Surface tension and quasi-emulsion of cavitation bubble cloud

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ABSTRACT

A quasi-emulsion phenomenon of cavitation structure in a thin liquid layer (the thin liquid layer is trapped between a radiating surface and a hard reflector) is investigated experimentally with high-speed photography. The transformation from cloud-in-water (c/w) emulsion to water-in-cloud (w/c) emulsion is related to the increase of cavitation bubble cloud. The acoustic field in the thin liquid layer is analyzed. It is found that the liquid region has higher acoustic pressure than the cloud region. The bubbles are pushed from liquid region to cloud region by the primary Bjerknes forces. The rate of change of CSF increased with the increase of CSF. The cavitation bubbles on the surface of cavitation cloud are attracted by the cavitation bubbles inside the cloud due to secondary Bjerknes forces. The existence of surface tension on the interface of liquid region and cloud region is proved. The formation mechanism of disc-shaped liquid region and cloud region are analysed by surface tension and incompressibility of cavitation bubble cloud.

1. Introduction

Cavitaion refers to the formation and subsequent dynamic life of bubbles in liquids subjected to a sufficiently low pressure [1]. The high-energy concentration and the mechanical, optical, acoustical, and chemical effects of cavitation attracted the multitudinous scientist's attention and the research interest [2]. Applications of cavitation span many industrial sectors, from peening treatment, through ultrasonic lithotripsy, sonochemistry, ultrasonic cleaning and wastewater treatment, to jet cutting. Each bubble in the cavitation field acts as a single localized "hot spot" or a sonochemical reactor. The visual observations [3] indicate that cavitation bubbles rarely exist in isolation and are present in the form of clusters or clouds. Thus, the bubble dynamics should also be influenced by the growth and collapse of the surrounding bubbles. Hence it is more realistic to consider a cluster or cloud rather than a single bubble for the investigation of cavitation phenomenon. It is generally known that cavitation bubble distribution is spatially inhomogeneous; they can form different structures in the ultrasound field [4,5]. Iskander S. Akhatov [6] (1996), Ulrich Parlitz [7] (1999) and Robert Mettin [8] (1999) investigated the dynamics of acoustic

Lichtenberg figure in acoustic cavitation fields. Alexei Moussatov [5] (2003), Bertrand Dubus [9] (2010) and Olivier Louisnard [10] (2012) investigated conical bubble structures in the vicinity of the radiating surface of an ultrasonic transducer. Lixin Bai [11,12] (2012, 2014) investigated experimentally smoker cavitation structure and the cavitation structures produced by artificially implanting nuclei.

The conditions and characteristics of different types of cavitation structures are different. The cavitation in thin liquid layer was first investigated by Alexei Moussatov [13] (2005). He found that this configuration lead to a large amplification of the acoustic pressure which makes the generation of cavitation possible at low power or in a wide frequency range. García-Atance Fatjó [14] (2010) investigated the cavitation ring in a thin liquid layer using a theoretical model based on the combination of Fluid Mechanics and Analytical Mechanics. Lixin Bai [15] (2016) investigated the memory effect and redistribution of cavitation nuclei in a thin liquid layer.

The cavitation structures in a thin liquid layer show some new characteristics because of the two-dimensional nature of thin liquid layer. In this paper, a quasi-emulsion phenomenon of cavitation bubble cloud in a thin liquid layer is investigated. The present work is, from the authors' knowledge, the first analysis of surface tension of cavitation bubble cloud.

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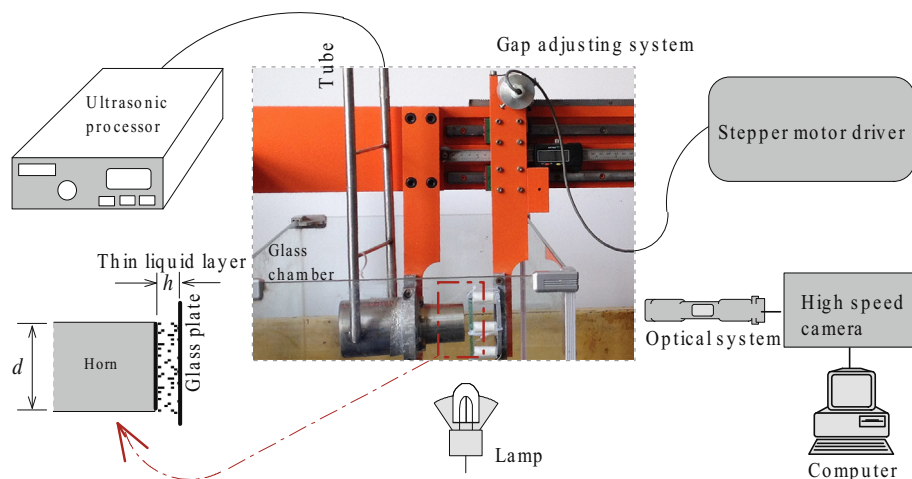
Fig. 1. Experimental set-up to visualize the cavitation structures in a thin liquid layer of varying thickness. The subfigure in the lower left corner is a schematic diagram of thin liquid layer.

2. Experiment

Fig. 1 illustrates the experimental setup when the cavitation structure in the thin liquid layer is recorded. The experimental setup consisted of the ultrasonic cavitation devices, the high-speed imaging and illumination system, step motor-driven gap adjusting system, etc. The piezoceramic sandwich transducer is well enveloped and can be submerged in water completely. The ultrasonic horn is mounted horizontally in a transparent chamber (600 mm × 330 mm × 330 mm). Fresh tap water (with many nuclei) is used in the experiment so as to reduce the cavitation threshold. The similar results can be obtained in deionized water but with less cavitation bubbles, as compared to in tap water. The high power ultrasound is produced by three ultrasonic processors (Jiuzhou Ultrasonic Technology Co., Ltd. China) with a frequency of 20 kHz (radiating surface diameter, d = 50 mm), 30 kHz

