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Memory effect and redistribution of cavitation nuclei in a thin liquid layer

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ABSTRACT

Temporal evolution and spatial distribution of acoustic cavitation structures in a thin liquid layer were investigated experimentally with high-speed photography. The inception and disappearance processes of cavitation bubble cloud revealed that the metastable cavitaton structures formed in the thin liquid layer caused a long-term "memory effect". A factor which weakens the memory effect was identified. The distribution of cavitation nuclei was investigated by changing the temporal decay of the memory effect.

1. Introduction

After cavitation bubbles collapse, remnants of cavitation bubbles (nuclei) persist in the original location and act as seeds for subsequent cavitation events. We call this physical process "memory effect". The investigation on memory effect will help us understand the relationship of cavitation bubble cluster and cavitation nuclei, and will contribute to the application of cavitation in ultrasonic sonochemistry, ultrasonic cleaning and ultrasonic medical treatment [1].

Because there are cavitation nuclei (stabilized or unstabilized) in the liquid, cavitation can occur at lower acoustic pressure than the tensile pressure of liquid [2–4]. Harvey [5] (1944), Fox [6] (1954) have noticed that the nuclei (unstabilized) may form as fragments of bubbles that persist from collapse of transient cavities. Flynn [7] (1984), Henglei [8] (1986), Fowlkes [9] (1988) have discussed the process of above-mentioned unstabilized nuclei becoming new cavitation bubbles. In addition, Yavas [10] (1994) investigated the enhancement of acoustic cavitation at a liquid–solid interface fol1owing laser-induced bubble formation. Their experimental results indicate that metastable ultramicroscopic bubbles formed on the solid surface cause a long-term "memory effect" on acoustic cavitation. Bai [11] (2009) observed the ejection process of micro-bubbles from the top of a cavitation bubble which is located in a pit structure by means of high-speed photography. They give an explanation of why the pit structures act as a source of nuclei. Wang [12] (2012) investigated the spatial distribution of the cavitation bubbles in response to each histotripsy pulse. Then found that cavitation memory may have distinct influence on the lesion development process in histotripsy.

On the basis of the above research, this study investigated the memory effect and redistribution of cavitation nuclei in a thin liquid layer (between two parallel solid walls). The two-dimensional nature of thin liquid layer brings about some new characteristics to bubbles and nuclei. To our knowledge, there has not been any study on the cavitation memory effect in a very thin liquid layer.

2. Experiment

The experimental setup consisted of the ultrasonic cavitation devices, the high-speed imaging and illumination system, fixing and adjusting devices, hydrophone and oscilloscope, etc (as shown in Fig. 1(a)) (the experimental setup photo see also Bai [13] (2014)). The ultrasonic horn was submerged in water in a transparent chamber (600 mm × 330 mm × 330 mm). Fresh tap water is used in the experiment. The impurities or dissolved gas in tap water will reduce the threshold at which cavitation appears. The similar results can be obtained in deionized water but with less cavitation bubbles as compared to in tap water. The water temperature in the experiments is about 20 °C. Cavitation structure is recorded with a high-speed camera (Photron Fastcam SA-1, Photron Ltd., Japan), and is illuminated with high-brightness light sources.

Fixing and adjusting devices are used to fix the transducer and adjust the distance between the radiating surface (diameter:

