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The characterization of acoustic cavitation bubbles – An overview

Muthupandian Ashokkumar

School of Chemistry, University of Melbourne, VIC 3010, Australia

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ABSTRACT

Acoustic cavitation, in simple terms, is the growth and collapse of preexisting microbubbles under the influence of an ultrasonic field in liquids. The cavitation bubbles can be characterized by the dynamics of oscillations and the maximum temperatures and pressures reached when they collapse. These aspects can be studied both experimentally and theoretically for a single bubble system. However, in a multibubble system, the formation of bubble streamers and clusters makes it difficult to characterize the cumulative properties of these bubbles. In this overview, some recently developed experimental procedures for the characterization of acoustic cavitation bubbles have been discussed.

1. Introduction

Ultrasound, when passing through a liquid medium causes mechanical vibration of the liquid. In addition to this effect, ultrasound also generates acoustic streaming within the liquid. If the liquid medium contains dissolved gas nuclei, which will be the case under normal conditions, they can be grown and collapsed by the action of the ultrasound. The phenomenon of growth and collapse of microbubbles under an ultrasonic field is known as "acoustic cavitation" [1]. When cavitation bubbles oscillate and collapse, several physical effects are generated, namely, shock waves, microjets, turbulence, shear forces, etc. The physical effects of ultrasound have been used for a number of applications that include emulsification, extraction, cleaning, etc. [2]. The collapse of the acoustic cavitation bubbles is also near adiabatic and generates temperatures of thousands of degrees within the bubbles for a short period of time [3]. Under this extreme temperature conditions, highly reactive radicals are generated. For example, if water is the medium, H and OH radicals are generated by the homolysis of water. These radicals have been used to achieve chemical reactions that include the synthesis of nanomaterials, polymers, degradation of organic pollutants, etc. [1,2,4–7]. In addition, acoustic cavitation is found to be useful in diagnostic and therapeutic medicine [8].

Despite the use of ultrasonics and sonochemistry in a variety of applications [4–12], the studies devoted to the fundamental understanding of the characteristics of cavitation bubbles are limited. We have been, for the past 15 years, developing a number of experimental procedures for the characterization of acoustic cavitation bubbles. An overview of these experimental procedures and their significance in understanding and controlling of acoustic cavitation bubbles has been provided. In particular, the experimental techniques for the characterization of the growth, temperature, lifetime and capability (chemistry vs. light emission) of cavitation bubbles have been briefly discussed in this overview. For detailed information on these techniques, appropriate references that have been cited can be referred.

2. Bubble growth

Unlike in a single bubble system, the bubble growth in a multibubble system involves two processes, namely, rectified diffusion and bubble coalescence [13]. While it is possible to use experimental techniques such as light scattering, stroboscopic or fast video recording to monitor the rectified diffusion growth of the bubbles in a single bubble system [3,14], these techniques cannot be easily adapted for multibubble systems. Added to this complexity is the contribution from bubble coalescence to the growth of the bubbles. Despite the complexities involved in the bubble growth process, a simple experimental technique based on the initial growth of multibubble sonoluminescence (MBSL) has been developed by us to qualitatively monitor the bubble growth by rectified diffusion and bubble coalescence.

It has been shown that several acoustic pulses are required to attain a steady-state MBSL in aqueous solutions under pulsed sonication conditions, in particular at high ultrasound frequencies [15,16]. The reason for this induction period to reach a steady-state MBSL is the absence of resonance sized bubbles at the initial stages of sonication. The bubble nuclei present in the solution need to grow to reach the resonance size range (see Fig. 1 [17]).

E-mail address: masho@unimelb.edu.au

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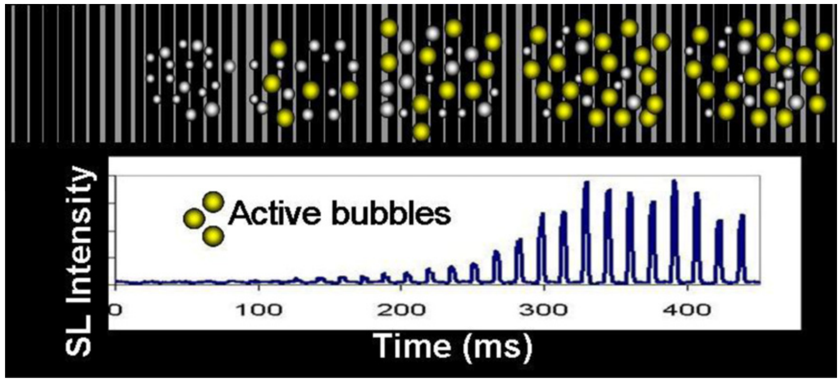

Fig. 1. Schematic representation of the growth of cavitation bubbles in an acoustic field and the corresponding experimental data (515 kHz, pulse on = 4 ms, pulse off = 12 ms) on the growth of MBSL. Adapted from Ref. [17].

