannon EOS 100D). However, no bulge was created for the case without gold particle.

A Q-switched Nd:Yag laser delivered a single pulse of 5 ns in width with an energy of 7.5 mJ at a wavelength of 1064 nm to the gold particle or liquid at the center of the cell. The Nd:Yag laser light was focused at the center of the flask using a 25 mm diameter lens with an effective focal length of 36.3 mm. Bubble formation and subsequent growth and collapse were visualized by a high- speed camera (V2511, Phantom, USA). The camera can take images up to with 1 Mfps (million frames per second). However, the volume of the evaporated liquid due to laser irradiation was not obtained by such visualization. Time-dependent radius was also obtained by the light scattering method as a reference purpose. The scattered intensity from a bubble illuminated by the He-Ne laser was received by a photomultiplier tube (PMT: Hamamatsu, R2027) and was recorded in an oscilloscope. The received angle of the scattered light of the He-Ne laser was chosen to be 80° where one-to-one relationship exists between the scattered intensity and the bubble radius [11]. The scattering data were calibrated using the maximum radius for another bubble, which was obtained by high-speed camera.

The shock strength during the expansion stage of bubbles was measured by a calibrated needle hydrophone (HPM1, Precision Acoustics, UK) at various distances from the center of the cell for different bubbles. The hydrophone can measure acoustic signals ranging from 1 kPa to 20 MPa. The hydrophone was attached to a three-dimensional micro stage so that fine control of the positioning of the hydrophone was possible.

3. Theory

The irradiation of a high-power laser on a gold particle immersed in water produces a rapid temperature increase inside the particle due to the absorption of photons [12–15] within tens of nanoseconds. The heat inside the particle diffuses into the liquid around the particle up to 2–3 times the radius of the particle layer within a few tens of microseconds, which may be estimated by a lumped analysis. If the temperature of the liquid layer is above the superheat of water, i.e., 576 K, and the thickness of the liquid layer exceeds a certain value, the liquid in the layer evaporates and expands rapidly. The pressure of the evaporated vapor that has the same volume of its liquid state given temperature, which was confirmed from the experiments on the evaporation of liquids at their superheat limits [16,17], is approximately 820 atm (P_n) at the superheat limit of water, 576 K (T_s) [18]. The detailed description of a model for laser-induced cavitation is given by Byun and Kwak [19]. A brief description of the model is given as follows.

3.1. Shock propagation due to rapid expansion of the evaporated liquid

The rapid expansion of the evaporated liquid state adjacent to the surface of a metal particle may emit a shock wave. The velocity and the pressure fields in the liquid, caused by the shock waves, may be obtained using the Kirkwood-Bethe hypothesis [20] which assumes that the invariant quantity given in Eq. (1) propagates in the medium with a characteristic velocity $c + u$. This is given by

$$Y = r\left(h + \frac{u^2}{2}\right) = R_b\left(H_b + \frac{U_b^2}{2}\right) \tag{1}$$

The ordinary differential equations for the velocity and the pressure for the outgoing shock wave, which can be obtained from the mass and momentum equation of the liquid, are as follows [20].

$$\left.\frac{du}{dt}\right)_{char} = \frac{1}{c-u}\left[(c+u)\frac{Y}{r^2} - \frac{2c^2u}{r}\right], \tag{2}$$

$$\left.\frac{dp}{dt}\right)_{char} = \frac{\rho_\infty}{r(c-u)}\left(\frac{p+B}{p_\infty + B}\right)^{1/n}\left[2c^2u^2 - \frac{c(c+u)}{r}Y\right], \tag{3}$$

where the propagation velocity of the shock wave is given by

$$\left.\frac{dr}{dt}\right)_{char} = c + u. \tag{4}$$

In deriving the above equations, it is assumed that the density of the liquid is a function of pressure only and that the compression of the liquid is an isentropic process. Tait's equation [21] is appropriate for describing the state of a liquid under these conditions. The equation of state is given by

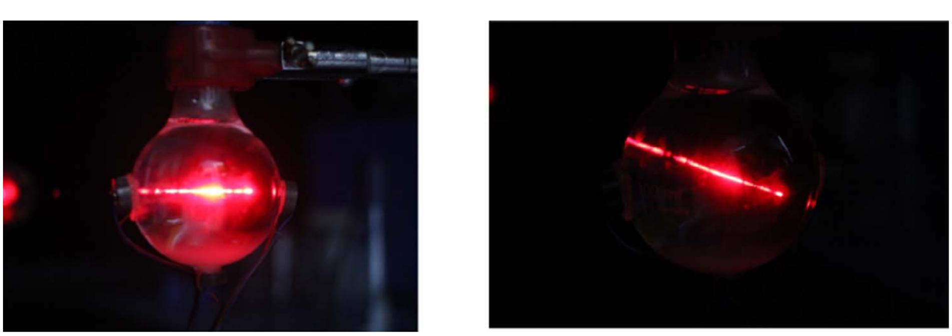

Fig. 1b. Visualization of the light path of a He-Ne laser when the high-power laser irradiates on the center of the flask with (left) and without (right) a gold particle at the center.