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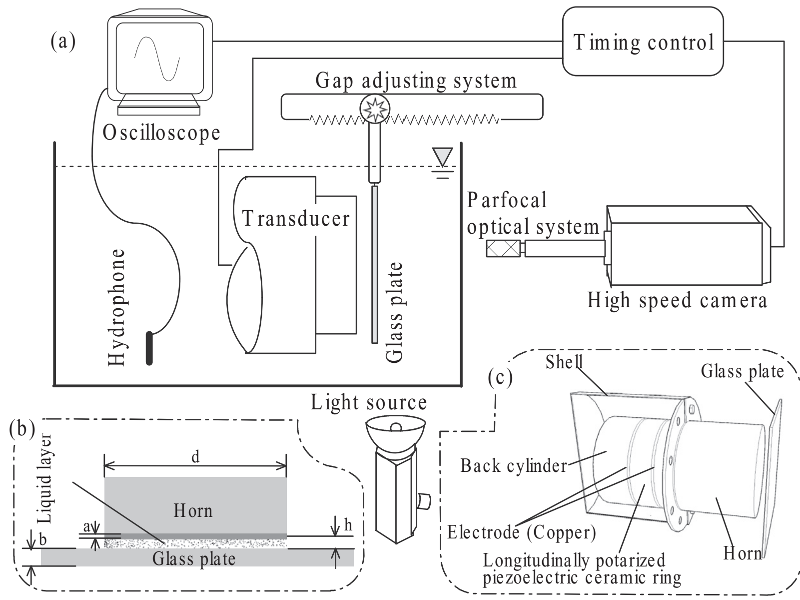

Fig. 1. (a) Experimental setup; (b) Thin liquid layer between horn and glass plate; (c) Piezoceramic sandwich transducer.

$d = 30$ mm) and reflection plane (glass plate thickness: $b = 5$ mm) in the experiment (as shown in Fig. 1(b)). The piezoceramic sandwich transducer (frequency: 40 kHz) is a continuous work in the power-type transducer (140–160w in our experiment, exclude the power loss due to voltage conversion). The transducer is well enveloped and can be submerged in water completely (as shown in Fig. 1(c)).

3. Results

The cavitation structures vary for different liquid layer thickness in the experiment (as shown in the Fig. 2). When gap distance is 8.6 mm, smoker cavitation structures are formed [14]. The cavitation bubble cluster will link to one another with the decrease of gap distance. The non-cavitation areas will be surrounded by cavitation bubble clusters. Under the effect of cluster surface tension, the cavitation structure shows circular pattern (as shown the subfigures $\tau = 2.416$ s, $\tau = 3.008$ s in the Fig. 2). The formation mechanism of cavitation structures in thin liquid layers will be described by the current authors in another paper in the near future. Layer thickness = 1.01 mm was selected in our experiment to investigate the memory effect, because there is much position information for the circular pattern: the cavitation area and non-cavitation area intertwine with clear boundaries (as shown in the Fig. 3(b)). The position information will contribute to a more accurate evaluation of cavitation memory effect. There are no cavitation bubbles in the liquid of circular areas (as shown the dark areas in the Fig. 3(b)). The circular pattern remains stable in dozens of millisecond. The memory effect of the cavitation structure was investigated in the same condition as in Fig. 3.

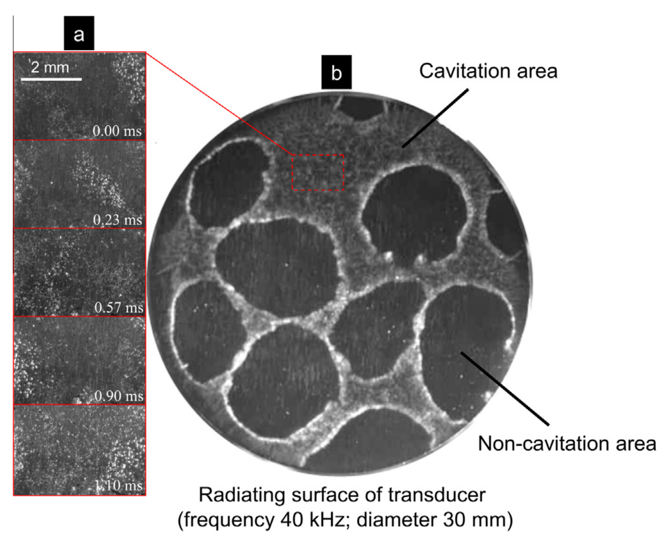

Fig. 3. Cavitation structure in thin liquid layer. (a) Cavitation cluster; (b) Snapshot of cavitation pattern.

