Progress in Physics of Applied Materials 4 (2024) 161-164

Semnan University

Progress in Physics of Applied Materials

journal homepage: https://ppam.semnan.ac.ir/

Explaining Unwanted Radial Oscillations in Single-Bubble Sonoluminescence

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ARTICLE INFO

Article history:
Received: 24 July 2024
Revised: 15 August 2024
Accepted: 18 August 2024

Keywords:
Bubble Oscillations
Bubble Dynamics
Sonoluminescence

ABSTRACT

This study presents a theoretical model to explain the bubble oscillation phenomenon that occurs after each flash in single-bubble sonoluminescence (SBSL). Our model reveals that these fluctuations are caused by the pressure effect of electrons produced during the flash, which interact with the surrounding fluid and cause bubble formation. The authors use the Monte Carlo method to calculate the number of released electrons and demonstrate that the amplitude and frequency of these oscillations can be reduced by manipulating the electron density and energy distribution. By controlling the released electrons, we show that it is possible to reduce the number of unwanted oscillations and increase the number of flashes that can be performed in a given time interval. The results provide new insights into the mechanism of SBSL and have implications for its application in various fields. Furthermore, our findings offer a method for reducing these oscillations, which limit the number of flashes that can be produced in a time interval, allowing for more efficient and reliable operation. The results from our theory are in good agreement with experimental results, validating our understanding of this phenomenon.

1. Introduction

In recent years, many studies are presented to show the reason of light emission in single bubble sonoluminescence (SBSL) phenomenon [1-3] which is conversion of sound to light through an oscillating gas bubble trapped in a liquid [4-6]. Some studies based on in viscid spherical hydrodynamics [7-9] suggest that a converging shock produces high temperature and pressure and the reflected diverging shock quenches them in picoseconds time scale [8-10]. This model describes the emergence of a picoseconds time scale as well as the large energy concentration [11]. Figure 1 illustrates the nonlinear radial for the modest applied pressure amplitude illustrated in response of sonoluminescence bubble to an applied sound field, and fitted with a bubble dynamics computer code [12].

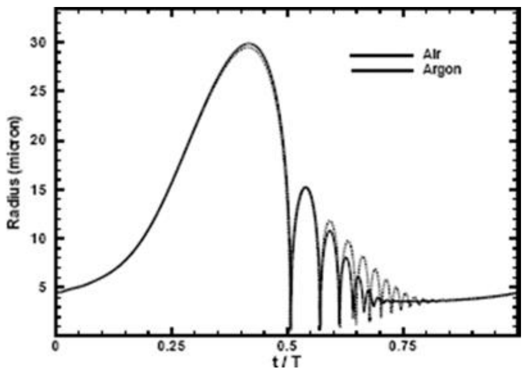

Fig. 1. The nonlinear, radial response of a bubble in normal gravity subject to an oscillating acoustic pressure field of 0.14 MPa. The heavy line is the calculated bubble radius, the dashed line is the normalized acoustic drive pressure, and the solid points are the experimentally measured bubble radius (proportional to the square of the scattered light intensity). The arrow indicates where, in the hydrodynamic motion of the bubble, the light flash occurs [12].

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Cite this article as:
Mansouri, M., Molaei F. and Vaezzadeh M., 2024, Explaining Unwanted Radial Oscillations in Single-Bubble Sonoluminescence. *Progress in Physics of Applied Materials*, *4*(2), pp161-164. DOI: **10.22075/ppam.2024.34837.1110**
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Some studies investigated influence of some parameters on a sonoluminescence bubble. For example, a possible contributing factor for the generation of instabilities, specifically, the effect of the gravitational force on a sonoluminescence bubble is investigated by Matula [13]. The Raleigh-Plesset equation with an appropriate state equation can describe exactly variations of radius of bubble in SBSL [14] but there is not any physical reason for ringing after each high intensity collapse (unwanted oscillations) in SBSL in the equation. In this paper, we present a theoretical model for physical explanation of unwanted oscillations after each high intensity collapse and next, to prove our theory, we calculate the number of released electrons (according to our model) and their equation of motion is calculated. To show the accuracy of our theory, we plotted the equation of motion of released electrons as a function of time. Our captured data from the model is in good agreement with both experimental and theoretical results for radial variations of bubble.

2. Model and Objective

Experimental data show that behavior of relative intensity of bubble luminescence corresponds to black body behavior. Figure 1 shows the relative intensity as a function of wavelength for water at different temperatures [15].

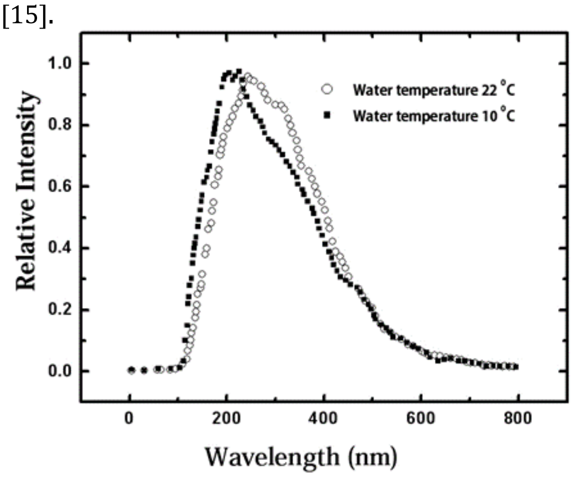

Fig. 2. Black body radiation of SBSL in water at two temperatures.

