High speed observation of HIFU-induced cavitation cloud near curved rigid boundaries

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Abstract. This paper focuses on the experimental study of the influence of surface curvature to the behaviour of HIFU-induced cavitation cloud. A Q-switched ruby pulse laser is used to induce cavitation nuclei in deionized water. A piezoelectric ultrasonic transducer (1.7 MHz) provides a focused ultrasound field to inspire the nucleus to cavitation cloud. A PZT probe type hydrophone is applied for measuring the HIFU sound field. It was observed that the motion of cavitation cloud located near the boundary is significantly influenced by the distance between cloud and boundary, as well as the curvature of the boundary. The curvature was defined by parameters $\lambda$ and $\xi$. Convex boundary, concave boundary, and flat boundary correspond to $\xi < 1$, $\xi > 1$ and $\xi = 1$, respectively. Different behaviours of the cloud, including the migration of the cloud, the characteristics of oscillation, etc., were observed under different boundary curvatures by high-speed photography. Sonoluminescence of the acoustic cavitation bubble clouds were also studied to illustrate the characteristics of acoustic streaming.

1. Introduction

In recent years, precision damage with cavitation bubbles attracts more and more attentions, especially in the field of therapeutics, etc. It is recognized that the damaging power of cavitation bubbles is mainly caused by the high-speed microjet during the collapse of the bubble near a boundary wall. The behaviors of the bubble and the microjet are strongly influenced by the physical and geometrical conditions of the boundary.

Benjamin [1] found that a solid boundary induces asymmetric flow around a bubble, resulting in bubble migration toward the boundary due to the secondary Bjerknes force [2], and finally the formation of a liquid microjet. Tomita [3] recognized that the strength of jet is related to the parameter $\lambda (\lambda = L/R_{\text{max}})$, the distance between bubble center and target wall over the maximum radius of the migrate bubble. In recent research, Tomita’s experiments [4] show that when a comparable sized bubble is located near a rigid boundary the bubble motion is significantly influenced by the surface curvature of the boundary. The curvature is characterized by a parameter $\xi$, giving convex walls for $\xi < 1$, concave walls for $\xi > 1$ and a flat wall when $\xi = 1$. Uneven target walls lead to larger velocity of a liquid jet than the flat wall.

In the study of utilizing acoustic cavitation for calculus fragmentation, the cavitation clouds are induced by a HIFU (High Intensity Focused Ultrasound) device near the surface of the stones. The collective behavior of the bubble clouds, resulting from the interactions between clouds and the targets’
surface [5], will have significant influence on the fragmentation efficiency. It has been shown that some similarities exist between the ensemble oscillations of the cavitation clouds induced by HIFU, and a single bubble oscillation model, in terms of the oscillating frequency spectrum [6]. It is thus postulated that the behavior of the cavitation clouds, and hence the fragmentation efficiency, might be influenced by the curvatures of the boundary walls.

A series of experiments has been designed and carried out to study this relationship between surface curvature and the behavior of cavitation clouds induce by HIFU, and preliminary results are presented below.

2. Experimental arrangements
In order to experimentally investigate the influence of surface curvature on the behavior of the HIFU-induced cavitation clouds, the following procedure was established:

1) Cavitation clouds were generated near the surfaces with different curvatures of artificial kidney stones made from a ceramic Begostone powders, by exposure under the acoustic field of a HIFU transducer in deionized water. The volumetric loss of the stones against time were then recorded, by using a 3D scanning technique, in order to evaluate the fragmentation efficiency.

2) In order to observe the behavior of the cavitation clouds, another set of experiments was carried out in degassed NaCl solutions. Surfaces with different curvatures were realized with machining of stainless steel samples. A Q-switched ruby laser was used to induce cavitation nuclei at prescribed locations. Cavitation clouds then grew from these nuclei under the radiation of HIFU acoustic field. A high-speed video camera was utilized to observe the oscillation and movement of the clouds.

3) In order to identify the cavitation intensities and the characteristics of acoustic streaming, sonoluminescence tests were carried out in luminol solutions, by utilizing a photomultiplier and a digital SLR camera.

An overall schematic of the experimental setup is shown in figure 1. Detailed experimental devices are illustrated below.