As mentioned above, the bubble growth in a multibubble filed can occur by either rectified diffusion or bubble coalescence or by a combination of both processes. We have used the initial MBSL growth data to qualitatively understand the bubble growth under pulsed sonication conditions. Fig. 2 shows that about fifteen 4 ms pulses (duration between pulses is 12 ms) are required to reach a steady-state bubble population of sonoluminescence bubbles in water. Compared to water, the number of pulses required to reach steady-state increases to about 30 in aqueous solution containing 1 mM of a surfactant (sodium dodecyl sulfate, SDS). Let us return to this observation after some discussion on the role of surfactants in bubble coalescence.

Surfactants are known to adsorb at bubble solution interface and reduce the coalescence between bubbles [13]. We have used a capillary technique to monitor bubble coalescence among cavitation bubbles in the absence and presence of surface active solutes [18]. The capillary technique involves the attachment of a capillary that can measure the change in volume (ΔV_T) that occurs due to the formation of large inactive bubbles formed by coalescence among cavitation bubbles. This is schematically shown in Fig. 3 along with a photograph of a 500 kHz ultrasound generator and capillary setup. Thus, a large ΔV_T means more coalescence and a small ΔV_T means less coalescence between bubbles.

Fig. 3 also shows that the relative coalescence between cavitation bubbles in 1 mM SDS solution is significantly reduced to about 20% compared to that observed in water. The photographs shown in Fig. 4 also support the above discussion. In water, large coalesced bubbles are clearly visible whereas, they are completely absent in 1 mM SDS solution.

Returning back to the discussion regarding the initial growth of MBSL (Fig. 2), it is possible to interpret the data by bubble coalescence and rectified diffusion processes. In water, bubble coalescence occurs as shown by the capillary technique data (Fig. 3). Hence, the initial growth of the cavitation bubbles may occur by bubble coalescence pathway. However, rectified diffusion also contributes to this growth. The support for this argument comes from the SDS data in Fig. 3, which shows that SDS retards bubble coalescence. Hence, in the presence of SDS, the growth of cavitation bubbles by bubble coalescence pathway is significantly reduced. The initial growth of MBSL observed in Fig. 2 must then be due to the growth of cavitation bubbles primarily by rectified diffusion pathway. Based on the number of acoustic pulses required for steady-state MBSL in water, it can be suggested that the contributions for the bubble growth form bubble coalescence and rectified diffusion are approximately equal. In the absence of bubble coalescence, almost double the number of acoustic pulses is required in SDS solution where the bubbles primarily grow by rectified diffusion pathway. It should be clearly understood that the observed results are for a given ultrasound frequency under specific experimental conditions (power, duty cycle, etc.). The number of acoustic pulses required may be different under different experimental conditions.

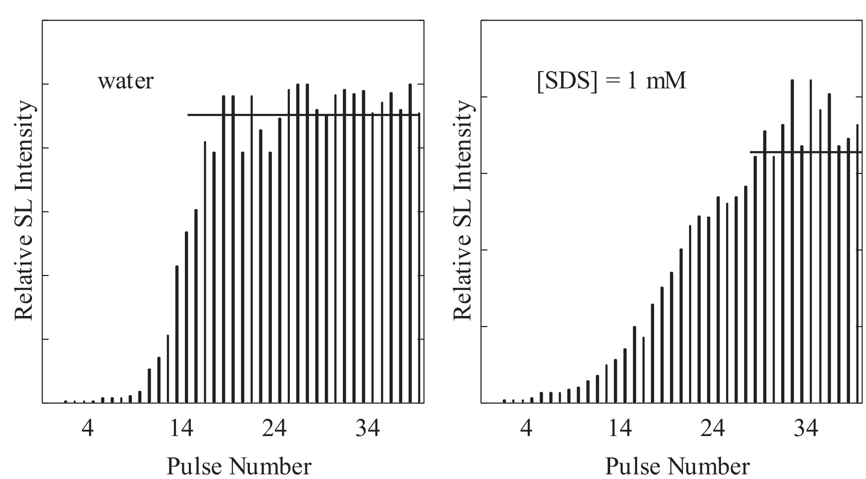

Fig. 2. The initial growth of MBSL as a function of acoustic pulse number. Frequency = 515 kHz, duty cycle = 4 ms on, 12 ms off.