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Plasma in sonoluminescing bubble

Yu An *

Physics Department, Tsinghua University, Beijing 100084, PR China
Institute of Acoustics, Chinese Academy of Science, Beijing 100080, PR China

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Abstract

With the new accommodation coefficient of water vapor evaluated by molecular dynamics model, the maximum temperature of a sonoluminescing bubble calculated with the full partial differential equations easily reaches few tens of thousands degrees. Though at this temperature the gas is weakly ionized (10% or less), the gas density inside a sonoluminescing bubble at the moment of the bubble's flashing is so high that there still forms a dense plasma. The light emission of the bubble is calculated by the plasma model which is compared with that by the bremsstrahlung (electron-ion, electron-neutral atom) and recombination model. The calculation by the two models shows that for the relatively low maximum temperature (<30000 K) of the bubble, the pulse width is independent of the wavelength and the spectrum deviates the black body radiation type; while for the relatively high maximum temperature (∼60000 K), the pulse width is dependent of the wavelength and the spectrum is an almost perfect black body radiation spectrum. The maximum temperature calculated by the gas dynamics equations is much higher than the temperature fitted by the black body radiation formula.

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Keywords: Sonoluminescence; Plasma; Bremsstrahlung; Black body radiation

1. Introduction

A single oscillating gas bubble can be trapped at the velocity node of an acoustic standing wave in water. A fascinating accompanying phenomenon is the periodic emission by the bubble of very short light pulses in harmony with the oscillation of the acoustic field, known as single-bubble sonoluminescence or SBSL. There are various models with different approximations try to simulate the dynamic processes of the sonolumninescing bubble motion, and all calculations roughly indicate that the maximum temperature inside the sonoluminescing bubble is from ten thousands to few tens of thousands degrees and the gas inside the bubble at that moment is weakly ionized. What we call attention to is that though the gas is weakly ionized when the bubble is at its collapsing phase, the gas density is as high as its liquid state density, therefore, those weakly ionized electrons and ions are dense enough to form a dense plasma. Thus, it is natural that the gas bubble embodies some plasma features.

With the bremsstrahlung and recombination model [1,2], some typical characteristics of SBSL can be well interpreted, such as the full width at half maximum (FWHM) of the light pulses are in the range of 40–300 ps and for the argon bubble FWHM is wavelength independent [3], and the light intensity is sensitive to the ambient temperature. The latter character is due to the temperature sensitivity of water vapor pressure and it is regarded as the evidence of the existence of water vapor inside the bubble [4]. The water vapor is believed to lower the maximum temperature in the bubble [5,6] and this is also the reason why the accommodation coefficient of water vapor plays a very important role in the calculation of the bubble temperature. However, some other characters of SBSL, such that the light spectrum is sometimes an almost perfect black

* Fax: +86 10 62781604.
E-mail address: anyuw@tsinghua.edu.cn

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body radiation type [7] and the FWHM of argon bubble sometimes is wavelength dependent [8], are not well interpreted yet. In the present paper, by dint of the plasma model [9] and the bremsstrahlung and recombination model, I will present below that whether the spectrum is black body radiation type and whether the FWHM of argon bubble is wavelength dependent depend on how much the maximum temperature of the bubble is.

Though the conclusion of this paper is based on the quantitative calculation, it does not mean that the results can be directly compared with the experimental data, because the chemical dissociation and some other possible mechanisms of the light emission, such as the radiative attachment, are not included in the present calculation. Therefore, the interpretations mentioned above and below are correct only in the qualitative meaning.

2. Theoretical model

2.1. Gas dynamics model

The dynamics computation of the sonoluminescing bubble motion is to solve the equation of radial motion of the bubble wall, which is so-called the RP equation, in conjunction with the fluid mechanics equations, the formula of water evaporation and vapor condensation at the bubble wall, and the energy equation in liquid for exterior temperature evaluation. The type of RP equation affects the results very much [6], but in the present paper I will not discuss this problem but simply choose the Keller–Miksis formulation [10], which can be expressed as follows:

$$(1-M)R\ddot{R}+\frac{3}{2}\left(1-\frac{M}{3}\right)\dot{R}^2 = (1+M)\frac{1}{\rho}[p_1-p_\infty-p_s(t+t_\mathrm{R})]+\frac{t_R}{\rho}\dot{p}_1 \tag{1}$$