Hiller et al. [15] believe that after bubble luminescence, electrons of bubble become free and distribute in environment. In our model, these electrons play the most important role in bubble unwanted oscillations after each flash. The relative intensity as a function of wavelength for water at temperature 22°C is plotted theoretically in Figure 3 by using Planck's law [16]. The difference between theoretical and experimental results in Figure 3 shows the environmental energy absorption (i.e. by water and glass). In interval 400-800 nm, energy absorption is related to phonon absorption which increases temperature of environment and cannot release electrons. So, wavelength zone between 90 nm and 180 nm which is the wavelength zone of bubble ionization is investigated in the presented model.

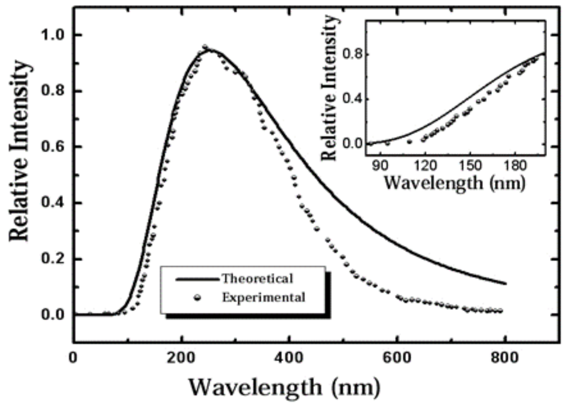

Fig. 3. Theoretical and experimental relative intensity as a function of wavelength between 0 nm and 800 nm. The bubble ionization occurs between 90 nm and 180 nm.

The number of released electrons in the ionization is calculated by using wavelength zone of bubble ionization. Density of states in a frequency interval [17], D(ω), of the electromagnetic field in an oscillating bubble with volume, V, is

$$D(\omega) = \frac{dN(\omega)}{d\omega} = \frac{V}{2\pi^2 c^3}\omega^2 \tag{1}$$

where ω and C are frequency of electromagnetic field and velocity of light, respectively. So the number of modes N(ω), in the bubble is:

$$N(\omega) = \frac{V}{6\pi^2 c^3}(\omega_2^3 - \omega_1^3) \tag{2}$$

where ω_1 and ω_2 identify frequency zone of bubble ionization.

Just before flash, radius of bubble, R, is 0.5×10^{-5}m. By using Eq. (3), number of modes in the frequency zone of bubble ionization is 0.1645×10^{17}. This value must be compared to its experimental result to obtain the number of modes which absorbs photons to release electrons.

Using Monte Carlo method in the frequency zone of bubble ionization leads to

$$\frac{N_{Exp}(\omega)}{N_{Theo}(\omega)} = \frac{N_{EXP}(\omega)}{0.1645\times10^{17}} = 0.73 \tag{3}$$

So, in the first approximation, the number of released electrons (Ne) is,

$$N_{e0} = N_{Theo} - N_{Exp} = 20.8\times10^{15} electrons \tag{4}$$

Although the number of released electrons is small but it plays the most important role to explain unwanted oscillations of bubble after each flash.

3. Unwanted oscillations of a bubble after each flash

After each flash, there is a waste time interval which is related to bubble unwanted oscillations after luminescence. Reduction of this interval leads to power increasing. Under pressure, radius of bubble suddenly becomes small and in center of bubble a flash is produced. The flash ionizes bubble and releases electrons. Because of coulomb repulsive, positive charges go away from each other and cause to increase radius of bubble. Then, because of coulomb attraction of positive ions, the velocity of released electrons decreases and in equilibrium state becomes zero and after that released electrons come back. Figure 4, shows this process.

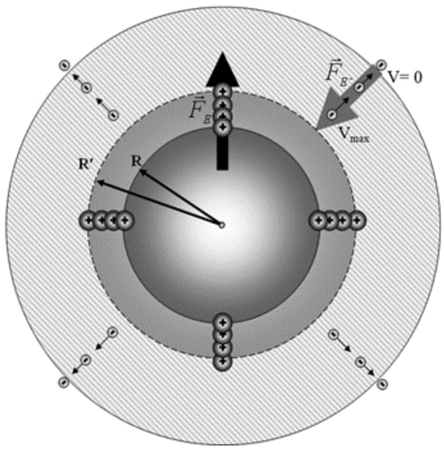

Fig. 4. Illustration of ionized bubble after flash. Movement of released electrons outward causes to increase radius of bubble from R to R′.

Some electrons are absorbed by ionized bubble and other electrons pass through positive charges grid. When passed electrons come back to the center of bubble, they attract the ionized bubble and decrease radius of bubble. Figure 5 illustrates radius reduction of bubble which happens by coulomb attraction between released electrons in center and ionized bubble.