(d = 38 mm) and 40 kHz (d = 30 mm) and a maximum input electric power of 100 W. The radiating surface diameter of the sandwich piezoelectric ceramic ultrasonic transducer equals to the diameter of piezoelectric plate. Step motor-driven gap adjusting system (minimum adjustment distance: 20 μm) is used to fix the transducer and adjust the distance (liquid layer thickness, h) between the radiating surface and transparent reflection plane (glass plate thickness: 5 mm) in the experiment. Cavitation structure is recorded with a high-speed camera (Photron Fastcam SA-1, Photron Ltd., Japan) equipped with two long distance microscopes (Zoom 6000, Navitar, USA; LM50JCM, Kowa, Japan) respectively. The pictures are taken in a framing rate of 500 fps (1024 × 1024 pixels and 20 μm pixel size) to 100,000 fps (320 × 128 pixels) for the whole or the part of cavitation structures. The frames are illuminated with HALOGEN lamp (2600 W) and PI-LUMINOR high-light LED lamp (150 W). The positions of
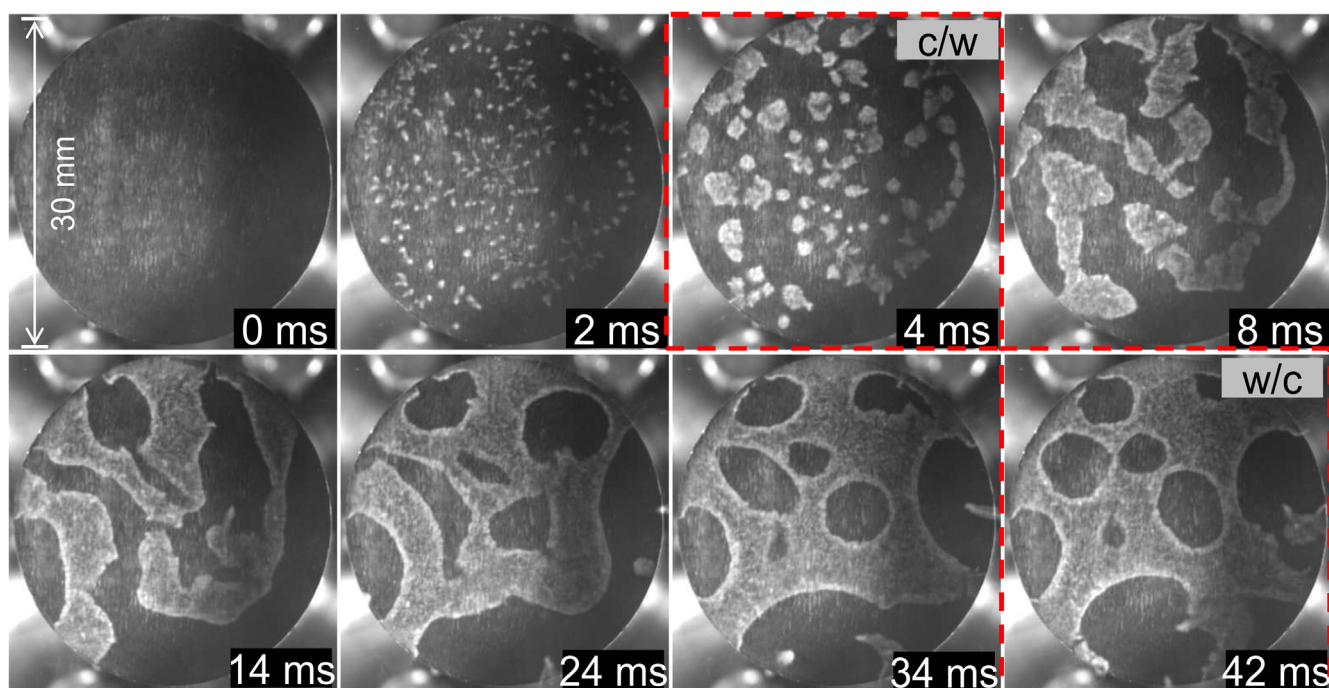
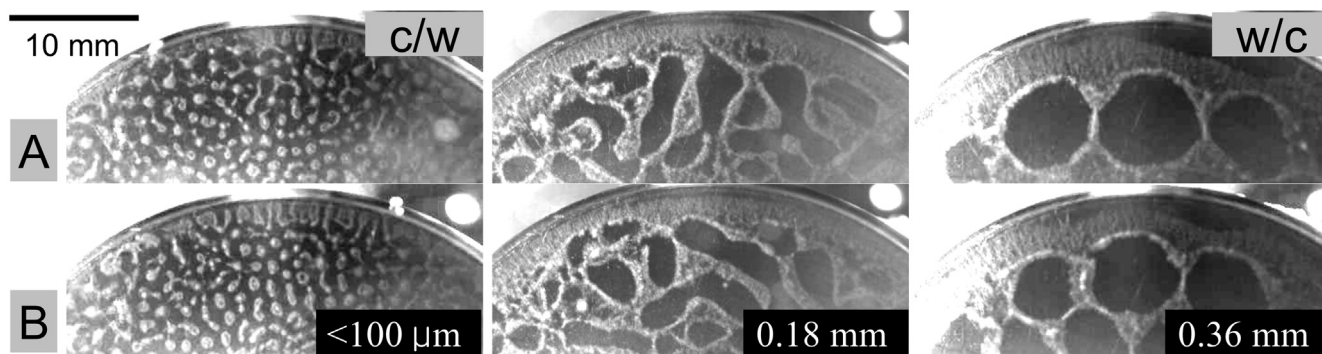**Fig. 2.** The inception of cavitation structures (f = 40 kHz, h = 1.01 mm).

Fig. 3. Cavitation structures as a function of liquid layer thickness (f = 20 kHz). (A) and (B) were captured at different time of the same experiment.
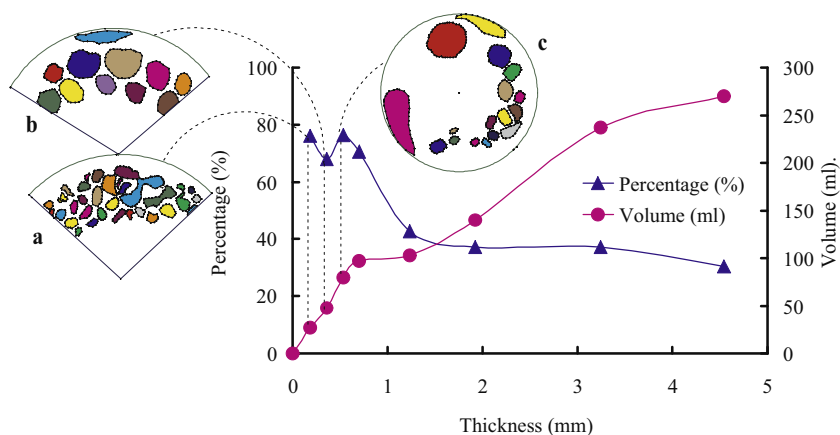

Fig. 4. The volume and percentage of cloud region in the thin liquid layer (f = 20 kHz).
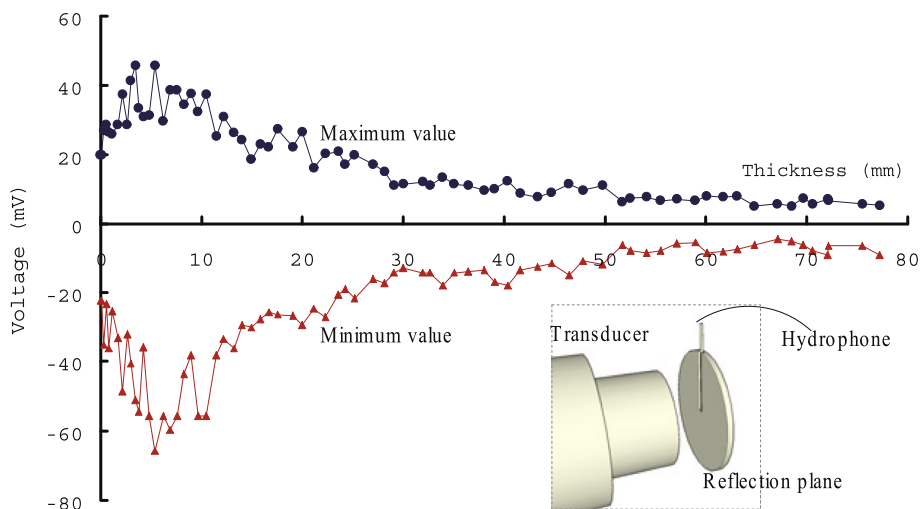

Fig. 5. The acoustic pressure in the thin liquid layer (f = 20 kHz). The vertical coordinate is defined by voltage of an uncalibrated hydrophone. The subfigure in the lower right corner is a schematic diagram of the measurement system.

light source and high-speed camera (shooting angle) were adjusted for a better photographic effect.

