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The effect of viscosity, applied frequency and driven pressure on the laser induced bubble luminescence in water–sulfuric acid mixtures

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ABSTRACT

Production and oscillation of sonoluminescence bubbles by laser pulse in the presence of acoustic field in water and different concentrations of sulfuric acid are investigated. In the presence of acoustic field, the laser causes variable speed of sound, surface tension and density; and the host liquid acts as a compressible one and strongly affects the bubble's dynamics equations. The effect of various concentrations of sulfuric acid as a host liquid on the oscillation of bubble radius, bubble wall velocity and bubble interior temperature is studied. Furthermore, the effect of applied frequency on LI-SCBL in the presence of the acoustic field is investigated and an optimum sound wave frequency for the bubble oscillation and bubble interior temperature in pure water and SA is introduced. Based on the modification of RP equation, by applying the optimum frequency, the results indicate that the maximum bubble radius for LI-SCBL in the presence of the acoustic field is increased up to 7×10^{-4} m as this article presents, which is more than 40% improvement. This amount results in interior temperature of more than three times, from almost 5000 K in the previous works to almost 16 000 K in the present report. This is very similar to the experimental measurements for bubble radius induced by laser. Furthermore, the effects of driving pressure amplitudes on the bubble radius, the bubble interior temperature and the bubble wall velocity in different host liquids and in optimum frequency are investigated.

1. Introduction

Sonoluminescence is radiation of gas bubbles in different liquids. Generally, bubbles are produced by a sound field, which mostly leads to the creation of multi-bubble sonoluminescence (MBSL) and deals with interaction of many bubbles [1,2]. Single-bubble sonoluminescence (SBSL) is also produced in special utilizing conditions [2]. Many features of SBSL and MBSL are studied, including intensity and spectrum of the emitted light [3,4] which depend on various parameters such as ambient pressure and temperature [5], host liquid [6,7], the dissolved gas in liquids [8], the conditions of bubble stability and the phase diagrams [9,10], and the modification of the initial Rayleigh–Plesset (RP) equation considering various effects of the medium such as compression viscosity of the liquids [11,12].

In addition to the sound field, other methods are also used to create bubbles such as focusing laser beam into the liquids, using electrical discharge [13] and syringe injection of gas into liquids [14]. Recently, applications of a focused laser beam have become a very attractive way of obtaining SCBL [15]. Adopting this approach, an intense laser pulse is focused on transparent buffer liquid such as water, and the bubbles induced by the laser are named as laser-induced single cavitation bubble luminescence (LI-SCBL). During the optical breakdown process as a result of a focused laser beam, the energy of the laser pulse transmitted to the medium is absorbed, scattered, or reflected [16]. Part of the laser energy that is absorbed in the transparent media goes into the cavitation bubble energy, the shock-wave energy, the plasma radiation, and the evaporation energy, as recently explained in detail [17]. In this process, the bubble collapses violently and eventually following the shock wave, a flash of light is emitted. The bubble's oscillation is estimated to have only a few rebounds and after that, the bubble expands again and oscillations are repetitive [18]. The duration of flash light for LI-SCBL is in order of a few nanoseconds and their reported maximum radii are 10–30 times larger than the SBSL [15]. Larger bubble volume makes the LI-SCBL method even particularly attractive in some applications such as sound amplification by stimulated emission of radiation (SASER) [19].

The role of various liquids in SBSL parameters has been studied theoretically and experimentally by researchers to find the effect of different solutes in the host liquids, such as water, alcohols, salts

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solutions, liquid polymer, acid and deuterated acetone [20–22]. It is noticed that each of these liquids, because of their complicated structures and strong hydrogen-bonded, has its own effect on the luminescence parameters and a minimal quantity of them can have very strong effect on the emission parameters of the bubble. One of these important effects that has aroused scientists' interest and has been widely investigated in many fields is the influence of liquid viscosity on the bubble [9,11]. It should be realized that all of these investigations are related to the bubbles generated without laser assistance.

In spite of the glowing reports of the laser induced cavitation bubbles in water, pure glycerol and water–glycerol mixture [17,23,24], only the effect of viscosity is experimentally studied [23]. These experimental works using LI-SCBL in glycerol shows that viscosity plays a significant role in dampening mechanical energy during the growth and collapse of the bubble. These primary procedures indicate that by increasing the viscosity of the fluid, the bubble radius oscillation time is prolonged [23,24]. However, a limited simulation considers only the viscous dissipation and neglects some fundamental parameters such as the surface tension variation, fluid compressibility, and thermal effects. Therefore, some discrepancy exists between their numerical and experimental results [24]. Recently, we studied some luminescence parameters such as bubble radius, interior temperature and pressure and found that in addition to increase the bubble radius, its temperature is decreased resulting in different bubble parameters. Therefore, we came to the conclusion that a comprehensive study of LI-SCBL is needed [17].