The memory effect of cavitation structure was achieved by repeated turn-on and turn-off of transducer (as shown in the Fig. 4). The circular pattern of cavitation bubble cloud changed greatly with time ($t = 0$ ms, 100 ms, 200 ms, 300 ms). After turning

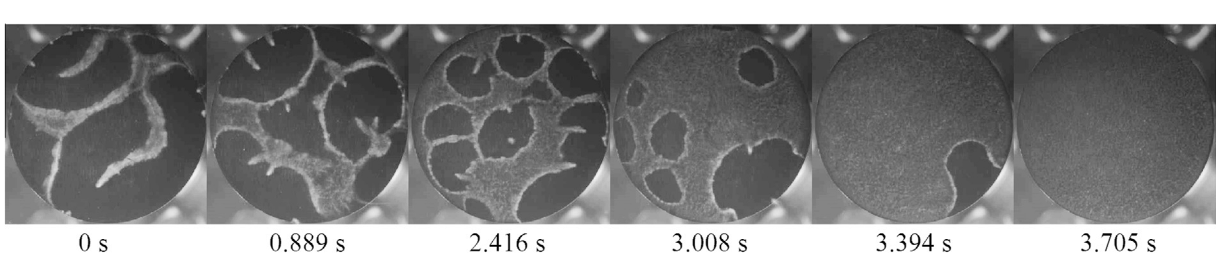

Fig. 2. The evolution of cavitation structures in a thin liquid layer when the gap distance vary from 8.6 mm to dozens of microns driven by stepmotor.