3. Results and discussion

In an emulsion, one liquid (the dispersed phase) is dispersed in the other (the continuous phase). A quasi-emulsion phenomenon

of cavitation structures is found in a thin liquid layer in a strong ultrasonic field.

Transient process: The inception of cavitation structures in a thin liquid layer just after turning on the transducer is shown in Fig. 2. It can be seen that light areas are cavitation region or cloud region (cavitation bubble cloud), and dark areas are non-cavitation region or liquid region (water without bubbles). With the increase of cavitation cloud, the cavitation structures transformed form
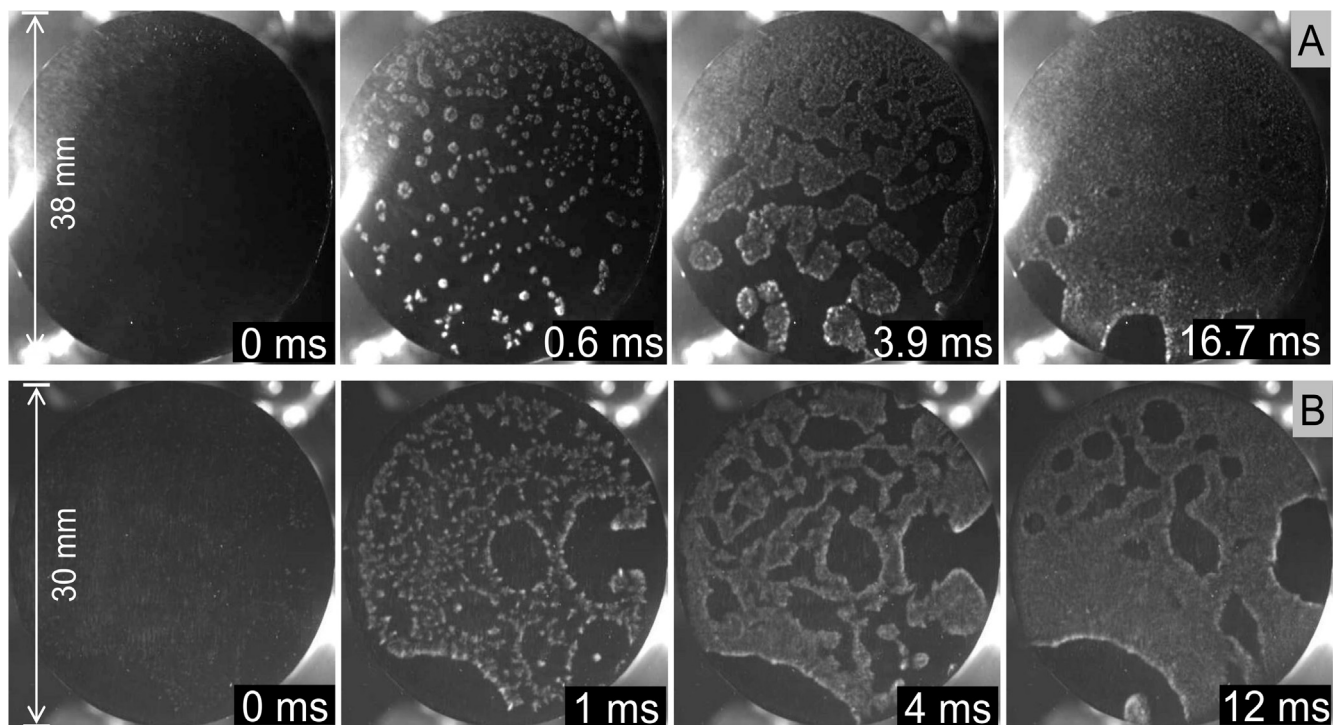
Fig. 6. The influence of cavitation nuclei distribution. (A) f = 30 kHz, h = 0.2 mm; (B) f = 40 kHz, h = 1.01 mm.
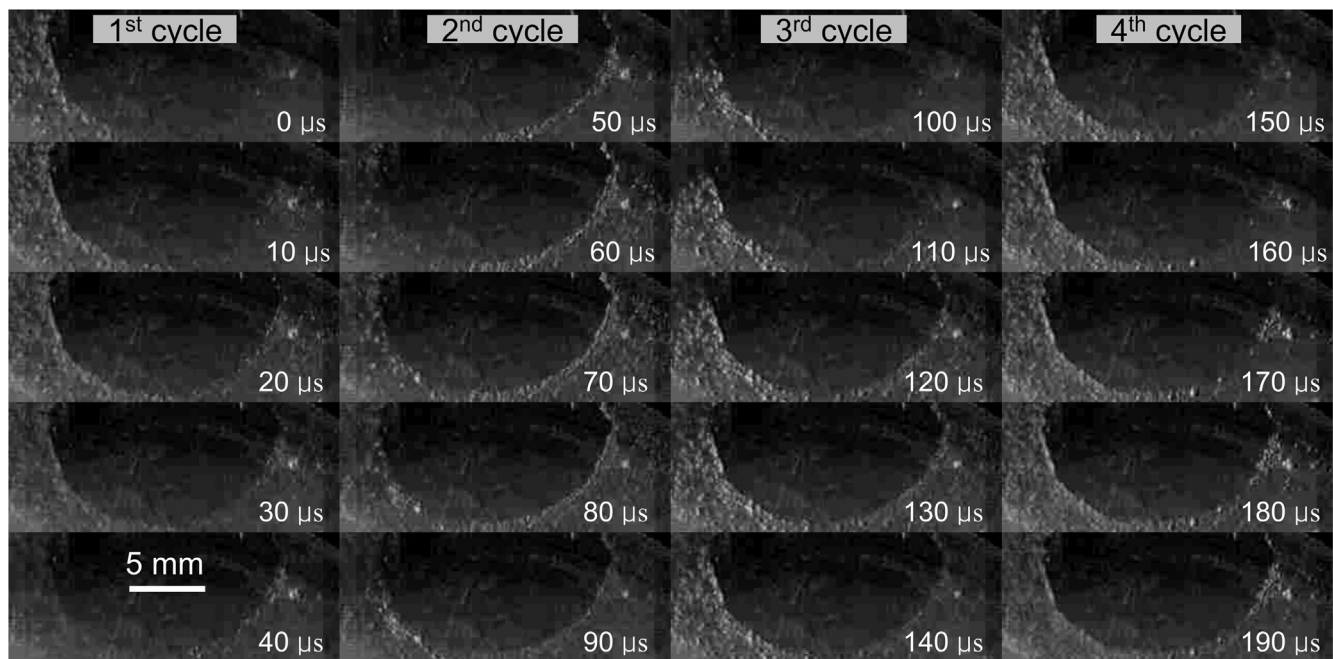

Fig. 7. The growth and collapse of cavitation bubble cluster in the four vibration cycles of the transducer (f = 20 kHz, h = 0.36 mm).

cloud-in-water (c/w) emulsion (as shown the subfigures (τ = 4 ms) in Fig. 2) to water-in-cloud (w/c) emulsion (as shown the subfigure (τ = 42 ms) in Fig. 2).