2.1. Water chamber
Since the focused sound field produced by HIFU transducer possesses a conical shape, and the cavitation clouds appear at the spindle-shaped focal region, the chamber was specially designed around the focus of the transducer. The main body of the chamber was fabricated with plexiglass, with a quartz glass window on each of the four side walls, forming a 60×60×80 mm viewing zone. This will
benefit the observation of the behavior of cavitation clouds. A PZT HIFU transducer was secured vertically at the chamber bottom, as shown in figure 2.

![Figure 2. Water chamber.](image)

2.2. **HIFU system**
Two PZT HIFU transducers have been used in the research, with natural frequency of 1.7 MHz and 1.1 MHz, and diameters of 70 mm, a focal length of 150 mm and 100 mm, respectively. The transducers were driven by a waveform generator (100 Msa/s sampling rate, 14 bits vertical resolution, frequency range $1 \mu \text{Hz} \sim 12 \text{ MHz}$), connected to a power amplifier (power amplification 50 dB). The focal region pressure reaches 1 MPa (cavitation threshold $\sim 0.7$ MPa [6]) when input voltage comes to 0.3 V.

2.3. **High speed video camera system**
A VRI Phantom V711 high speed video camera ($2.156 \times 10^5 \text{ fps} @ 128 \times 64 \text{ bit}$), together with a long-range microscope (magnification $0.11 \times \sim 67.5 \times$, working length 100 mm) were used to observe the behavior of cavitation cloud.

2.4. **Laser systems**
In order to induce stable cavitation clouds at prescribed locations, a Q-switched ruby laser (INNOLAS ltd. QSR laser, wavelength 694.3 nm, peak energy 1.5 J/pulse, pulse width 20 ns) was used for nuclei production in degassed NaCl solutions. An optical lens system was designed to focus the laser beam into the focal region of the HIFU transducer. The beam was first expanded through a concave lens, then converged through two convex lenses (figure 3).

![Figure 3. Lens system.](image)

2.5. **Laser system**
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production in degassed NaCl solutions. An optical lens system was designed to focus the laser beam into the focal region of the HIFU transducer. The beam was first expanded through a concave lens, then converged through two convex lenses (figure 3), to have a large converge angle. A continuous wave (cw) He-Ne laser with a similar wavelength was utilized to precisely adjust the location of the nuclei.

2.6. Artificial stone samples
As stated above, two types of artificial stone samples, made from ceramic Begostone powders, and stainless steel, were fabricated, for the purposes of measuring volumetric loss and observing the behavior of cavitation clouds, respectively. As shown in reference [4], a curved wall can be expressed as a steady streamline as a result of the combined flows induced by two point sources with different strengths.

![Figure 4. Surface curvature.](image)

The curved wall can be expressed as a stable streamline induced by two point sources. Cavitation cloud oscillates at $O(0, 0, h)$, and point source $A$ is at $(0, 0, -\xi h)$. The strength of point source $B$ is $\xi^2$ times that of $A$. The formula for the curve in the $(r, z)$ plane is expressed as:

$$f(r, z) = \left[ r^2 + (h - z)^2 \right]^{1/2} \left\{ \xi^2 \left( z + \xi h \right) + \left( 1 - \xi^2 \right) \left[ r^2 + (z + \xi h)^2 \right]^{1/2} \right\}$$

$$- (h - z) \left[ r^2 + (z + \xi h)^2 \right]^{3/2} = 0$$

In case of $h=10$, 5 different curves can be obtained when $\xi=0.10, 0.20, 0.50, 0.75, 1.00$, as shown in figure 4.

3. Results and Discussions

3.1. Calculus fragmentation observation
Figure 5 shows the high speed recording of the calculus fragmentation process, of the case $\xi=0.2$, HIFU inducer frequency 1.75 MHz, driving voltage 1.5 Vpp. Figure 6 shows the 3D scan of the erosion pattern during the fragmentation process, analyzed with Geomagic software package. A vertical bright streak in the middle of the view in figure 5 indicates the variation of refractive index caused by the strong acoustic field. The length of the horizontal black line in the figure is 1mm. It can be seen from these two figures that, in the 6 minutes of observation, two stages of the fragmentation
can be distinguished. A circular erosion pattern occurs in the first stage, until the center of the surface is grinded flat. In the second stage, erosion mainly occurs in the center, forming a crater in the end.

**Figure 5.** High speed photographic observation of calculus fragmentation process ($\zeta=0.2$, HIFU inducer frequency 1.75 MHz, driving voltage 1.5 Vpp).

The volumetric loss with different surface curvatures during the fragmentation process can be seen in figure 7. The overall rule of fragmentation efficiency is that, smaller the value of $\zeta$ is (the more convex the surface is), faster the samples are eroded. This trend is no longer obvious when $\zeta>0.5$.

**Figure 6.** 3D scan of the erosion pattern.
3.2. High speed observation of cavitation cloud behaviour

The purpose of this experiment is to have a clearer observation on the behavior of cavitation cloud. Since minute particles in the liquid generated in previous fragmentation experiments on Begostone artificial stone samples will bring difficulties in clear visual observation of cavitation cloud, cavitation cloud was generated near stainless steel samples in NaCl solutions in this experiment. The schematic of this experiment is shown in figure 8. 20g/L NaCl solutions were used to reduce the content of dissolved gases. A converging laser beam with energy just below cavitation threshold was used to induce cavitation nuclei in the prescribed location. The HIFU transducer with 1.1 MHz frequency was driven with 0.5 Vpp voltage input to excite the nuclei. The behavior of the cavitation cloud was then observed by high speed photography.

Figure 9 shows the high speed observation results of $\xi=0.2$. The cloud grows from the nuclei induced by the laser beam, under the exposure to the acoustic field. It then moves towards the surface of the sample, due to the effect of acoustic streaming. A circular cavitation ring is then formed and oscillates on the surface, while the center of the surface is cavitation free.

Comparing with the erosion pattern described before, it is postulated that this form of cavitation ring is responsible for the ring-shaped damage in the first stage of fragmentation on the Begostone samples. More analysis shows that the diameter of the cavitation ring is related to the value of $\xi$. The bigger the value of $\xi$ is, the larger the diameter. The moving speed of the cavitation cloud toward the surface is also related to the value of $\xi$. Smaller value of $\xi$ corresponds to faster movement. The quantitative relationships are still under investigation.
3.3. Sonoluminescence tests
Sonoluminescence tests were carried out to study the cavitation intensity, and the behavior of acoustic streaming in the process. 0.01mol/L Luminol solutions and 0.1mol/L NaOH solutions were mixed for the purpose of observing cavitation sonoluminescence. A Nikon D7000 SLR camera (exposure time 10s) was used for the measurement of the light distribution. A Hamamatsu CR 105 photomultiplier (output resistance 82.5kΩ) was used for the measurement of the variation of light intensities.

Figure 9. Oscillation of cavitation cloud($\zeta=0.2$, inter frame interval 0.2 ms, length of horizontal black line 1mm).

Figure 10. Cavitation sonoluminescence near surface with different curvatures.

Figure 10 shows the results of cavitation sonoluminescence near surface with different curvatures. Larger value of $\zeta$ corresponds to larger reverse flow, and lower light intensity.

Figure 11 shows the measured light intensity, which is an indication of cavitation intensity, during the process. It is observed that the larger value of $\zeta$ corresponds to lower light intensity, and slower acceleration rate of the light intensity. Changing in the value of $\zeta$ causes smaller variation in cavitation intensity, when the value of $\zeta$ is small.
4. Conclusions
A series of experiments was designed and carried out to investigate the influence of surface curvature on the behavior of HIFU induced cavitation cloud. Preliminary results show that:

1) The process of calculus fragmentation can be distinguished into two stages: a circular erosion pattern occurs in the first stage, until the center of the surface is grinded flat; in the second stage, erosion mainly occurs in the center, forming a crater in the end.

2) Smaller the value of $\xi$ is (the more convex the surface is), faster the samples are eroded. This trend is no longer obvious when $\xi>0.5$.

3) The form of cavitation ring is responsible for the ring-shaped damage in the first stage of fragmentation on the Begostone samples. The diameter of the cavitation ring is related to the value of $\xi$.

4) Larger value of $\xi$ corresponds to larger reverse flow, a lower cavitation intensity, and a slower acceleration rate of the cavitation intensity in the beginning of exposure to HIFU acoustic field.

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