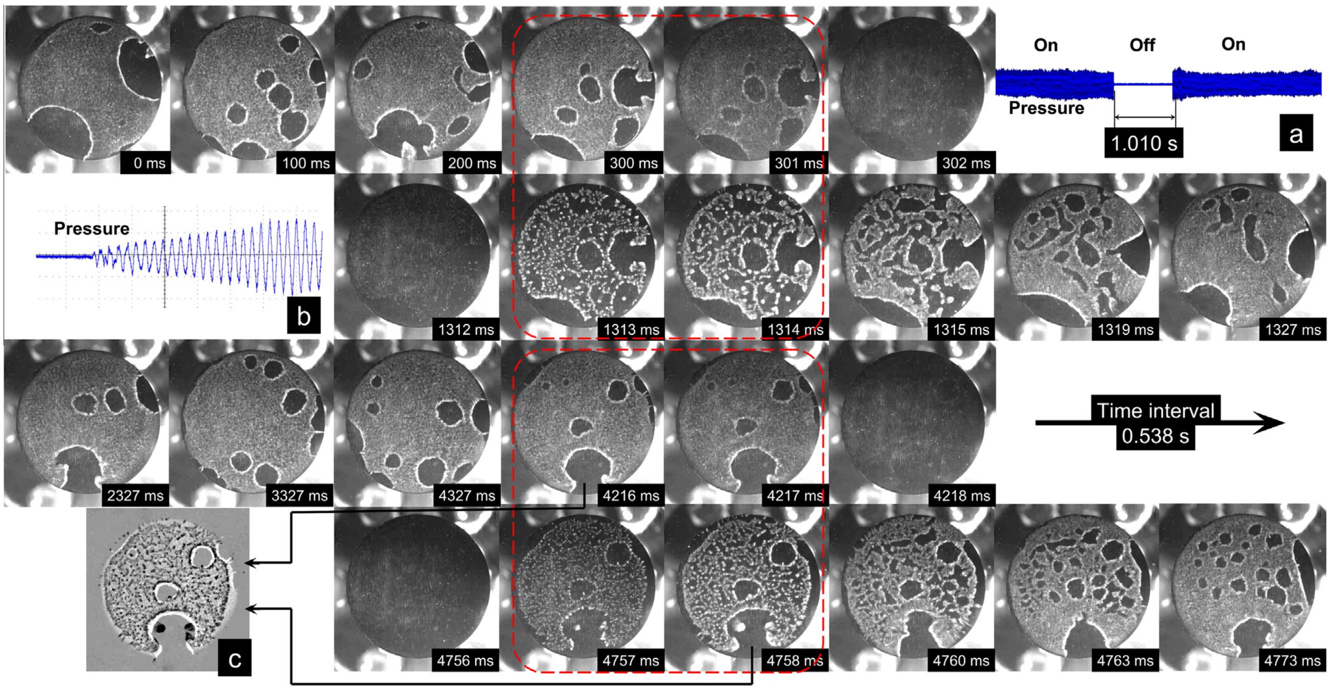

Fig. 4. Memory effect of cavitation structures in a thin liquid layer. (a) Repeated turn-on and turn-off of the transducer; (b) Acoustic pressure when turn on the transducer; (c) Comparison of cavitation structure in two pictures.

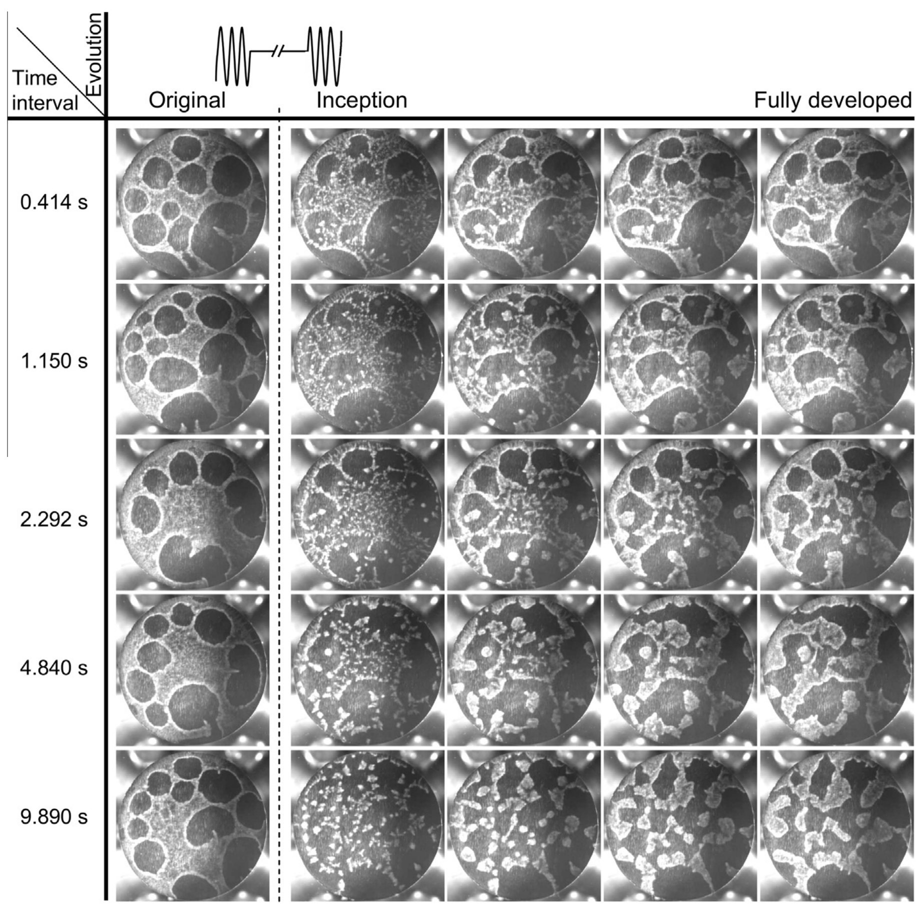

Fig. 5. Evolution of cavitation structures in different time intervals.

off the transducer for 1.01 s (as shown in the Fig. 4(a)), the transducer was turned on (as shown in the Fig. 4(b)) and the circular pattern was restored to the original shape (t = 300 ms, 301 ms, 1313 ms, 1314 ms) because of memory effect. Similar physical process was repeated again from t = 2327 ms to t = 4773 ms. We adopted methods of image subtraction to remove background from

