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Observation of Discharge Plasma inside Cavitation Bubble Produced in Water
水中キャビテーション気泡内で生成された放電プラズマの観察

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Discharge plasmas were produced inside acoustic cavitation bubbles which were induced by ultrasonic wave at a frequency of 27 kHz and a power of 50 W. The discharge and the bubble were produced on the edge surface of a copper electrode of 1 mm in diameter. The discharge turned on and off at the same frequency as the ultrasonic wave. The expansion and shrink dynamics of the cavitation bubble within a cycle of the ultrasonic wave were observed by shadowgraph imaging. As a result, it was found that the ignition and the quenching of the discharge were observed at the expansion and shrink phases of the cavitation bubble, respectively.

1. Introduction

Recently, plasmas produced in bubbles in water have attracted attention as an interesting method for generating reactive oxidants such as hydrogen peroxide and hydroxyl radical, in conjunction with applications to water treatment, synthesis of nanoparticles, and sterilization [1-3]. Various kinds of discharges in water using DC [4-5], RF [6-7], and microwave powers [1,8] have been reported. The electrical power induces the bubble formation due to Joule heating of water, and discharges are produced inside the bubbles. The bubbles with macroscopic sizes in these experiments have an atmospheric pressure inside them.

On the other hand, it is well known that ultrasonic wave propagating in liquid can produce acoustic cavitation bubbles. The cavitation bubbles have the dynamics of expansion, shrinkage, and collapse, which result in temporal change in the pressure inside the bubbles. A cavitation bubble with the maximum size has a reduced pressure, while the bubble pressure at the collapse is as high as 1 GPa. Although the discharge inside a controlled static bubble has been reported [9], a study on the discharge inside a dynamic cavitation bubble has not been reported yet. In this work, we report the production of a discharge plasma inside acoustic cavitation bubbles.

2. Experimental

A rectangular vessel of 90x90x120 mm^3 shown in Fig. 1 was prepared for this experiment. The vessel was filled with distilled water with no gas bubbling. An ultrasonic wave at a frequency of 27 kHz and a power of 50 W propagated from the bottom of the vessel to the water surface. An aluminum punching plate with a surface area of 30x30 mm^2 and a thickness of 1 mm was inserted into water from the top. Many acoustic cavitation bubbles were generated below the punching plate [10]. The generation efficiency of cavitation bubbles was significantly sensitive to the water depth and the position of the punching plate. A copper electrode of 1 mm in diameter, which was covered with an alumina tube (1.2 mm in diameter), was inserted into the cloud of cavitation bubbles. We observed that a part of cavitation bubbles was attached on the edge

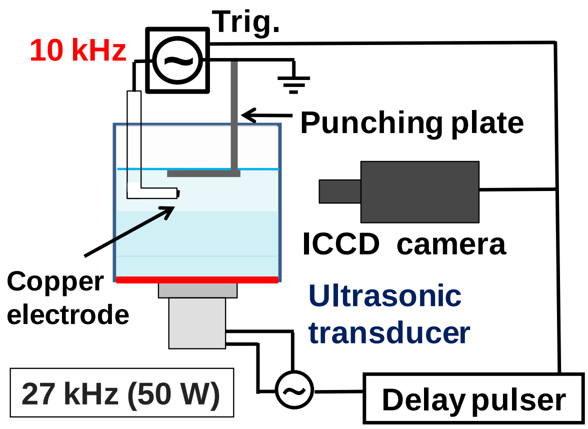

Fig.1. Schematic drawing of experimental setup.

surface of the electrode. A high-voltage (5-10 kV) power supply was connected to the electrode, while the punching plate was electrically grounded. The high voltage had pulsed waveform at a repetition frequency of 10 kHz. The dynamics of cavitation bubbles were measured by shadowgraph imaging. The optical emission image from the discharge was captured using a charge coupled device camera with an image intensifier.