Steady-state process: The cavitation structures, when we increased the liquid layer thickness, are shown in Fig. 3. Upper pictures and lower pictures were captured at different time of the same experiment. It can be seen that, with the increase of liquid layer thickness, the cavitation structures transformed form c/w emulsion to w/c emulsion. Fig. 4 shows the volume and percentage

of cloud region in the thin liquid layer in a certain moment (as shown the subfigure a, b, c). Experiments show that the percentage of cloud region is rather stable with time for a fixed thickness. The volume was calculated by the area percentage and thickness. It can be seen that the volume of cloud region increased with the liquid layer thickness. So the transformation from c/w emulsion to w/c emulsion is also related to the increase of cavitation bubble cloud.

The phase inversion (transient process) is a common phenomenon for the cavitation cluster in the thin liquid layer, which will
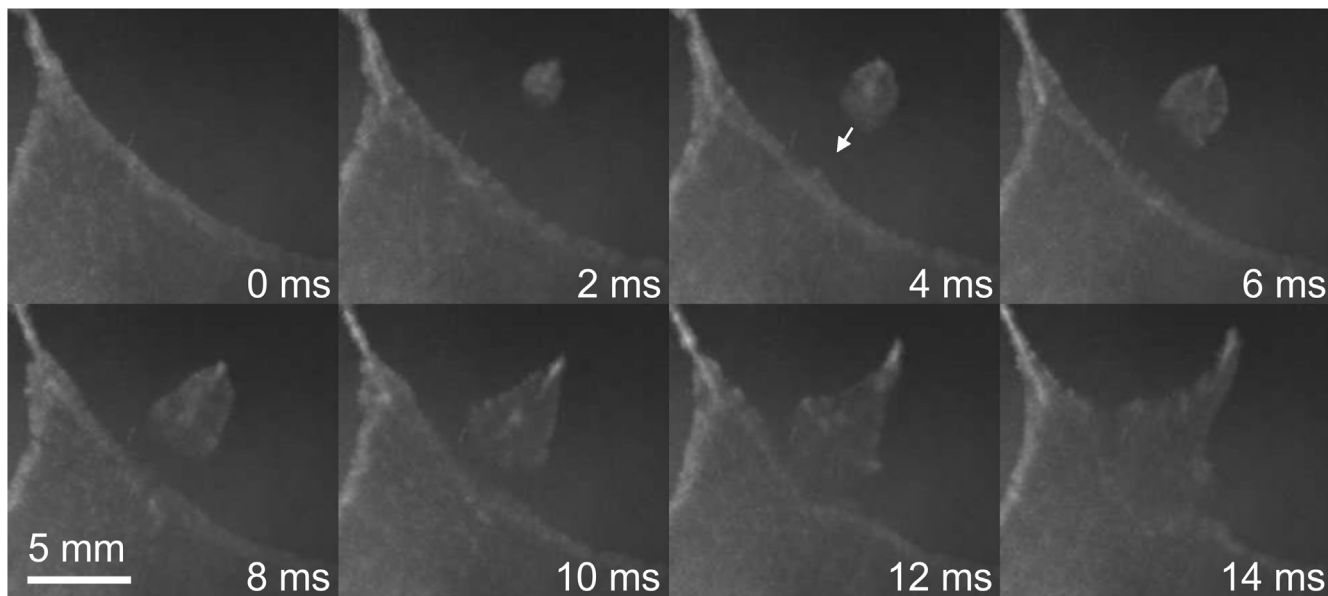
Fig. 8. The formation of a smoker in liquid region (f = 20 kHz, h = 0.7 mm).

occur when 0.3 mm < h < 0.82 mm (20 kHz), 0.3 mm < h < 1 mm (30 kHz), 1 mm < h < 2 mm (40 kHz) in our experiments. The phase inversion (steady-state process) can occur in the thin liquid layer in 20 kHz ultrasonic field; however it did not occur in 30 kHz and 40 kHz ultrasonic field (There is no c/w emulsion). We assume that it is because the transducer of 20 kHz has a smoother surface compared with the transducers of 30 kHz and 40 kHz in our experiments. The phase inversion is related to the volume of cavitation bubble cloud. When there are not enough bubbles, the cavitation bubble clouds are small and isolated, and have no chance to merge with each other (c/w emulsion). When there are enough bubbles, these bubble clouds will spread and cross-link with each other and form w/c emulsion.

Fig. 5 shows the acoustic pressure in the thin liquid layer. The hydrophone is embedded in the interior of the reflection plate. The two curves respectively represent the maximum voltage and minimum voltage of the hydrophone in 40 acoustic cycles. It can be seen that the pressure first increase and then decrease. The pressure increases monotonically with the thickness of thin liquid layer in our experiments of cavitation bubble cloud (h < 4 mm). This explains the increase in the volume of cavitation bubble cloud with the thickness.

Fig. 6 shows the influence of cavitation nuclei distribution (c/w emulsion) on the cavitation cluster distribution (w/c emulsion). When there are fewer nuclei in the lower part of in liquid layer, there will be larger liquid region in the lower part (as shown in Fig. 6A). When the cavitation nuclei are distributed in certain pattern, the cavitation cluster will have similar distribution (as shown in Fig. 6B). For more detailed information about the influence of cavitation nuclei distribution see also [15].

