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Effects of bovine serum albumin on a single cavitation bubble

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ABSTRACT

The dynamics and sonoluminescence (SL) of a single cavitation bubble in bovine serum albumin (BSA) aqueous solutions have been experimentally and theoretically investigated. A phase-locked integral imaging has been used to record the bubble pulsation evolutions. The results show that, under the optimum driving condition, the endurable driving pressure, maximum radius, radius compression ratio and SL intensity of the cavitation bubble increase correspondingly with the increase of BSA concentrations within the critical micelle concentration, which indicates that the addition of BSA increases the power capability of the cavitation bubble. In addition, BSA molecules dampen the interfacial motion, and especially the rebounds of the bubble after its collapse. BSA molecules modify the dilatational viscosity and elasticity of the bubble wall. A viscoelastic interfacial rheological model that mainly emphasizes on the description of the bubble wall has been introduced and modified to theoretically explain the measured bubble dynamics. A good consensus between the experimental observation and model calculation has been achieved.

1. Introduction

Acoustic cavitation has been researched for over a century. The investigation on the dynamics of cavitation bubbles in liquids has stimulated considerable interest since the pioneering research of Rayleigh [1]. Sound waves with large amplitude in liquids cause cavitation in the form of glowing bubble clusters, which is named the multi-bubble sonoluminescence (MBSL). Research conducted by Gaitan et al. [2] that a single bubble could be levitated and glow in the degassed liquids, naming the single bubble sonoluminescence (SBSL), greatly favors the experimental study of the bubble dynamics.

The effects of surfactants, including alcohols, sodium dodecyl sulphate (SDS), *etc.*, on both dynamics and sonoluminescence (SL) of cavitation bubbles have been investigated in recent years [3–6]. It was reported that a drop of alcohol can extinguish SBSL [7], which arouses broad attentions of scientists on SBSL in aqueous liquids with surfactants [8,9]. Volatile and nonvolatile surfactants can affect the bubble cavitation behaviors differently [10]. Ashokkumar et al. found that both MBSL [11,12] and SBSL [10,13,14] are substantially suppressed in water with small amounts of surfactants, while the radial dynamics of the bubble is not dramatically affected. They attributed the influence of the surfactants to the accumulation of surfactant molecules within the bubble over a number of acoustic cycles and the physical and chemical reactions inside the bubble that follows. The similar trends were also reported in Refs. [15,16]. However, the experimental research of SBSL in water with the presence of other surfactants by Stottlemyer and Apfel [17] showed a different story. They found that Triton X-100, providing free interfacial motion, reduces the maximum radius of the single bubble from 65 μm in pure water to 62 μm in 0.1 critical micelle concentration (CMC) Triton X-100 aqueous solutions; in contrast, bovine serum albumin (BSA), hindering the interfacial motion, permits a higher driving pressure and increases the maximum radius of the bubble from 65 μm in pure water to 69 μm in 1.0 CMC BSA aqueous solutions [17]. Based on this work [17], the theoretical study of Kyuichi Yasui suggested that the effect of the surfactant Triton X-100 is caused by the inhibition of the condensed water vapor at the collapse [18].

To further explain the effects of BSA on the SBSL and the bubble dynamics, we have conducted the experiments on the radial vibration and SL of the bubble in BSA aqueous solutions with various concentrations. BSA greatly changes the rheological properties of the bubble wall, so that Rayleigh-Plesset equation for the free cavitation bubble can no longer describe the dynamics of the bubble in BSA aqueous solutions. A viscoelastic interfacial rheological model [19] for the encapsulated bubble concentrating on the interface description has been modified to explain our experiments in this paper. Both the SBSL and the bubble dynamics in BSA aqueous solutions with various concentrations have been reported in this paper.

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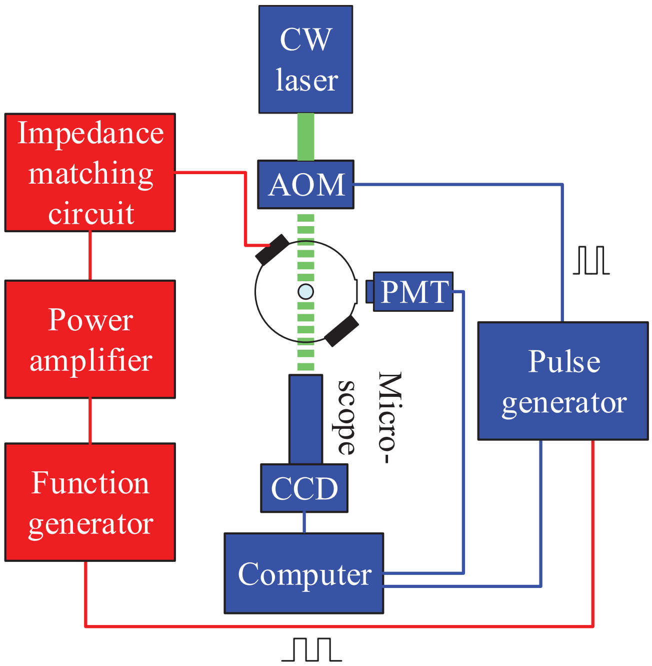

Fig. 1. The sketch of experimental setup.