3. Results

Figure 2 shows the dependence of the optical emission intensity (the spatial integration of the optical emission image) of the discharge on the frequency of the ultrasonic wave. Typical optical emission images at different frequencies are also shown in Fig. 2. The discharge voltage had a bipolar polarity with a peak voltage of 8 kV. We observed two types of discharge. One was glow-like discharge emitting pale pink radiation, which was observed at the center of the electrode. The other was arc-like discharge emitting bright white radiation, which was observed at the edge of the electrode. The glow-like discharges were observed when the ultrasonic frequency was adjusted between 26.9 and 27.8 kHz. We also observed the cloud of cavitation bubbles in this frequency range.

Figure 3 shows the optical emission images of discharges and the shadowgraph images of cavitation bubbles, which were taken from the side of the electrode. The ultrasonic frequency was 27.0 kHz. The dashed lines in the images indicate the surface of the electrode. The discharge image shown in Fig. 3(a) was observed at a phase of the ultrasonic wave, where the cloud of cavitation bubbles had the maximum size (Fig. 3(b)). It is known that the size and the shape of the discharge image roughly coincide with those of the cloud of cavitation bubbles. Figures 3(c) and 3(d) were observed at the relative phase of π with respect to that in Figs. 3(a) and 3(b). The cloud of cavitation bubbles had the minimum size at this phase. We observed no discharge at this phase as shown in Fig. 3(c). It is speculated from this result that the inside of the expanded cavitation bubble has a suitable condition for the discharge. We will compare the temporal variation of the bubble pressure with the ignition and the quenching characteristics of the discharge inside it.

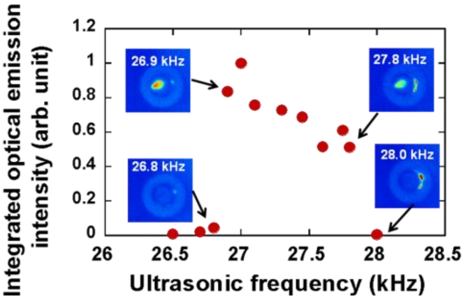

Fig.2. Relationship between the optical emission intensity of the discharge and the frequency of the ultrasonic wave.

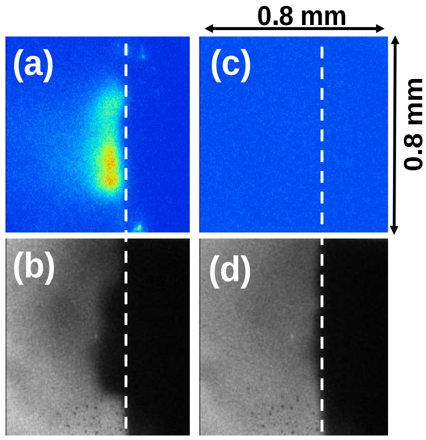

Fig.3. Images of optical emission of discharge ((a) and (c)) and shadowgraph of cavitation bubble ((b) and (d)). The phase difference between the group (a)/(b) and (c)/(d) was π.

References

[1] T. Takahashi, N. Takada, and H. Toyoda: Jpn. J. Appl. Phys. **53** (2014) 07KE01.
[2] M. Sato, T. Ohgiyama and J. S. Clements: IEEE Trans. Ind. Appl. **32** (1996) 106.
[3] J. Hieda, N. Saito and O. Takai: J. Vac. Sci. Technol. A **26** (2008) 854.
[4] B. Sun, M. Sato, and S. J. Clements: J. Phys. D **32**, (1996) 1908.
[5] H. Akiyama: IEEE Trans. Dielectr. Electr. Insul. **7** (2000) 646.
[6] T. Maehara, H. Toyota, M. Kuramoto, A. Iwamae, A. Tadokoro, S. Mukasa, H. Yamashita, A. Kawashima, and S. Nomura: Jpn. J. Appl. Phys. **45** (2006) 8864.
[7] K. Kitano, H. Aoki, and S. Hamaguchi: Jpn. J. Appl. Phys. **45** (2006) 8294.
[8] S. Nomura, H. Toyota, M. Tawara, H. Yamashita, and K. Matsumoto: Appl. Phys. Lett. **88 (2006)** 231502.
[9] K. Tachibana, Y. Takekata, Y. Mizumoto, H. Motomura and M. Jinno: Plasma Sources Sci. Technol. **20** (2011) 034005.
[10] Y. Iwata, N. Takada, and K. Sasaki: Appl. Pys. Express **6** (2013) 127301.