Because the thickness of liquid layer is much smaller than the wavelength, no standing wave can be formed. And because of the motion of cavitation bubbles inside the liquid layer, the acoustic field is unstable. Fig. 7 shows the growth and collapse of cavitation bubble cluster in the four vibration cycles of the transducer (f = 20 kHz). It can be found that bubbles are not growth and collapse at the same time, and the phase of bubble oscillation will change with time. However, the amplitude distribution of acoustic field is much more stable. The liquid region has higher acoustic pressure than the cloud region, which can be proved by the generation and motion of smoker.
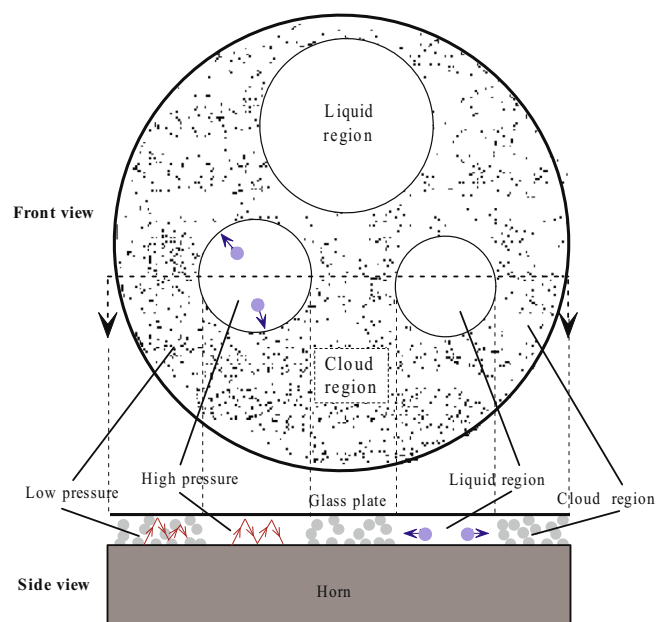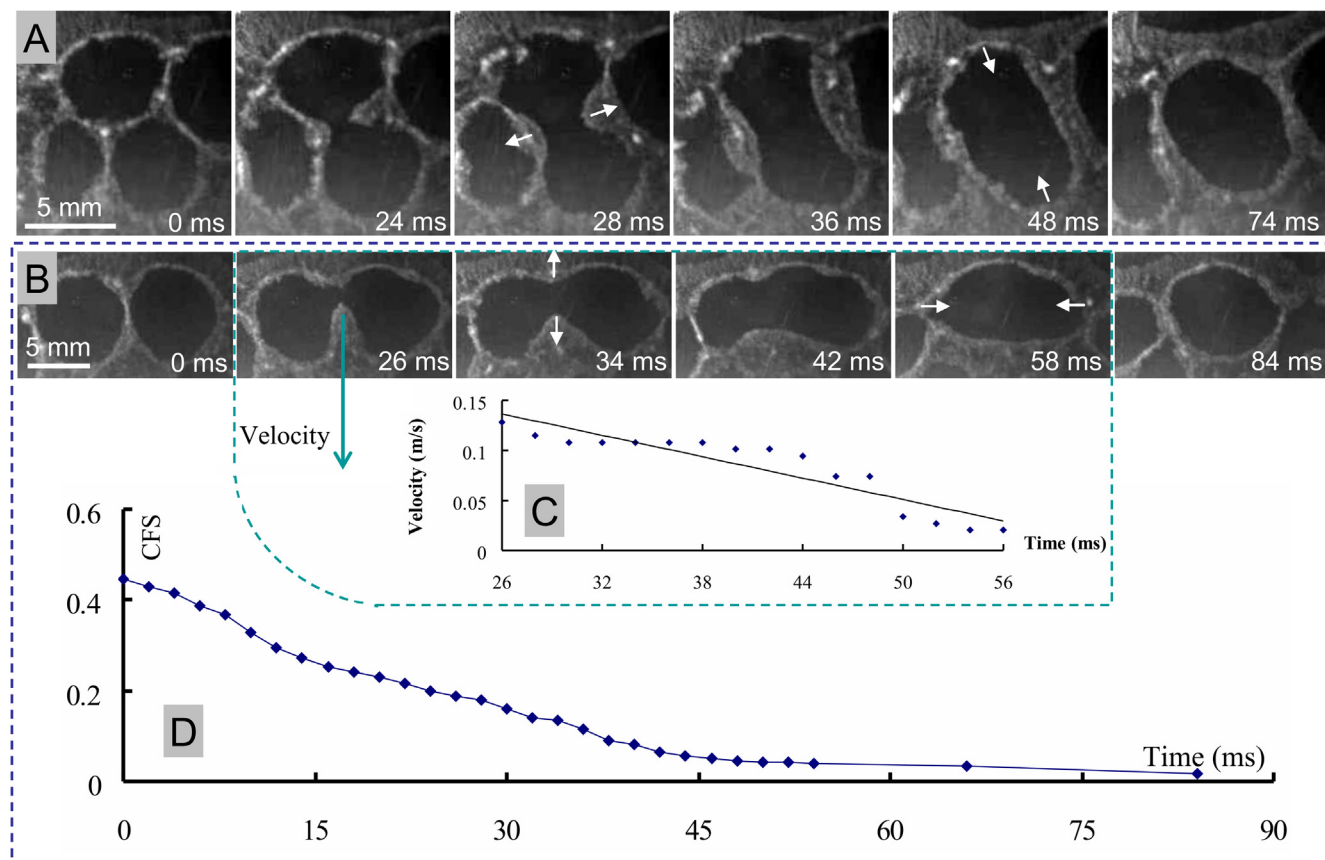

Fig. 9. The motion of cavitation bubbles in the thin liquid layer.

Smoker is a special kind of cavitation structure. Smoker is bound to the surface with a small tip and a big tail. The bubbles in smoker will always move towards the direction of pressure reduction (from tip to tail) [3,12]. So smoker can be used as an indicator to judge the direction of pressure gradient. The head of the smokers which appeared in the thin liquid layer are always toward to the center of liquid region (higher acoustic pressure). Fig. 8 shows the process of formation of a smoker. The bubbles moved form the liquid region to the cloud region. The liquid region has higher acoustic pressure than the cloud region, which is closely related to shielding effect of cavitation bubble cloud.

The motion of cavitation bubbles in the thin liquid layer is shown in Fig. 9. The cloud region (cavitation region) is formed by numerous cavitation bubbles. The acoustic intensity is weakened

Fig. 10. The motion of interface between cloud region and liquid region (*f* = 20 kHz, *h* = 0.36 mm). (A) and (B) The coalescence of two disc-shaped liquid regions. (C) The motion of cavitation bubble cluster on the lower interface of the liquid region in (B). (D) The variation of CSF of the liquid region in (B).

by the absorption and scattering of bubbles. As a result, the acoustic pressure in the liquid region (water without bubbles) is much higher than that in the cloud region. When the pressure amplitude in the liquid region exceeds a threshold value, cavitation bubbles tend to move along the direction of pressure drop [7,3]. The bubbles are pushed from liquid region to cloud region by the primary Bjerknes forces (as shown in Figs. 8 and 9). Because there are no bubbles in the liquid region, the ultrasound will be reflected and superimposed between two solid walls. So the cloud region and liquid region will remain stable for a long period (tens of milliseconds to seconds). If we do not consider the translational motion of liquid region and cloud region, stabilization time will be much longer (from seconds to minutes).

The above description and discussion explained the formation and stability of cloud region and liquid region. However, it cannot explain the circular pattern of the cavitation structures in thin liquid layers. The cloud region is disc-shaped in cloud-in-water (c/w) emulsion (as shown the subfigure (*τ* = 4 ms) in Fig. 2, the subfigure (*h* < 100 μm) in Fig. 3, the subfigure (*τ* = 0.6 ms) in Fig. 6A and the subfigure (*τ* = 1 ms) in Fig. 6B). The liquid region is disc-shaped in water-in-cloud (w/c) emulsion (as shown the subfigure (*τ* = 42 ms) in Fig. 2, the subfigure (*h* = 0.36 mm) in Fig. 3, the subfigure (*τ* = 16.7 ms) in Fig. 6A and the subfigure (*τ* = 12 ms) in Fig. 6B). Curved boundaries between the liquid region and cloud region is a very stable structure – so stable, in fact, that it is the final form of the structure evolution.

Fig. 10A, B shows the coalescence of two disc-shaped liquid regions. When two disc-shaped liquid regions are located very close to each other, a straight bar shaped cavitation structure between two liquid regions will be formed (as shown the subfigure
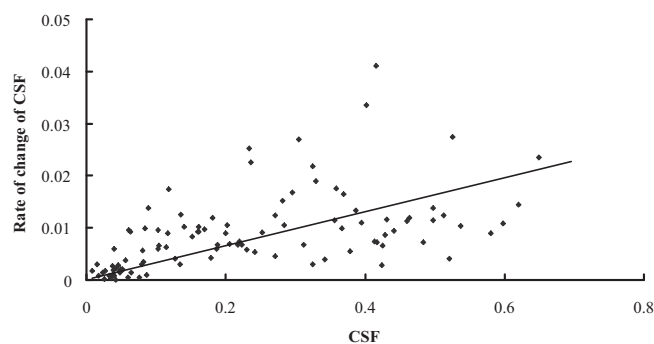
Fig. 11. The variation of rate of change of CSF with CSF (*f* = 20 kHz, *h* = 0.36 mm).