In this work the effect of viscosity, applied frequency and driven pressure on the laser induced bubbles luminescence in water–sulfuric acid mixtures is studied in detail. In the produced bubbles by the laser in the presence of the acoustic field, the tension variation, fluid compressibility, thermal effects and density variations on a complete cycle of bubble are scrutinized. For this purpose, a fundamental modification of sound velocity by considering the effect of compression viscosity of the liquid is implemented in the RP equation. It is noticed that at the lower applied frequency, the interior temperature of LI-SCBL rises in different host liquids. The effect of different concentrations of sulfuric acid as a host liquid on the oscillation of bubble radius, bubble wall velocity and bubble interior temperature is studied. It is found that by increasing the sulfuric acid concentration, the bubble interior temperature decreases. The effects of the driving pressure amplitudes on the bubble radius, bubble interior temperature and bubble wall velocity in different host liquids are also investigated. It is noticed that by the driving pressure amplitude increment, the bubble radius decreases in all cases, however, the bubble interior pressure and temperature increase. This process is explained in detail.

2. The model

Various models have been introduced to investigate the evolution of the processes inside a SL bubble such as isothermal, hydrochemical, and quasiadiabatic models [8,25–28]. Our research is carried out in the light of the quasiadiabatic model, in which the evolutions at the moment of collapse will be assumed adiabatic due to the rapid compression of the bubble wall and it is isothermal in the rest of the cycle [29]. The fluctuation of a single-bubble SL was studied in the presence of a laser pulse and a sound field in water as a host liquid [17]. Based on this model, a complete cycle of bubble radius variation is represented for LI-SCBL in two different host liquids in various applied frequencies and ambient temperatures. One of these liquids is water and the other one is sulfuric acid in different concentrations. By altering the host liquids, some parameters such as speed of sound in fluid, density, surface tension and viscosity are varied. These considerations allow us to monitor how viscosity affects the dynamics of the bubbles. By using this model, the important bubble parameters such as bubble radius, bubble interior temperature and bubble wall velocity are presented for the above mentioned host liquids. The relevant approach and achievement are discussed in detail.

The bubble radius dynamic is described by Rayleigh–Plesset equation [30]:

$$\left(1-\frac{\dot{R}}{C}\right)R\ddot{R}+\frac{3}{2}\left(1+\frac{\dot{R}}{3C}\right)\dot{R}^2 = \left(1+\frac{\dot{R}}{C}\right)\frac{(P_l-P_a-P_0)}{\rho}+\left(\frac{R}{\rho C}\right)\frac{dP_l}{dt} \quad (1)$$

In this equation R, $\dot{R}$, $\ddot{R}$, ρ, P_0 and P_l are the bubble radius, the bubble wall velocity, the bubble wall acceleration, the density of the host fluid, the ambient and liquid pressure, respectively. In the quasiadiabatic process, the liquid pressure on the bubble wall is a function of the bubble radius and the radial velocity of the bubble wall which is calculated from [12]:

$$P_l(R,\dot{R}) = P_g - \frac{2\sigma}{R} - \frac{4\mu\dot{R}}{R} \quad (2)$$

where σ is the surface tension and μ is the dynamic viscosity. In this equation, P_g is the uniform gas pressure in the volume of the bubble which is determined by van der Waals equation of state [8]:

$$P_g = \left(P_0+\frac{2\sigma}{R_0}\right)\left(\frac{R_0^3-a^3}{R(t)^3-a^3}\right)^{\gamma} \quad (3)$$

Here R_0 is the ambient bubble radius that is induced by laser [17], $a = \frac{R_0}{8.86}$ is hard-core van der Waals [31] and γ is the adiabatic exponent for the Argon gas inside the bubble [32]. In addition P_a is a sinusoidal acoustic driving pressure [33]:

$$P_a(t) = P_A \sin(2\pi f t) \quad (4)$$

where the frequency of the driving acoustic field and amplitude are $f = \frac{\omega}{2\pi}$ and P_A, respectively. The applied frequency for the SBSL is between 30–38 kHz [5,34]. However, in the presence of laser and an acoustic field, this frequency was suggested to be between 4.5 and 9.2 kHz [33] because in contrast with SBSL, some part of the energy that is needed for the bubble generation and its oscillations is supplied by the laser. Therefore, a lower frequency is required to produce the bubble and its oscillation. As this paper illustrates, because of the different effects, such as surface tension variation, fluid compressibility, thermal effects and density variations, the applied frequency is decreased.

In SBSL approach, the driving pressure amplitude by the acoustic field is negligible. Consequently, the fluid cannot be considered compressible. Therefore, the speed of sound in water is constant which is equal to $C_0 = 1483$ m/s. However, in the presence of the laser, the induced pressure of the laser that is followed by the shock wave is so great that the environment acts as a compressible fluid. Consequently, some parameters are changed requiring new equations for justification of their variations. Variations of the sound velocity (c) and surface tension (σ) as a result of variation of the compressibility are shown as follows [17,35,36]:

$$\sigma = \int_{\rho_0}^{\rho} \frac{C}{\rho} d\rho, \quad \text{where } C = \sqrt{\frac{dP_l}{d\rho}} \quad (5)$$

ρ_0 is the ambient density of the liquid and ρ is the liquid density that is affected by the fluid compressibility. It is worth mentioning that the liquid density is acquired from the Tait equation of state that is shown by: