Experimental investigation of laser-induced bubble dynamics near elastic/soft material in distilled water

This content has been downloaded from IOPscience. Please scroll down to see the full text.
2009 J. Phys.: Conf. Ser. 147 012026
(http://iopscience.iop.org/1742-6596/147/1/012026)
View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 54.191.40.80
This content was downloaded on 01/09/2017 at 10:41
Please note that terms and conditions apply.

You may also be interested in:

Effect of Liquid Viscosity on a Liquid Jet Produced by the Collapse of a Laser-Induced Bubble near a Rigid Boundary
Xiu-mei Liu, Jie He, Jian Lu et al.

Bubbles unbound II: AdS and the single bubble
Keith Copsey

Growth and collapse of laser-induced bubbles in glycerol–water mixtures
Liu Xiu-Mei, He Jie, Lu Jian et al.

Growth and Collapse of a Single Bubble near a Plate by Spark Discharge in Water
I Akcam, K Inaba, K Takahashi et al.

Deformation of a Single Bubble with Ultrasonic Irradiation
Shinobu Mukasa, Hiroshi Itami, Shinfuku Nomura et al.

Laser-Induced Temperature Radiation
Takashi Kushida

Search of Fusion Reactions During the Cavitation of a Single Bubble in Deuterated Liquids
M Barbaglia, P Florido, R Mayer et al.

The weighted average test method for the maximum radius of a laser-induced bubble
Li Beibei, Li Ruirui, Wang Bingyang et al.

Bubble dynamics in soft materials: Viscoelastic and thermal effects
Eric Johnsen and Lauren Mancia
Experimental investigation of laser-induced bubble dynamics near elastic/soft material in distilled water

S. Nakajima 1, Y. Yamamoto 1, M. Ota 2, K. Maeno 2

1 Graduate Student, Graduate School of Engineering, Chiba University, 1-33 Yayoi, Inage, Chiba, 263-8522, JAPAN
2 Graduate School of Engineering, Chiba University, 1-33 Yayoi, Inage, Chiba, 263-8522, JAPAN

maeno@faculty.chiba-u.jp

Abstract. This study deals with an experimental investigation of the dynamics of laser-induced single bubble near the rigid material plate and near the elastic/soft material plate in the distilled water at room temperature under atmospheric pressure. A pulsed Nd:YAG laser was focused into the distilled water to make plasma and single bubble. The bubble repeated expanding and shrinking motion several times, and then collapsed. This behavior occurred on the sub-millisecond timescale. The solid wall near the bubble makes an asymmetric flow field. Many experiments on the behavior of laser-induced bubble near the rigid material have been reported. The bubble near the solid wall moves toward the rigid wall during its shrinking and rebounding process. The behavior of laser-induced bubble near the soft material, however, has not been well clarified. The soft material such as body tissue can deform and influence the behavior of the laser-induced bubble. Since the high peak power laser has been applied in the field of bioengineering and medical treatment, it is of great importance to clarify the effect of the soft material near the laser-induced cavitation bubble. In this research the behavior of laser-induced bubble near the elastic/soft material was visualized with schlieren method and investigated.

1. INTRODUCTION

Recently, the high power laser has been applied in the field of medical engineering, where optical breakdown is occasionally realized by laser beam focusing. Laser-induced optical breakdown generates shock waves and bubbles, and is used for medical applications (A. G. Doukas et al., 1991: Rok Petkovšek et al., 2007). Laser-induced shock waves and bubbles sometimes cause damage to tissues. Therefore, the propagation of laser-induced shock waves and the behavior of laser-induced bubble near the soft materials as body tissues need to be clarified. Many experiments on the behavior of laser-induced bubble near rigid material have been reported (Ed Zwaan et al., 2007). Rigid wall near the rebounding bubble makes an asymmetric flow field. Behavior of the single bubble near the solid wall is affected by the asymmetric flow field. It is well known that the bubble near the rigid wall moves toward the wall, and then unsteady movement of the bubble strongly depends on the positional relation between the bubble and rigid wall(s) (Ed Zwaan et al., 2007). The behavior of laser-induced bubble near the soft material, however, has not been clarified enough.

Our research has concentrated on the behavior of laser-induced bubble near a rigid wall and near an elastic/soft wall by visualization. We have analyzed the behavior of the bubble using the visualized bubble images, and then clarified that the behavior of laser-induced bubble is changed by the difference of material near the bubble. The observed bubble behavior is discussed in this paper.