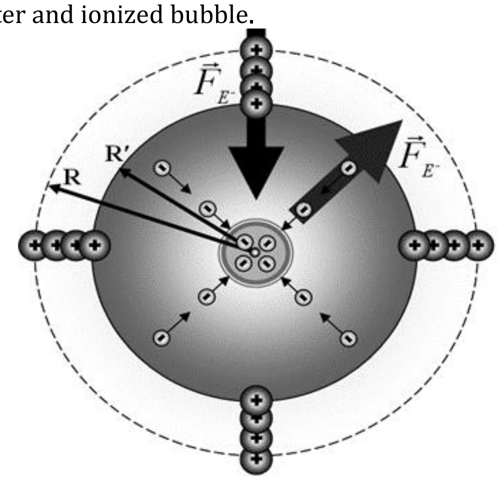

Fig. 5. Illustration of released electron movement into the center of bubble which decreases radius of bubble.

In center of bubble, the released electrons become close to each other and their velocity becomes zero. In this situation, the repulsive force between electrons makes them to go away from each other. This process is repeated and causes bubble unwanted oscillations. By passing time, amplitude of oscillations is reduced due to electrical resistivity of solution. So, bubble unwanted oscillations after each flash can be explained by calculating diffusion mean path of released electrons in solution.

Movement of released electrons is presented by:

$$N_e m \frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = 0 \qquad (5)$$

Where m, x, and b are mass of electron, diffusion mean path of released electrons, and damping constant which depends on electrical resistivity (ρ) respectively. K is stiffness coefficient which is related to attractive and repulsive of Coulomb force and given by:

$$k = m\omega_0^2 \qquad (6)$$

Where ω_0 is natural frequency of electron oscillation. Movement of released electrons produces a weak current, i, which is calculated by

$$i = nevs = \frac{N_e}{Ls}evs \qquad (7)$$

where s, v, and L are cross section of current transmission, electron velocity, and amplitude of electron oscillation, respectively. Power loss in the system is:

$$P = bv^2 = Ri^2 = \frac{\rho N_e^2 e^2}{Ls}v^2 \qquad (8)$$

So damping constant is given by

$$b = \frac{\rho N_e^2 e^2}{Ls} \qquad (9)$$

The number of released electrons decreases in each period due to electron-proton recombination. So,

$$N_e = N_{e0}(1 - \frac{t}{T}) \qquad (10)$$

where T is period of electron oscillation. By using Equations 6 to 10 and, Eq. (5) is rewritten as,

$$\frac{d^2x}{dt^2} + \frac{\rho N_{e0}e^2}{mLs}(1 - \frac{t}{T})\frac{dx}{dt} + \frac{\omega_0^2}{N_{e0}(1 - \frac{t}{T})} = 0 \qquad (11)$$

By definition, $A = \frac{\rho N_{e0}e^2}{mLs}$, $B = \frac{1}{T}$ and $C = \frac{\omega_0^2}{N_{e0}}$,

$$\frac{d^2x}{dt^2} + A(1 - Bt)\frac{dx}{dt} + \frac{C}{(1 - Bt)}x = 0 \qquad (12)$$

By using Eq. (12), the diffusion mean path of released electrons which implies the variation of bubble radius during time is plotted by Rang-Kota method order 4 in Figure 6.

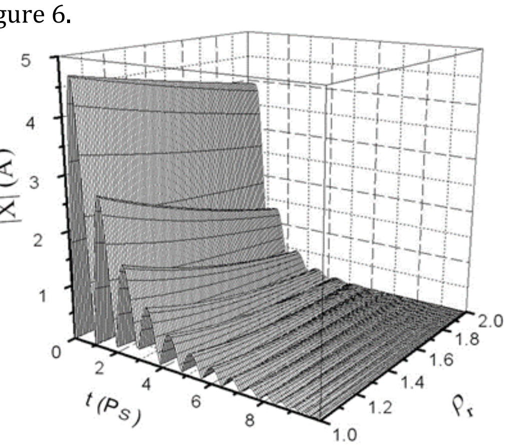

Fig. 6. The diffusion mean path of released electrons as a function of time and relative electrical resistivity.

Fig. 6, shows that amplitude of unwanted oscillations decreases during time which is demonstrated by experimental results [15]. In addition, Figure 6 demonstrates that the absorption of electrons depends on resistivity of surrounding fluid and influences on temperature of system. It is clear that it is possible to find a fluid with high resistivity to reduce the number of unwanted oscillation but it can perturb principal oscillation (first collapse) of bubble (Because of temperature effect). So, we suggest an external spherical conductor to control released electrons.

4. Conclusion

In this paper, a theoretical model based on oscillation of released electrons is presented to explain bubble unwanted oscillations after each flash in SBSL. For this purpose, first, the number of released electrons is calculated by using monte-Carlo method in diagram of black body radiation related to SBSL. Then, it is shown that oscillation of released electrons leads to bubble unwanted oscillations. Finally, diffusion mean path of released electrons is plotted and it is demonstrated consequences from model is in good agreement with experimental data.

Acknowledgements

This research received no external funding.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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