LA-UR- 99-697

Approved for public release;
distribution is unlimited.

CONF-990611--

Title: ASPHERICAL BUBBLE DYNAMICS
AND OSCILLATION TIMES

Author(s): Alfred Vogel and Joachim Noack
Medizinisches Laserzentrum Luebeck
D-23562 Luebeck, Germany

Edward J. Chapyak and Robert P. Godwin
Group XNH
Applied Theoretical and Computational Physics Division
Los Alamos National Laboratory, Los Alamos, NM 87545

Submitted to: The New Concepts in Therapeutic Laser Applications session of
CLEO / Europe, EQEC Focus Meeting, June 13-17, 1999,
ICM - Internationales Congress Center Muenchen-Munich,
Germany

RECEIVED

APR 12 1999

OSTI

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MASTER

Los Alamos

NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Form 836 (10/96)

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Aspherical bubble dynamics and oscillation times

Alfred Vogel and Joachim Noack

Medizinisches Laserzentrum Lübeck, D-23562 Lübeck, Germany
vogel@mll.mu-luebeck.de

Edward J. Chapyak and Robert P. Godwin

Los Alamos National Laboratory, MS F664, Los Alamos, NM 87545, USA
rpg@lanl.gov

Novel features of aspherical bubble dynamics are explored by time-resolved photography and numerical simulations. The growth-collapse period of cylindrical bubbles of large aspect ratio (length:diameter ~ 20) differs only slightly from twice the Rayleigh collapse time for a spherical bubble with an equivalent maximum volume. This fact justifies using the temporal interval between the acoustic signals emitted upon bubble creation and collapse to estimate the maximum bubble volume. As a result, hydrophone measurements can provide an estimate of the bubble size and energy even for aspherical bubbles. The change of the oscillation period of bubbles near solid walls and elastic (tissue-like) boundaries relative to that of isolated spherical bubbles is also investigated.

INTRODUCTION

The cavitation bubbles common in laser medicine are rarely perfectly spherical and are often located near tissue boundaries, in vessels, etc., which introduce aspherical dynamics. It is, on the other hand, desirable to be able to determine a bubble's volume and energy by very simple means. The bubble oscillation period can be determined from hydrophone measurements of the pressure pulses emitted at bubble generation and collapse. For spherical bubbles, the relation between bubble volume (radius) and oscillation period (twice the collapse time) can be approximated by the Rayleigh equation

$$T_c = 0.915 R_o \sqrt{\frac{\rho}{p_\infty - p_v}}, \quad (1)$$

where ρ , $\ll p_\infty$, ρ , p_∞ , p_v , and R_o are the fluid density, background fluid pressure, effective pressure of vapor and gas within the bubble and maximum bubble radius respectively. Bubbles associated with medical applications of lasers often have cylindrical geometry. Examples include long-pulse infrared laser experiments and short-pulse water breakdown experiments. We checked the accuracy of the Rayleigh relation for aspherical dynamics by experimental and numerical investigations of cylindrical bubble dynamics in an infinite fluid volume and of initially spherical bubbles near a wall and in a tube. For isolated cylindrical bubbles, we found that the Rayleigh model is a surprisingly good approximation. On the other hand, nearby planar and tubular walls the bubble oscillation period increases significantly over that of Rayleigh's model. Nevertheless, if information on the location of the bubble with respect to a nearby wall is available, corrections to the Rayleigh collapse time determined in this study allow an estimate of the bubble size and energy scale from hydrophone signals and Eq.(1) even in this case.

METHODS

Cylindrical bubbles were generated by focusing Nd:YAG laser pulses ($\lambda = 1064$ nm) with 30 ps duration and up to 4 mJ pulse energy into a cuvette with distilled water. We used a focusing angle of 4° and large pulse energies to produce strongly elongated plasmas and, hence, cylindrical bubbles. The bubbles were imaged with a framing rate of 200,000 s⁻¹ using an image converter camera. The bubble volume was determined for each frame assuming rotational symmetry of the bubbles around the optical axis of the laser beam.

Using the LANL MESA2D code, we numerically investigated the dynamics of cylindrical bubbles similar to those produced experimentally. The initial shape of the volume in the simulations was a cylinder with hemispherical end caps. Two initial conditions were examined: a water cavity filled with a $\chi=1.4$ perfect gas at a pressure of either 50.5 or 505 bars; χ is the gas specific heat ratio. We compared the dynamics of these initially cylindrical bubbles (initial length to diameter ratio $\sim 20:1$) to the dynamics of spherical bubbles of the same initial volume and gas fill.

When a cavitation bubble is produced in the vicinity of a solid boundary, a liquid jet directed toward the boundary is formed, and the collapse time is prolonged as compared to the collapse of an isolated spherical bubble. The prolongation factor k depends on the dimensionless distance $\gamma = s / R_{\max}$ between bubble and boundary, where s is the distance between bubble center and boundary at the time of bubble generation, and $R_{\max}$ is the maximum bubble radius. To determine the prolongation factor k , we measured the bubble oscillation periods for laser-produced initially spherical bubbles as a function of γ . The bubbles were produced by ns-Nd:YAG laser pulses with constant energy which were focused into a cuvette of distilled water with a large convergence angle. The pulse-to-pulse fluctuations of the energy were $\pm 2\%$ and we assumed that, regardless of γ , the volume fluctuations of the laser-generated bubbles also remained within these limits. To avoid vignetting of the laser beam at the solid boundary, which would change the effective laser pulse energy, we focused the laser pulses through a glass plate (microscope slide) submerged into the cuvette. The glass plate served as the solid boundary. The bubble oscillation periods $2T_c$ at various γ values were determined using a PVDF hydrophone to detect the pressure pulses emitted upon bubble generation and collapse. The reference time $2T_c$ for spherical bubble oscillations was determined at $\gamma > 20$.