© 2009 IOP Publishing Ltd
2. EXPERIMENTAL APPARATUS AND METHOD

In our research a pulsed Nd:YAG laser beam was focused into the distilled water in order to make plasma and a single bubble. Bubble behavior was visualized by schlieren method and shadowgraph method. Experimental apparatus for schlieren method is shown in Fig. 1. This experimental apparatus consists of Nd:YAG laser, water vessel, test wall, lens system, flash lamp and digital still camera. A pulsed Nd:YAG laser (LOTIS TII, LS-2135, 532nm, 10-12ns pulse duration) oscillated at 1.0Hz. The emitted laser beam was shaped by the beam trimming parts, and converged into the distilled water. Distilled water was kept in acrylic water vessel at room temperature under the atmospheric pressure. Lens array was fixed on the vessel. Test wall was fixed near the focusing position of laser beam in water. The position of the test wall was adjusted with XYZ stage. We used flat plate of aluminum, foam rubber, sponge, and whetstone as a test wall in this research.

The laser beam was converged near the test wall to make plasma and a single bubble. At the same time, laser irradiation signal was sent from laser controller to delay generator (SUGAWARA Laboratories, RE-306), and then by the signal a flash lamp (SUGAWARA Laboratories, NPL-5) emitted a pulse light (180ns duration) after designated delay time. The emitted light passed through lens, water vessel, pinhole and R.B.filter (KAISER OPTICAL SYSTEMS, Rejection band filter #2891, 532nm) and entered into the digital still camera. A pinhole and R.B.filter were settled at a focusing position near the camera to weaken the laser light noise. We analyzed the behavior and shape of the bubble using these taken image data.

A high-speed camera (KEYENCE, Motion Analyzing Microscope VW-6000, Maximum 24000fps) was also used in order to observe the behavior of bubble with high-speed frame mode. Experimental apparatus for high-speed camera is shown in Fig. 2. Laser, water vessel, test wall were same as above-mentioned apparatus (Fig. 1). Light source was included in VW-6000, and light for visualization was supplied through optical fiber. The laser beam was converged near the test wall and made plasma and a single bubble. Light source for visualization emitted light continuously. Tracing paper was settled between light source and water vessel in order to diffuse the emitted light. An R.B.filter was settled between the water vessel and the camera to weaken the laser light noise. We observed the behavior of bubble and the deformation of test wall at 24000fps.
3. FUNDAMENTALS OF LASER-INDUCED BUBBLE BEHAVIOR

In this section, the fundamental aspects of laser-induced bubble behavior are described.

(1) Pulsed laser beam focused into liquid makes plasma (Fig. 3 (a)).

(2) The single bubble is produced in liquid and rapidly expands by internal high temperature. At the same time, the strong pressure wave is generated by bubble inflation (Fig. 3 (b)).

(3) The bubble stops its growing. By inertial force the bubble grows beyond pressure equilibrium surface (described with broken line in Fig. 3). At this phase the pressure inside the bubble is lower than surrounding pressure (Fig. 3 (c)).

(4) The bubble starts to shrink because surrounding pressure is higher than the pressure inside the bubble (Fig. 3 (d)).

(5) During shrinking phase, the bubble shrinks beyond pressure equilibrium surface by inertia of bubble and surrounding. At the end of this shrinking phase, the bubble is at high pressure and high temperature (Fig. 3 (e)).

(6) The bubble re-expands. At this phase the strong pressure wave is generated by bubble inflation (Fig. 3 (f)).

(7) As above described, the bubble shows several expanding and shrinking, and collapses on sub-millisecond time scale.

The solid wall near the bubble makes asymmetric flow field. Behavior of the single bubble near the solid wall is affected by the asymmetric flow field. The flow field makes lower pressure region during shrinking phase as shown in Fig. 4. As the results, the bubble moves toward the wall, and sometimes makes micro-jet as shown in Fig. 5. It is known that the behavior of bubble in asymmetric flow field strongly depends on the distance between bubble and solid wall.

4. DEFINITION OF PARAMETERS

In this section the definitions of several parameters for analyzing bubble dynamics are described as follows.

(1) Elapsed time \( t \): The pulsed Nd:YAG laser emits light at time \( t = 0 \). Elapsed time \( t \) can be changed by the delay generator at most 1 \( \mu \)s temporal resolution.