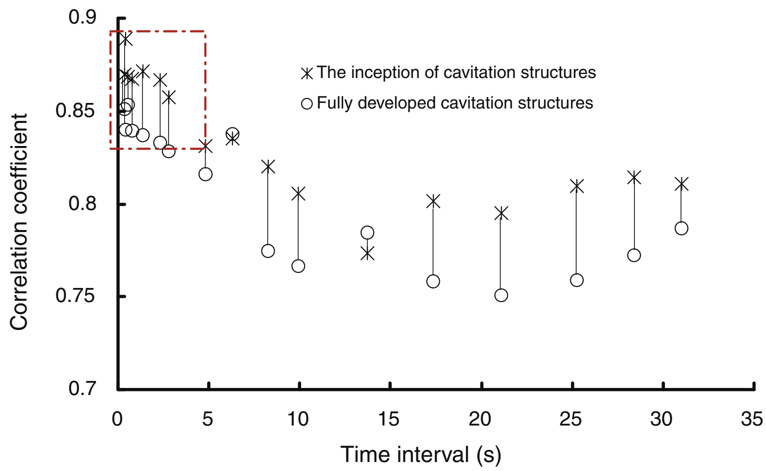

Fig. 6. Correlation coefficient of cavitation structures for increasing time intervals.

the pictures before and after the time interval (as shown in the Fig. 4(c)). It can be seen that the two pictures are very similar ($t = 2416$ ms and $t = 4758$ ms).

It was found in the experiment that the memory effect of cavitation structure was closely related to the time interval (as shown in the Fig. 5). The first column represents the original shape of cavitation structure just before turning off the transducer. The second column (the inception of cavitation structures) to the forth column (fully developed cavitation structures) represents the shape of cavitation structure just after turning on the transducer (frame rate: 500 fps). As the time interval increases the memory effect will become weak. To better evaluate the memory effect, the cross correlation coefficient between cavitation structure patterns was calculated using the following equation [12]:

$$Cross\_correlation\_coefficient = \frac{\sum_i X_{before}(i) X_{after}(i)}{\sqrt{\sum_i X_{before}(i)^2}\sqrt{\sum_i X_{after}(i)^2}}$$

where $X_{before}(i)$ and $X_{after}(i)$ are the binary images before and after the time interval and i is the pixel index on the images.

Correlation coefficient was used to measure the similarity between cavitation structures before and after the time interval (as shown in the Fig. 6). Two $X_{after}(i)$ are used to represent the cavitation structure after the time interval (inception and fully developed). It can be seen that the original shape was well recognizable when the time interval less than 5 s in our experiment condition (correlation coefficient >0.82). The correlation coefficient decreased rapidly when time interval <15 s. However, the correlation coefficient increased slowly when time interval >15 s, which is not consistent with the facts. This method is not suitable for evaluation of low similarity.

To find out the factors which weaken the memory effect, we thus tracked the small air bubbles that formed just after the transducer is turned off. When the transducer is turned off, cavitation bubbles will stop radial vibration, air bubbles of different size will be formed in the liquid. It was found in the experiments that almost all the recognizable air bubbles moved very fast just after turning off the transducer. The direction and velocity of these movements were different in different position of liquid layer for each experiment. The velocity of these movements decreased rapidly to zero (or nearly zero). Then these air bubbles began to slowly float upward (the thin liquid layer was placed vertically in the chamber). Fig. 7 shows the motion of a typical air bubble which was caught by high-speed camera when turning off the transducer. The image that shows the trajectory of the air bubble (as shown in