RESULTS

Cylindrical bubbles

High speed photography revealed that the cylindrical bubbles initially expand radially with hardly any axial motion. Then, after reaching their maximum volume (length to diameter ratio: 5:1), they collapse along their long axis with relatively slow radial motion. Figure 1 shows the temporal evolution of the bubble length and diameter. Both the length and diameter are, in different degrees, asymmetric for the expansion and collapse phases of the bubble. The temporal evolution of the bubble volume, however, is more symmetric. This symmetry is demonstrated by plotting the equivalent diameter of a spherical bubble which has at each time the same volume as the cylindrical bubble investigated experimentally. In Fig. 2, the evolution of the equivalent spherical diameter of the cylindrical bubble of Fig. 1 is compared to the diameter-time curve of a spherical bubble with the same oscillation time. The curve for the spherical bubble is almost perfectly symmetric, whereas the curve for the cylindrical bubble is slightly asymmetric. The maximum size of both bubbles is, however, almost the same. The oscillation time thus depends almost exclusively on the bubble volume and hardly at all on the bubble shape. This remarkable result justifies the use of Eq. (1) to estimate the maximum bubble volume of aspherical bubbles from the time interval between the acoustic signals emitted upon bubble creation and collapse. We will see below, however, that this applies for bubbles produced in the bulk of a liquid, but not for bubbles near material boundaries.

Fig. 1 Axial length and radial diameter of a cylindrical bubble produced with a 4 mJ laser pulse. Also plotted is the diameter of an equivalent spherical bubble which has at each time the same volume as the cylindrical bubble.

Fig. 2 Equivalent spherical diameter of the cylindrical bubble in Fig. 1 and diameter-time curve for a spherical bubble with the same oscillation time.

In the MESA simulations of the evolution of bubble shape for the low (50.5 bar) initial pressure case, the bubble retains a cylindrical shape throughout most of the dynamics, but finally collapses with jet formation inward along the cylindrical axis. The behavior in this simulation is similar to that of the experimental photo series. The cylindrical bubble with an initial fill pressure of 505 bars grows to a more spherical shape (aspect ratio 1.2:1 at maximum expansion) before collapsing with an inward jet developing along the cylindrical axis. With still higher

initial pressures, the bubble dynamics becomes nearly spherical at all but very early and very late times in the growth-collapse cycle. Cylindrical and spherical bubbles reach almost the same volume and have very similar collapse times, as observed experimentally. As in the experiment, the cylindrical bubble reaches its maximum slightly before half of the oscillation cycle has passed.

Bubbles near solid or elastic boundaries

Figure 3 shows the results of our measurements of the prolongation factor for bubble oscillations near a solid boundary. Note that the collapse time has a maximum at $\gamma = 1$ and decreases for $\gamma \rightarrow 0$. This behavior is probably related to the fact that the collapse at $\gamma = 0$ is nearly hemispherical, that is, exhibits less deviation from spherical than the collapse at $\gamma = 1$.

Fig. 3 Prolongation factor, k , for the oscillation period of a bubble near a solid wall plotted against the distance to the wall normalized by the maximum bubble radius.

Szymczak et al.¹ calculated the bubble dynamics for $\gamma = 1$ near a rigid wall and obtained a prolongation factor $k = 1.20$, in good agreement with the experimental result, $k = 1.18 \pm 0.02$. Our simulations with the MESA2D for $\gamma = 1.1$ were performed with three slightly different situations: 1. Collapse of an initially spherical empty cavity 2. a spherical cavity with a low-pressure gas fill, and 3. the growth-collapse cycle of a small high-pressure spherical seed bubble with the pressure chosen so that the maximum volume would correspond to that of the bubble of case 2. The k values deduced from these three numerical simulations are 1.18, 1.19, and 1.16, respectively.

We have also simulated the effect of both elastic and rigid tubular walls on the bubble oscillation period of an initially high-pressure seed bubble. These cases approximate the configuration of many laboratory and clinical laser medical applications. As one might expect, the period prolongation of nearby tubular walls is much stronger than that of a nearby planar wall. At comparable bubble-wall distances, a planar wall produces a prolongation of $\leq 20\%$ and a tubular wall a prolongation of $\sim 2x$. For elastic tissue-like boundaries, the oscillation time was shortened by 5% for $\gamma = 1$, and by 15% for $\gamma = 0$.

CONCLUSIONS

Both experiments and simulations show that the oscillation period of large aspect ratio cylindrical bubbles differs only slightly from twice the Rayleigh collapse time for a spherical bubble with an equivalent maximum volume. The oscillation time depends almost exclusively on the bubble volume and hardly at all on the bubble shape. Eq. (1) can therefore serve to estimate the maximum bubble volume of aspherical bubbles from the time interval between the acoustic signals emitted upon bubble creation and collapse. In order to use Eq. (1), one needs only to define the equivalent maximum bubble radius as

$$R_o \equiv \left(\frac{3}{4\pi} V_o \right)^{1/3}, \quad (2)$$

where V_o is the maximum bubble volume. The bubble energy relates to the equivalent spherical radius by $E_B = V_o(p_\infty - p_v)$. This approximation will be also be useful for non-spherical bubbles with shapes other than cylindrical. The approximation cannot, however, be used with bubbles near material interfaces. Nearby rigid walls significantly increase the bubble growth-collapse period. This prolongation of the period is a systematic function of the distance of the bubble from the wall. As a result, if one knows the distance of a bubble from a nearby wall and the prolongation factor $k(\gamma)$, one can relate the measured growth-collapse oscillation period determined from hydrophone signals to the maximum bubble volume and thereby to the bubble energy.