2. Experimental details

The present experimental system is similar to the previous one [20]. The system is mainly composed of two parts, the SBSL generating part and the measurement one, as shown in Fig. 1. The generating part is composed of a function generator, a power amplifier, an impedance matching box, and an acoustic resonator. A 100 mL spherical flask with a quartz window cemented symmetrically and horizontally with two piezoelectric transducers (PZT) is used to levitate a single gas bubble and to generate sonoluminescence. The flask filled with the solutions resonates at the frequency of about 26 kHz. The bubble is seeded by injecting air with a microsyringe. The measurement part can record both the bubble dynamics and the SBSL intensity. We adopt a digital phase-locked integral imaging system to acquire the bubble evolution images [21]. A 532 nm CW laser, switched to pulses by an acousto-optic modulator (AOM), is used to illuminate the bubble. A long-distance microscope coupled with a video camera connecting to a computer is utilized to record the evolution images of the oscillating bubble. A photomultiplier tube (PMT) connected to an oscilloscope is used to record the SBSL intensity in pure dark environment. Both the bubble images and the SBSL intensity data are acquired and stored in the computer through an IEEE488 cable.

The BSA powder (> 99% purity) was used as purchased. Each of the host liquids (deionized water) used in the experiments were prepared identically. A certain amount of BSA powder was mixed into deionized water and then the mixed liquid was poured into the flask. The mixed liquid was degassed by keeping it in vacuum. Meanwhile, the BSA mixture was sufficiently dissolved through being constantly stirred with electromagnetic stirrer, which also contributed to the liquid degassing process. All the experimental liquids were degassed to the level of 2–3 mg/L, which was measured by an oxygen meter. The total preparation period for the host liquid was about 8 h at room temperature (25 ± 0.5 °C).

It took about half an hour for the power amplifier and the PZT transducer to reach a stable condition, so right before each experiment, half an hour was spared intentionally to eliminate the inaccuracy caused by time dependency. As reported in our earlier work [22], the driving parametric region of SBSL in alcohol aqueous solutions shrinks and shifts. In order to avoid the similar effects caused by additives, it is necessary to optimize the driving conditions for the stable SBSL in host liquids at various BSA concentrations. All the present experiments were conducted under room temperature.

3. Measurements of the bubble dynamics and SBSL in BSA solutions

The evolution images of the bubble in the BSA aqueous solutions have been recorded and some of the typical results have been illustrated in Fig. 2. In Fig. 2(a), (1)–(3) are images of a cavitation bubble at the maximum, minimum and rebound maximum sizes in pure water driven by the brightest SBSL pressure of 1.33 bar, and (4)–(6) are those in 1.34 μM BSA aqueous solution driven by the brightest SBSL pressure P_0 = 1.45 bar, respectively. In Fig. 2(a), we can see that the maximum size of the bubble in the BSA solution is larger than that in pure water, while the maximum rebound size is smaller. The radius evolution curve $R(t)$ of the bubble can be acquired from those images. A typical set of the bubble evolution curve in BSA solution is plotted in open dots in Fig. 2, which are transferred from the images (4)–(6) and others not displayed in Fig. 2(a). The radius evolution at the collapse period is magnified and illustrated in Fig. 2(b) for better observation.

It can be seen in Fig. 2 that both the first rebound amplitude of the bubble after its collapse and the rebound number in BSA solution (see open circles) are much less than those in pure water (see the dashed blue line calculated by Rayleigh-Plesset model). We attribute this phenomenon to the increase of interface viscosity and interface immobility of the bubble in BSA aqueous solutions. The details are discussed later.

Optimum driving parameters for the brightest SBSL in solutions with various BSA concentrations have been applied in the experiments. In order to study the effects of BSA on SBSL, the SBSL intensity under

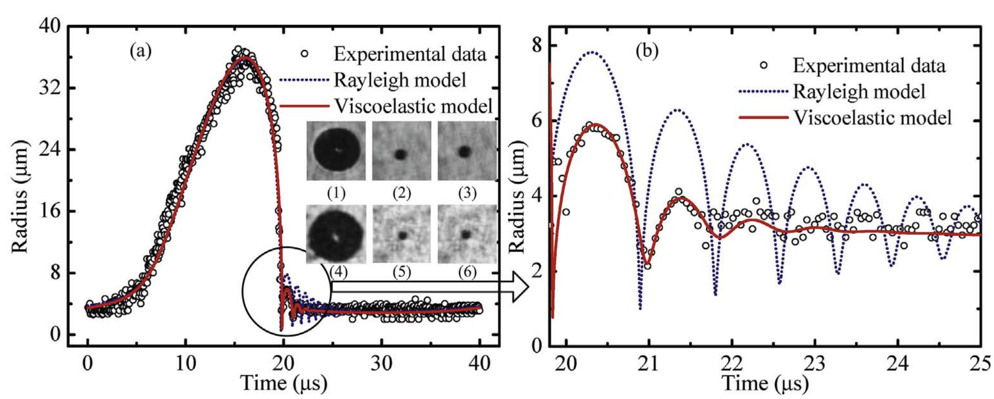

Fig. 2. The bubble dynamic evolution in the BSA aqueous solution. (a) The radius evolution for a sonoluminescing bubble in 1.34 μM (0.5 CMC) BSA aqueous solution driven by 1.45 bar at 25.8 kHz. The inset shows the images of two sonoluminescing bubbles. Images labeled as (1)–(3) are for the bubble in pure water driven by 1.33 bar, and (4)–(6) are for the bubble in 1.34 μM BSA aqueous solution driven by the pressure amplitude of 1.45 bar. (b) The magnified results of the bubble collapse and rebounds circled in (a).