(2) Coordinates and bubble position: The origin is test wall surface under the focusing position. Y-axis is taken perpendicular to wall surface, and \( y_t \) indicates position of bubble top, and \( y_b \) indicates bubble bottom.
(3) Aspect ratio: We introduce aspect ratio of the bubble in order to observe the change of bubble shape. Aspect ratio is defined by the following equation.

\[
\text{Aspect ratio} = \frac{H}{W}
\]

where \(H = y_t - y_b\) is the height of the bubble and \(W\) is the width of the bubble.

(4) Non-dimensional focusing position \(\gamma\): Bubble behavior is affected by the solid wall near the bubble. Relative distance between test wall and bubble is an important factor for bubble behavior. Non-dimensional focusing position \(\gamma\) is defined by the following equation.

\[
\gamma = \frac{h}{R_{\max}}
\]

where \(h\) is focusing position (i.e. distance from the test wall surface to the focusing position) and \(R_{\max}\) is maximum bubble radius.

5. EXPERIMENTAL RESULTS

In this section the experimental results are described. We performed four different types of experiments near an aluminum wall (\(h = 0.86\)mm), near a foam rubber wall (\(h = 0.85\)mm), near a whetstone wall (\(h = 0.93\)mm), and near a sponge wall (\(h = 0.85\)mm). The laser-induced single bubble visualized with schlieren method by digital still camera was observed as shown in Fig. 9.

5.1 Behavior of the Bubble near an Aluminum Wall (\(h = 0.86\)mm, \(R_{\max} = 0.69\)mm, \(\gamma = 1.24\))

Behavior of laser-induced bubble near a flat aluminum wall was visualized and investigated. Temporal variation of bubble shape visualized with schlieren method is shown in Fig. 10. Elapsed time \(t\) is
indicated under the each picture. Expansion of the bubble was observed until approximately $t = 61.2\mu s$. The bubble near an aluminum wall moves toward the wall and collides. Temporal variation of the bubble positions $y_t$ and $y_b$ are shown in Fig. 11 (a). Horizontal axis is the elapsed time $t$ [\mu s] and vertical axis is $y$ [mm]. Bubble positions ($y_t$ and $y_b$) are described with averaged value and $2\sigma$ error bar from $t = 1.2\mu s$ to $t = 241.2\mu s$ and observation interval is $20\mu s$. Broken line $y = 0.87mm$ describes the focusing position. Expansion, shrinking and rebounding of the bubble can be observed. Lower bubble surface (indicated by $y_b$) hardly moves during its shrinking phase. Temporal variation of Aspect ratio is shown in Fig. 11 (b). Horizontal axis is elapsed time $t$ [\mu s] and plotted open circles describe Aspect ratio of the observed individual bubbles. The bubble tends to keep spherical shape during the expanding phase. The bubble near an aluminum wall becomes slightly vertically elongated during the shrinking phase and horizontally elongated by collision with the aluminum wall.

![Fig. 10 Temporal variation of bubble shape near an aluminum wall](image)

![Fig. 11 Temporal variation of (a) bubble position and (b) aspect ratio near an aluminum wall](image)

5.2 Behavior of the Bubble near a Foam Rubber Wall ($h = 0.85mm$, $R_{max} = 0.65mm$, $\gamma = 1.32$)

Behavior of laser-induced bubble near a flat foam rubber wall was visualized and investigated. Foam rubber is elastic and soft material. Water cannot flow through the foam rubber. Temporal variation of the bubble shape visualized with schlieren method is shown in Fig. 12. Expansion of the bubble was observed until approximately $t = 61.2\mu s$. The bubble near a foam rubber wall becomes vertically elongated and moves away from the wall after expansion. Temporal variation of the bubble position is shown in Fig. 13 (a). Expansion, shrinking and rebounding of the bubble can be observed. Rapid growth of upper bubble surface (indicated by $y_t$) is observed during the rebounding phase (approximately $t = 120 \sim 180\mu s$). Temporal variation of Aspect ratio is shown in Fig. 13 (b). The bubble near a foam rubber wall tends to become horizontally elongated during its shrinking phase and vertically elongated during the rebounding phase. The dispersion of Aspect ratio near a foam rubber is greater than that near an aluminum wall. Thus, behavior of the bubble near a foam rubber wall is obviously different from that near an aluminum wall.