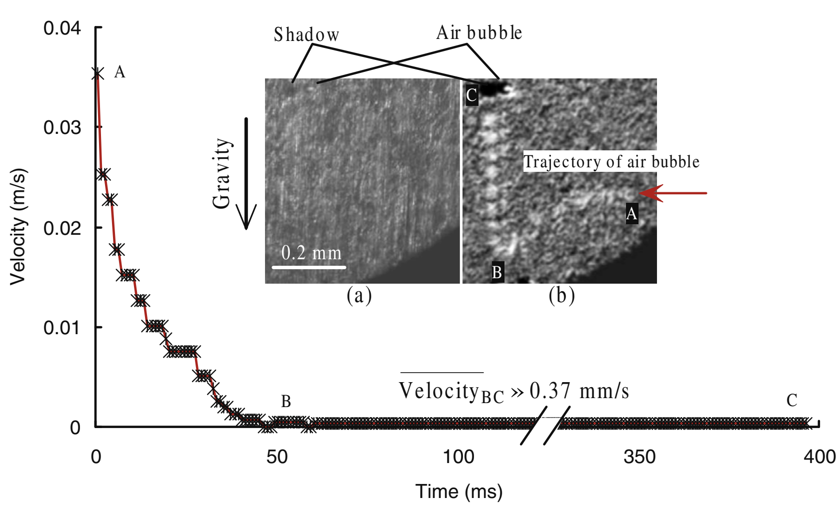

Fig. 7. The motion of a typical air bubble when turn off the transducer.

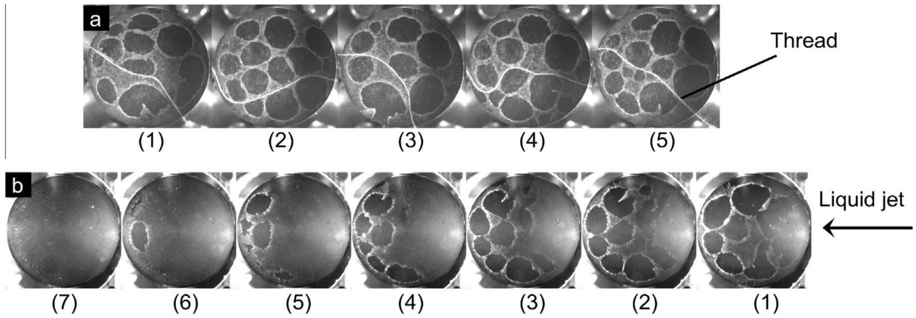

Fig. 8. Control of cavitation structures in a thin liquid layer. (a) A thread in the thin liquid layer; (b) The process of a liquid jet shooting into the liquid layer.

Fig. 7(b)) is a composite image of superimposing 16 high-speed photos (Fig. 7(a) is one of the photos) of the air bubble at typical position. The air bubble moved from A to B along the circular path in 50 ms, from B to C in 350 ms. The air bubble moved further and further away from the original location. Because these small air bubbles will become cavitation bubbles or bubble clusters when turning on the transducer, the motion of air bubbles inevitably change the distribution of cavitation bubble clusters and weaken the memory effect.

The air bubbles are not subjected to the action of acoustic radiation force or acoustic streaming when the transducer is turning off. The high-velocity motion of these air bubbles in the experiment is due to hydrodynamic force. If the gap distance is large enough, the air bubbles which are formed just after the transducer is turned off will stay at original position without high-velocity motion [15]. The sound field distribution in the thin liquid layer is very complicated. The sound field distribution will also vary with time. So the cavitation bubbles in the thin liquid layer will never collapse at the same time. Some bubbles are in the phase of growth, and some bubbles are in the phase of collapse at any time (as shown in the Fig. 3 (a)). This means there is a non-zero cavitation bubble volume ratio at any time. When the transducer is turned off all the cavitation bubbles will stop radial vibration. The variation of bubble cluster volume will cause fluid and air bubbles motion. If the gap distance is large enough, the variation of bubble cluster volume is too small (compare to the fluid volume in layer) to cause fluid and air bubbles motion.

4. Discussions and conclusions

The cavitation nuclei can be reordered by the motion of cavitation cluster (as shown in the Fig. 4 (τ = 1313 ms, τ = 4757 ms)). It is a spontaneous process caused by the interaction of cavitation bubble cluster and acoustic field. However, if we can control artificially the distribution of cavitation bubbles cluster, we can control the distribution of cavitation nuclei (by the memory effect). Two experiments give some hints towards the control of cavitation cluster distribution. Fig. 8(a) shows a thread in the thin liquid layer. As can be seen from the figure, cavitation bubble cluster tend to adhere to the thread, and the circular non-cavitation area is separated by the thread. Fig. 8(b) shows the process of a liquid jet shooting into the liquid layer. The liquid jet brings many new nuclei and form cavitation cluster in the incoming liquid. In this way it is possible to produce cavitation bubble cluster in particular position. In turn, the uneven distribution of nuclei can lead to the formation of cavitation bubble cloud with specific structure in a short time (several milliseconds) (as shown in the Figs. 4 and 5).

