Experimental study on the intensity variation of scattered light from ultrasonic cavitation bubbles

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Abstract

Variation in intensity of scattered light from cavitation bubbles in an ultrasonic standing wave field at different contents of dissolved air is studied experimentally. The number of cavitation bubbles that repeat expansion and contraction correlates with the sonochemical reaction yield and the evaluation of the number of bubbles is important for perspective on the yield. Peak-to-peak of intensity waveform of scattered light from cavitation bubbles corresponds to the number of the active bubbles which can contribute to the sonochemical reaction, because the waveform measured is the superposition of the waveform by independent bubble and a range of the active bubble radius is constrained due to its shape instability. In this paper, time evolution of the peak-to-peak intensity under the irradiation of 142 kHz ultrasound is measured at various contents of dissolved air. It is shown that, as time goes by, the light intensity varies intermittently with period of several second at most. The intensity variation is marked at high content of dissolved air and the tendency reduces at the lower content. From the results it is interpreted that, in the ultrasonic cavitation field, the following sequential process is repeated intermittently; 1. Generation of tiny cavitation bubbles, 2. Generation of large-sized cavitation bubbles due to coalescence of tiny bubbles, 3. Movement of the large cavitation bubbles towards the pressure node by Bjerknes force with quasi-acoustic streaming, and these are responsible for the intermittent variation of the number of cavitation bubbles.

Introduction

Irradiation of intense ultrasound into an aqueous solution generates a lot of cavitation bubbles\(^1\) and, by the violent collapse of multibubble, causes the hot spots with temperatures of several thousand Kelvin, pressures of about one thousand atm, and heating and cooling rates above \(10^{10}\) K/s\(^2,5\). In such extreme condition, water dissociation takes place easily to generate OH-radicals responsible for various chemical reactions often referred to as sonochemical reactions\(^2,6\).

Analysis of the mechanism of cavitation-bubble dynamics gives intelligence for accomplishment of high efficiency in cavitation-induced (sonochemical) reactions\(^7-11\). The method of light scattering suitable for such analyses is often used to study the oscillation of single cavitation bubble\(^2,13\). For multibubble, however, there were few studies, especially for the case of ultrasonic standing wave, except for the case of a progressive ultrasound with horn type transducer examined by Negishi\(^14\). The present report deals with the time evolution of intensity of scattered light from cavitation bubbles that repeat expansion and contraction in the ultrasonic standing-wave field.

Experiment

A cw sinusoidal signal of 142 kHz generated by a function generator was amplified with a 55-dB power amplifier. The electric output was fed to a 45 mm diameter Langevin-type transducer. The transducer was fixed to a stainless steel plate. A rectangular glass cell of 50 x 50 x 145 mm\(^3\) internal dimensions was set above the transducer. The thickness of the glass cell was 5 mm. Distilled water in the cell was 250 cm\(^3\) and the temperature was 20 °C. Air content of the distilled water was adjusted by bubbling air. The content of dissolved oxygen (DO) in the distilled water was measured with a DO meter and served as an index of the amount of dissolved air. Laser-sheet light was introduced into cavitation bubbles generated at an antinode of a sound pressure in the cell, and the intensity of scattered light from the bubbles were measured, where the illuminated area was 25 x 50 mm\(^2\) of tetragonal and half of one antinodal plane which one side was set closely to the sound beam axis. The thickness of the laser sheet was 0.5 mm. The scattering angle at the observation was 60 degrees. Large bubbles originated from the coalescence of tiny bubbles are expelled from the antinode due to the action of Bjerknes force\(^15,16\), and they are out of observation. Therefore, it is possible to detect the intensity of scattered light from only tiny bubbles by the present method. The intensity of scattered light from bubbles was measured with a photomultiplier tube through a converging lens and a slit. The waveform of scattered light, which is composed of superposition of scattered light intensity according to the scattering cross section of each bubble repeating expansion and contraction due to the acoustic cycle, is recorded with a digital oscilloscope controlled by a computer. Each data obtained was the one averaged over 32 times. In the present experimental condition, an ultrasonic power...
input to the cell was determined calorimetrically and the value is 11 W.

Results and Discussion

Figure 1 shows time evolution of peak-to-peak scattered light intensity at different dissolved oxygen (DO) contents. Each set of data plotted in the figure was obtained in 3 minutes, where the measurement was performed every 200 ms on average. After the irradiation DO content decreased at both cases. The decrease in DO content through the irradiation was marked for the case of high DO content at the start of the irradiation, that is, 0.51 mg/L in decrement at the case of 8.81 mg/L in initial content against 0.26 mg/L at the case of 5.79 mg/L. Isolated data was obtained at the beginning of irradiation at both cases, where the bubble-bubble interaction is still weak to successfully manage to produce a large number of individual oscillating bubbles, and the value of the isolated data was larger at higher DO content. This effect reminds us of the well-known operation of pulsing irradiation\textsuperscript{17}. The pulsing operation to produce tiny active cavitation bubbles repeatedly is a good tool to accomplish high sonochemical reaction yield and will be more effective than continuous irradiation when the irradiation condition of the pulse such as duty ratio is set appropriate.

The vertical deviation for each data originates from cavitation-induced (quasi-acoustic) streaming\textsuperscript{18}, which is different from the acoustic streaming due to the nonlinearity in a medium\textsuperscript{19}. In such ultrasonic cavitation field, the following sequential process is repeated intermittently; 1. Generation of tiny cavitation bubbles, 2. Generation of large-sized cavitation bubbles due to coalescence of tiny bubbles, 3. Movement of the large cavitation bubbles towards the pressure node by Bjerknes force\textsuperscript{15,16} with quasi-acoustic streaming\textsuperscript{18}, and these are responsible for the intermittent variation of the number of cavitation bubbles. That is, the sudden increase in the number of tiny cavitation bubbles contributes to the increasing component of the light intensity on the deviation, and after that, the resultant large-sized bubbles are expelled from pressure antinode to be out of observation with the decreasing component. The expelled large bubble at last goes to degassing from the sound field, or is decomposed due to its shape instability into reborn tiny cavitation bubbles back to the pressure antinode\textsuperscript{16}.

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References


Figure 1 Time evolution of peak-to-peak intensity of scattered light from cavitation bubbles at different dissolved oxygen (DO) contents.