(*τ* = 0 ms) in Fig. 10A, B). It can be seen from Fig. 10A, B that inner concave surface move outside, and the outer convex surface move inside to make the interface a disc-shape. The physical process is very similar to the deformation of bubbles in water under the action of surface tension. It is found that translational speed of the lower interface of the liquid region in Fig. 10B reduced gradually (as shown in Fig. 10C). At the same time, curvature is also gradually reduced. In order to investigate the relationship between the motion and curvature of interface, a circular shape factor (CSF) is defined to represent the degree of deviation from the circular shape,

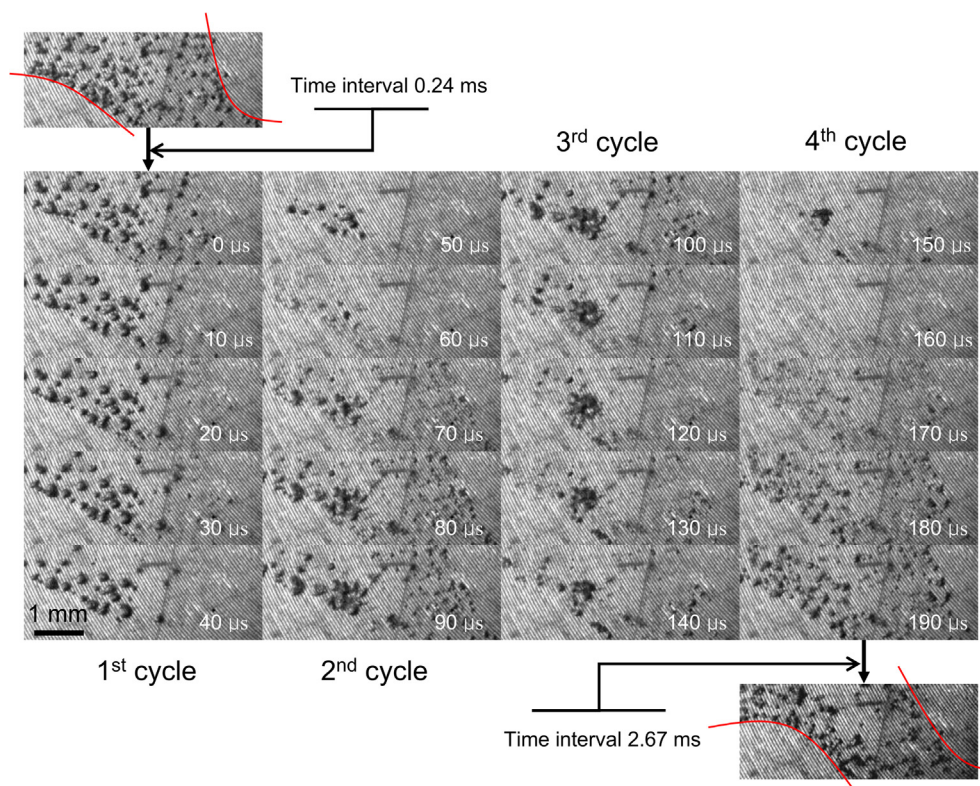$$CSF = \frac{C - \sqrt{4\pi A}}{\sqrt{4\pi A}}$$

Fig. 12. The aggregation of cavitation bubbles in the liquid layer (f = 20 kHz, h = 0.82 mm).

where C is the perimeter of liquid region, and A is area of liquid region. When CSF = 0, the shape is round. The CSF will vary over time during the deformation of circular shape.

Fig. 10D shows the variation of CSF of the liquid region in Fig. 10B. It can be seen that the value of CSF decreased gradually to nearly zero, and the slope also decreased gradually. Because the rate of deformation is related to the force, the relationship between CSF and rate of change of CSF is investigated. 6 coalescence processes of liquid regions in the same experiment are analysed (including the two coalescence processes in Fig. 10). It is found that rate of change of CSF increased with the increase of CSF (as shown in Fig. 11), which is the same with the deformation of bubbles in water under the action of surface tension. So we consider that a kind of surface tension (the elastic tendency of a cavitation bubble cloud surface which makes it acquire the least surface area possible) may exist on the interface between cloud region and liquid region. We have not found a suitable method to measure the surface tension of cavitation bubble cloud, however, which did not prevent us from analysing it.

To explore the mechanism of surface tension, we carry out experiment on bubble oscillation. Fig. 12 shows the aggregation process of cavitation bubbles between two liquid regions. It can be seen that a bubble cluster with high density is formed (as shown the subfigure (τ = 120 μs) in Fig. 12). The secondary Bjerknes forces between cavitation bubbles are responsible for the aggregation. The high density cluster is dispersed, without becoming larger (as shown the subfigure (τ = 190 μs) in Fig. 12). The secondary Bjerknes forces between cavitation bubble and boundary are responsible the uniform distribution. Acoustically hard object surfaces can attract bubbles due to secondary Bjerknes forces from reflections [1] (virtual mirror bubbles [13,14]). The bubble-boundary interaction prevents lateral migration and aggregation

of cavitation bubbles. In addition, cavitation nuclei or cavitation bubbles tend to attach to cracks or pits on the boundary [16]. So the bubbles tend to stay where they are.

The contour line (the interface between cloud region and liquid region) of bubble cluster is smooth (as shown the top left corner subfigure and lower right corner subfigure in Fig. 12). Fig. 13 shows the contour line of bubble cluster under a larger magnification. It can be seen that cavitation bubbles may across the border (as shown the subfigure (τ = 110 μs) in Fig. 13), but they return back in the next acoustic cycle. The numbers and diameters of cavitation bubbles in each acoustic cycle are different. The interaction between bubbles also changes with time. However, it can be see that the bubbles growth and collapse at the same time. Comparing with Fig. 7, we can see that despite the complexity and volatility of acoustic field in the thin liquid layer, within the scope of the secondary Bjerknes forces, most bubbles will oscillate in the same phase.