where $R(t)$ is the radius of the bubble, p_∞ the ambient pressure, $p_\mathrm{s}(t)=-p_\mathrm{a}\sin(\omega t)$ the driving acoustic pressure, $t_R\equiv R/c$, $p_1=p_\mathrm{g}(R,t)-4\eta\dot{R}/R-2\sigma/R$, the pressure on the liquid side of the bubble wall, $p_\mathrm{g}(R,t)$ the pressure on the gas side of the bubble wall, η the dynamic viscosity, σ the surface tension coefficient of the liquid. The parameter $M\equiv\dot{R}/c$ is the bubble-wall Mach number. For the convenience of description, we shall name the equations formed from different choices of ρ and c in Eq. (1) as follows: MRP1 when it takes $\rho=\rho_{1\infty}$, $c=c_{1\infty}$, where $\rho_{1\infty}$ is the ambient liquid density and $c_{1\infty}$ the sound speed in the liquid at the ambient temperature and pressure of 1 atm; MRP2 when it takes $\rho=\rho_1$, $c=c_1$, where ρ_1 is liquid density and c_1 the sound speed on the liquid side of the bubble wall, both of which can be computed from the Tait equation.

At the bubble wall, the phase transformation is supposed to take place, and the rate of the net mass increment of the condensed vapor (or of the evaporated water for negative sign) is evaluated by following formula [11],

$$\dot{m}=\left(\frac{M_1}{2\pi k}\right)^{1/2}\alpha\frac{\Gamma p_1-p_\mathrm{v}}{\sqrt{T_R}}\bigg|_{r=R} \tag{2}$$

where M_1 is the mass of a vapor molecule, k the Boltzmann constant, p_1 the partial pressure of the vapor on the gas side of the bubble wall, p_v the saturated vapor pressure at the temperature of the interface T_R. Γ is a correction for bulk motion to the interface which is close to 1. α, the accommodation coefficient of water vapor, is not very certain, and in the calculation of SBSL it used to be taken as 0.4 [5]. In the present paper, α is evaluated by the molecular dynamics model [12] and it is temperature dependent, which is almost unity as the temperature below 300 K and slowly decreases as the temperature increases. This will help to raise the maximum temperature inside the bubble. The reason is as follows: when the bubble is slowly being compressed from its maximum radius, $\alpha\sim1$ which makes more water vapor escape from the bubble than that in the case $\alpha=0.4$; when the bubble reaches the collapsing phase, the temperature at the interface increases and α decreases to be smaller than 0.4 which blocks the vapor transport heat from the bubble to the surrounding water. As a consequence, the maximum temperature inside the bubble in the present case is much higher than that in the case when α was set to be 0.4.

The partial differential equations (PDE) of fluid mechanics of two gas components, the inert gas and the water vapor, in the spherical symmetry form, the energy equation in liquid and the boundary conditions are exactly the same as those in [6] except that the diffusion coefficient of water vapor on argon gas is doubled in the present calculation for diminishing the amount of the residual vapor in the collapsing bubble, and for more details about the dynamics computation model see [6].

2.2. Radiation model

The electron-atom, the electron-ion bremsstrahlung and the recombination radiation model is exactly the same as those in [6], and I will not repeat the detailed formulae here. The formulae of the radiation from plasma are derived in [9]. The coefficient of absorption in the plasma κ is:

$$\kappa=\frac{2\omega\mu}{c} \tag{3}$$

where c is the light speed in vacuum, ω the angular frequency of electromagnetic wave. Once the coefficient of absorption is obtained, the radiation intensity, Watt per unit wavelength interval, solid angle, and projected surface area, that has traveled a distance s through a bubble (radius R) can be evaluated as follows:

$$I_\lambda(s,t)=\int_0^s n^2\kappa P_\lambda^{Pl}\mathrm{e}^{-\kappa x}\mathrm{d}x \tag{4}$$

where P_λ^{Pl} is the Planck radiation intensity, n the indices of refraction. Then the total emitted power from the bubble per wavelength interval at wavelength λ is,

$$P_\lambda(t)=8\pi^2\int_0^\mathrm{R} I_\lambda(s,t)y\mathrm{d}y \tag{5}$$