The cavitation bubble clusters show a particular spatial distribution pattern (cavitation structure) in a thin liquid layer. The disappearance and inception processes of the metastable cavitaton structures in a thin liquid layer are investigated in this study. There is much position information for the circular pattern of cavitation bubble clusters, which will contribute to a more accurate evaluation of cavitation memory effect. A long-term (several-second duration) memory effect was discovered in the thin liquid layer. A non-zero cavitation bubble volume ratio is responsible for the decrease of memory effect.

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References

[1] T.J. Mason, J.P. Lorimer, Applied Sonochemistry: Uses of Power Ultrasound in Chemistry and Processing, Wiley-VCH, Weinheim, 2002.
[2] R.D. Finch, Influence of radiation on the cavitation threshold of degassed water, J. Acoust. Soc. Am. 36 (1964) 2287–2292.
[3] N.F. Bunkin, F.V. Bunkin, Bubstons-stable gaseous bubbles in strongly dilute electrolytic solutions, Sov. Phys. JETP 74 (1992) 271–276.
[4] A.A. Atchley, A. Prosperetti, The crevice model of bubble nucleation, J. Acoust. Soc. Am. 86 (1989) 1065–1084.
[5] E.N. Harvey, D.K. Barnes, W.D. McElroy, A.H. Whiteley, D.C. Pease, K.W. Cooper, Bubble formation in animals. I. Physical factors, J. Cell. Physiol. 24 (1944) 1–22.
[6] F.E. Fox, K.F. Herzfeld, Gas bubbles with organic skin as cavitation nuclei, J. Acoust. Soc. Am. 26 (1954) 984–989.
[7] H.G. Flynn, C.C. Church, A mechanism for the generation of cavitation maxima by pulsed ultrasound, J. Acoust. Soc. Am. 76 (1984) 505–512.
[8] A. Henglein, M. Gutierrez, Chemical reactions by pulsed ultrasound: memory effects in the formation of NO_3- and NO_2- in aerated water, Int. J. Radiat. Biol. Relat. Stud. Phys. Chem. Med. 50 (1986) 527–533.
[9] J.B. Fowlkes, L.A. Crum, Cavitation threshold measurements for micro-second length pulses of ultrasound, J. Acoust. Soc. Am. 83 (1988) 2190–2201.
[10] O. Yavas, P. Leiderer, H.K. Park, C.P. Grigoropoulos, C.C. Poon, A.C. Tam, Enhanced acoustic cavitation following laser-induced bubble formation: long-term memory effect, Phys. Rev. Lett. 72 (1994) 2021–2024.
[11] L. Bai, W. Xu, F. Zhang, N. Li, Y. Zhang, D. Huang, Cavitation characteristics of pit structure in ultrasonic field, Sci. China Ser. E 52 (2009) 1974–1980.
[12] T. Wang, Z. Xu, T.L. Hall, J.B. Fowlkes, C.A. Cain, An efficient treatment strategy for histotripsy by removing cavitation memory, Ultrasound Med. Biol. 38 (2012) 753–766.
[13] L. Bai, J. Deng, C. Li, D. Xu, W. Xu, Acoustic cavitation structures produced by artificial implants of nuclei, Ultrason. Sonochem. 21 (2014) 121–128.
[14] L. Bai, C. Ying, C. Li, J. Deng, The structures and evolution of smoker in an ultrasonic field, Ultrason. Sonochem. 19 (2012) 762–766.
[15] L. Bai, W. Xu, J. Deng, C. Li, D. Xu, Y. Gao, Generation and control of acoustic cavitation structure, Ultrason. Sonochem. 21 (2014) 1696–1706.