Fig. 14A shows the schematic diagram of the formation of a disc-shaped liquid region surrounded by numerous cavitation bubbles. Fig. 14C shows the high-speed photos of a disc-shaped liquid region. The bubbles in the cavitation cloud will interact with one another because the distances maybe small compared with the dimensions of bubble diameters. Most cavitation bubbles attract one another driven by the secondary Bjerknes force. The cavitation bubbles on the surface of cavitation cloud are attracted by the cavitation bubbles inside the cloud (secondary Bjerknes force) and are repelled by the high pressure in the non-cavitation liquid region (primary Bjerknes force). The surface of cavitation cloud tends to contract to the smallest possible surface area. This general effect is surface tension of cavitation cloud, which causes the liquid region to be approximately disc-shape. Fig. 14E shows the forces exerted on the cavitation bubbles on the interface to the make the contour line smooth. When a cavitation bubble or bubble clus-
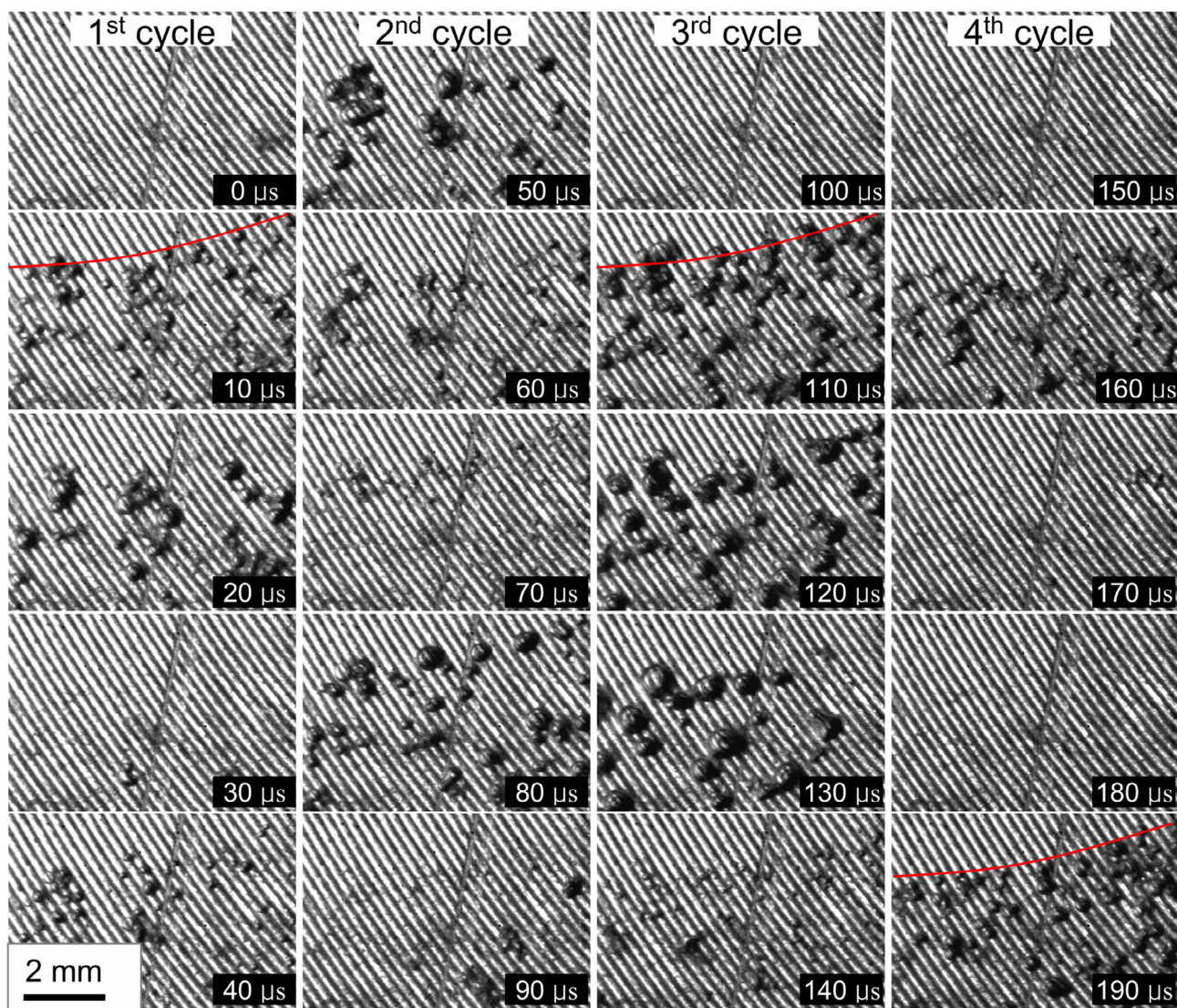
Fig. 13. The growth and collapse of cavitation bubbles near the interface of cloud region and liquid region (f = 20 kHz, h = 0.82 mm).

ter extends beyond the contour line, the secondary Bjerknes forces from neighboring bubbles will pull the bubble or bubble cluster back to the contour line, and the primary Bjerknes force from the acoustic field in the liquid region will also push the bubble or bubble cluster back to the contour line.

Fig. 14B shows the schematic diagram of the formation of a disc-shaped bubble cloud surrounded by water. Fig. 14D shows the high-speed photos of a disc-shaped bubble cloud (the continuous background has been subtracted in the lower subfigure). Because of the surface tension on the interface, the cloud region is disc-shape.

The attractive forces between bubbles tend to minimize the cavitation cloud. However, the area of cloud region does not decrease. There must be certain outward forces in the bubble cluster. Fig. 15 shows the growth of a disc-shaped cloud region when turn on the transducer. The expansion of cloud region is related to the fragmentation of cavitation bubbles. There are two opposite physical process which coexist in cavitation cloud: coalescence and fragmentation. Because the liquid layer is very thin, cavitation bubbles cannot stack together. When the cavitation bubble (or bubble cluster with high density) is too large, or the acoustic intensity is

increased, fragmentation effect is stronger than coalescence effect, and cavitation bubbles will split. When the acoustic intensity remains the same, the area of cloud region remains unchanged. The cloud region shows a certain incompressibility.

The area of liquid region may change with time. Fig. 16A shows the growth of a disc-shaped liquid region. Fig. 16B shows the disappearance of a disc-shaped liquid region. It can be seen that although the existence of surface tension on the interface of cloud region and liquid region make people tend to consider cloud region is a kind of fluid, and water region is another kind of fluid, much more work are needed to improve the model. For example, a phase change (between liquid region and cloud region) theory should be introduced to the model.