![Fig. 12 Temporal variation of bubble shape near a foam rubber wall](image)
5.3 Behavior of the Bubble near a Whetstone Wall ($h = 0.93$mm, $R_{max} = 0.64$mm, $\gamma = 1.47$)

Behavior of laser-induced bubble near a flat whetstone wall was visualized and investigated. Whetstone is rigid material that has rough surface. Water cannot flow through the whetstone. Temporal variation of bubble shape visualized with schlieren method is shown in Fig. 14. Expansion of the bubble was observed until approximately $t = 61.2$\mu s. The bubble near a whetstone wall becomes vertically elongated and moves toward the wall and collided. Temporal variation of the bubble position is shown in Fig. 15 (a). Expansion, shrinking and rebounding of the bubble can be observed. This tendency is similar to that of the result near an aluminum wall. Temporal variation of aspect ratio is shown in Fig. 15 (b). The bubble tends to become spherical during its expanding phase. The bubble near a whetstone wall becomes slightly vertically elongated during the shrinking phase and horizontally elongated by collision with the whetstone wall. This tendency is also similar to the result near an aluminum wall.
5.4 Behavior of the Bubble near a Sponge Wall ($h = 0.85\text{mm}$, $R_{\text{max}} = 0.74\text{mm}$, $\gamma = 1.14$)

Behavior of laser-induced bubble near a flat sponge wall was also visualized. Sponge is porous, elastic and soft material. Water can flow through the sponge. Temporal variation of bubble shape visualized with schlieren method is shown in Fig. 16. Expansion of the bubble was observed until approximately $t = 81.2\mu\text{s}$. The bubble near a foam rubber wall shifts away from the wall after its rebounding phase. Temporal variation of the bubble position is shown in Fig. 17 (a). Expansion, shrinking and rebounding of the bubble can be observed. The growth of upper bubble surface (indicated by $y_t$) is smaller than the result near the foam rubber wall. Temporal variation of aspect ratio is shown in Fig. 18 (b). The bubble tends to keep spherical shape during the expanding and the shrinking phases. The dispersion of this value, however, suddenly increases when rebound starts.

6. DISCUSSION

The behaviour of the laser-induced single bubbles near an aluminum wall and near a whetstone wall moved toward the wall and collided. On the other hand the bubble near a foam rubber wall and near a sponge wall moved away from the wall. The behavior of bubbles near a foam rubber wall and near a sponge wall cannot be explained by the fundamental scheme described in section 3. High-speed camera helps to clarify these phenomena. Slight deformation of the foam rubber wall was observed by high-speed camera visualization. Significant deformation of the sponge wall, however, was not observed. The deformation of solid wall makes higher pressure region between the bubble and the wall by its elasticity (Fig. 18). As a result, behavior of the bubble near an elastic and soft wall is inverted to the moving flow field near a rigid wall. According to the high-speed camera visualization, this wall deformation will be caused by primary pressure wave or bubble expansion, or both. These results imply that, in the case of medical laser application, the behavior of the laser-induced bubble near body tissue will be different from that near bone. Furthermore, it is shown that we can control behavior of the laser-induced bubble by changing material or position of wall near the bubble. Additional work is underway to clarify the effects of other materials for bubble behavior and shock waves.
7. CONCLUSION
In this research the behaviors of laser-induced bubble near an aluminum wall (rigid material), near a foam rubber wall (elastic and soft material), near a whetstone wall (rigid material) and near a sponge wall (elastic and soft material) in distilled water have been investigated by visualization technique. The main results are indicated as follows:
1. Laser-induced bubble in the distilled water was able to be visualized clearly with schlieren method by using a rectangular acrylic water vessel.
2. High-speed camera helped us to observe the behavior of the bubble and the rapid deformation of the test wall continuously.
3. The behavior of the bubble was able to be measured with schlieren photograph. The video taken by the high-speed camera at 24000fps was not so enough for analysis of bubble behaviour itself.
4. The directions of the bubble movement were obviously different near the different materials; the bubbles near an aluminum wall and near a whetstone wall moved toward the wall, and the bubbles near a foam rubber wall and a sponge wall moved away from the wall.
5. Slight deformation of the foam rubber wall was observed.
6. Aspect ratio was introduced as an index of bubble shape. Aspect ratio tended to change drastically after the first expanding.

REFERENCES