4. Summary and conclusions

A quasi-emulsion phenomenon of cavitation structure in a thin liquid layer is investigated experimentally. The transformation from c/w emulsion to w/c emulsion is related to the increase of cavitation bubble cloud. It is found that the phase of bubble oscillation will change with time. The liquid region has higher acoustic
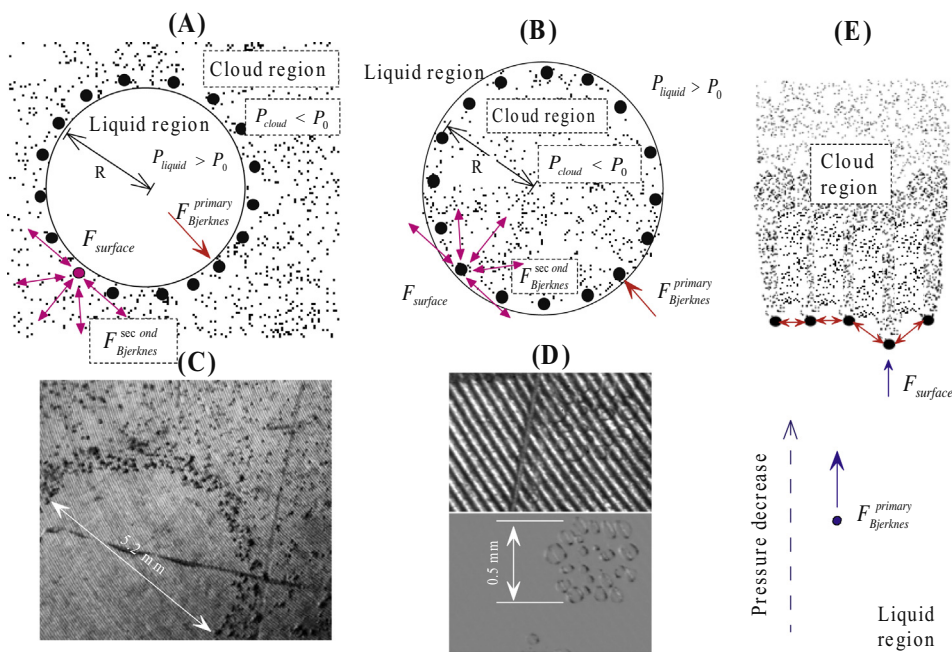
Fig. 14. The surface tension of cavitation bubble cloud. (A) and (C) A disc-shaped liquid region (f = 20 kHz, h = 0.82 mm). (B) and (D) A disc-shaped cloud region (f = 20 kHz, h < 100 μm). (E) The forces exerted on the cavitation bubbles on the interface.
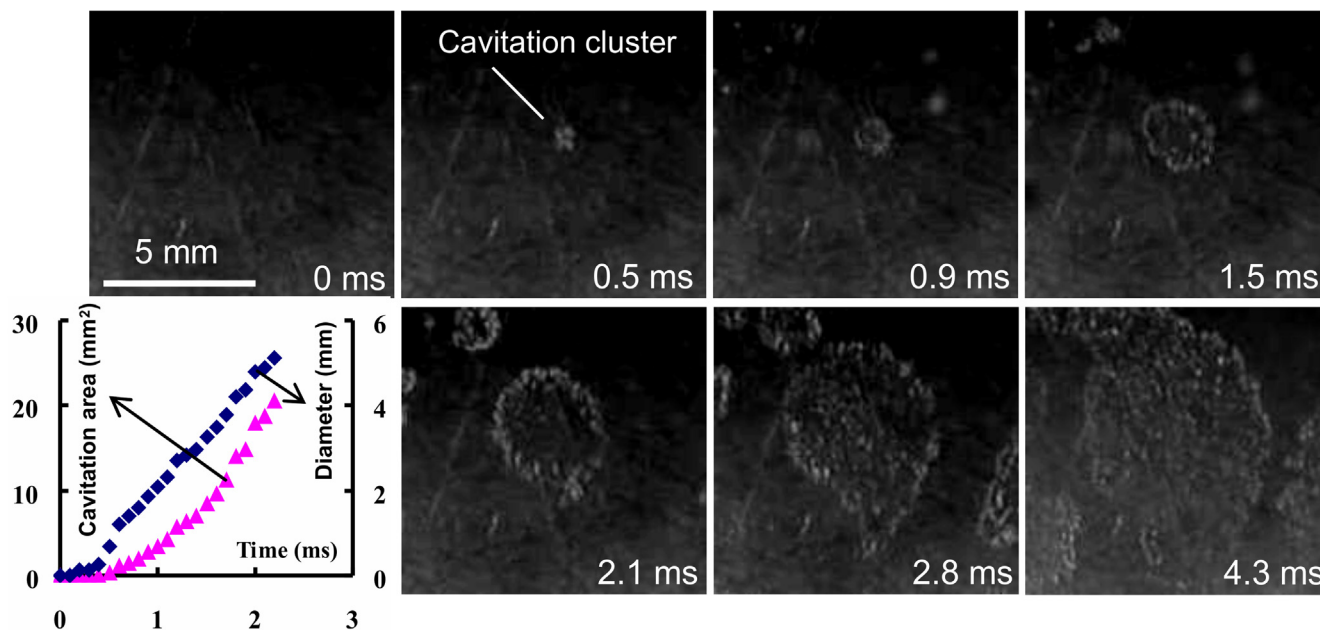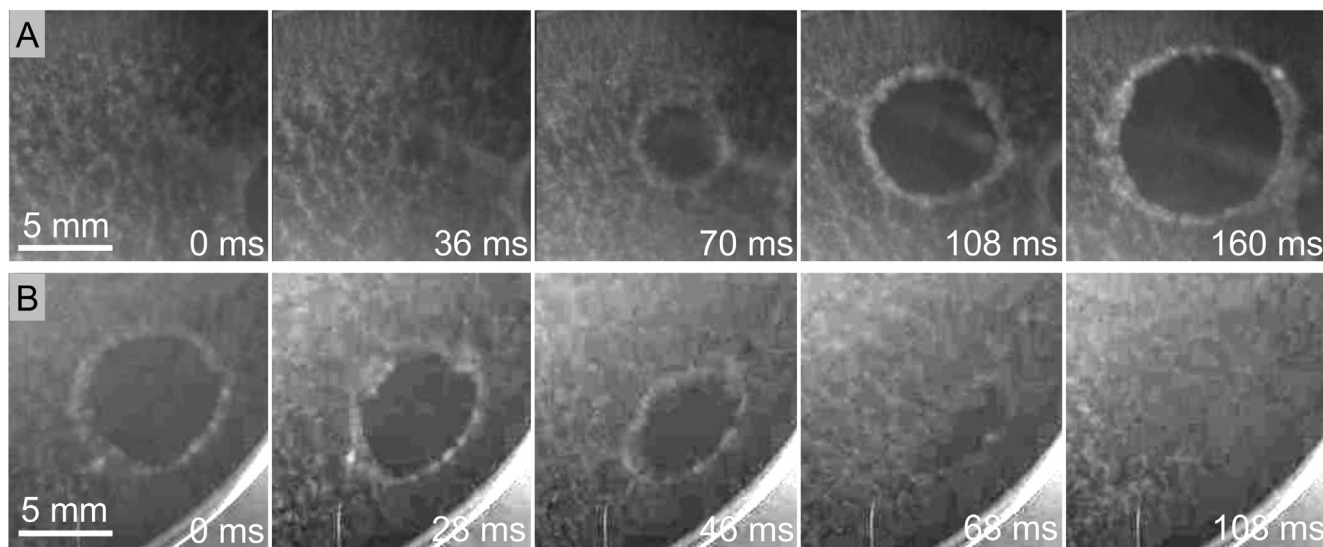

Fig. 15. The growth of a disc-shaped cloud region when turn on the transducer (f = 20 kHz, h = 0.18 mm).

pressure than the cloud region. The bubbles are pushed from liquid region to cloud region by the primary Bjerknes forces. It is found in the experiment that the rate of change of CSF increased with the increase of CSF. The cavitation bubbles on the surface of cavitation cloud are attracted by the cavitation bubbles inside the cloud (secondary Bjerknes force). This general effect is surface tension of cavitation cloud. The bubble-boundary interaction prevents lateral migration and aggregation of cavitation bubbles. Within the scope of the secondary Bjerknes forces, the bubbles will oscillate in the same phase. When the cavitation bubble (or bubble cluster with

high density) is too large, fragmentation effect is stronger than coalescence effect, and cavitation bubbles will split. Because of the surface tension on the interface, the cloud region and liquid region is disc-shape.

Fig. 16. (A) The growth of a disc-shaped liquid region (f = 20 kHz, h = 0.53 mm). (B) The disappearance of a disc-shaped liquid region (f = 20 kHz, h = 0.7 mm).

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