Role of the gas solution on the parameters of single bubble sonoluminescence

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ABSTRACT: By using the Bremsstrahlung model, the influence of gas solution is investigated on the emitted intensity of single bubble sonoluminescence in water at 20°C. Also, the relative radius, the internal temperature and the internal pressure of single bubble sonoluminescence are measured and compared for single bubble sonoluminescence in water with presence of noble gases: He, Ne, Ar, Kr and Xe. Temperature-dependent emission intensity of a bubble is based on Bremsstrahlung model for noble gas bubbles were compared. It is found that as the molecular weight of the gas increases the bubble temperature and the internal pressure increase, but the relative radius does not change substantially. Variety of the emitted intensity results in a violent increment in presence of different noble gases. As the emitted intensity maximum in five cycles increases of the order of 10^8 as the gas molecular weight increases from He to Xe.

Keywords: Bremsstrahlung model, Emitted intensity, Noble gas

INTRODUCTION

For many years, a phenomenon known as sonoluminescence (SL) has attracted the attention of researchers. Identifying various aspects and parameters of this cavitations' bubble has been an interest of SL scholars (Barber et al., 1997; Gaitan et al., 1992). Stabilizing an oscillating bubble and achieving extremely high pressures and temperatures during collapse has motivated scientists to perform numerous experimental and theoretical investigations (Vazquez and Putterman, 2000; Yasui, 2001). This tiny bubble actually became a very useful micro-device to test the features of various gases in extremely high temperatures which cannot be achieved with existing heaters and ovens (Brenner et al., 2002; Moshaii et al., 2008). The SL bubble is investigated in two major categories: single bubble sonoluminescence (SBSL) and multi bubble sonoluminescence (MBSL) (Imani et al., 2004; Sadighi-Bonabi et al., 2010; Sadighi-Bonabi et al., 2012; Yasui, 1999). Effective forces acting on the MBSL bubbles including interacting forces between bubbles are reported in various host liquids (Mettin et al., 1997). Various models have been proposed to explain the bubble radiation. At the early stages of studying SL radiation, it was believed that the black body radiation is the most dominant process to generate the light flashes (Hiller et al., 1992; Vazquez et al., 2002). The shortcoming of the black body theory, due to the assumption of the whole bubble luminous object, was soon proved and further attempts were made to introduce other theories to explain the radiation intensity more precisely. The black body radiation was criticized by Yasui (Yasui, 1999) and the Bremsstrahlung model of Moss (Moss et al., 1997) as the main process involved in generating the bubble flashes was proposed. The plasma formation inside the bubble during the bubble collapse was reported to have some effects on SL radiation through the dipole and the multi-pole emissions (Borissenok, 2008; Tsui, 1999). However, Bremsstrahlung radiation is well accepted to be governing process to generate electrons at high temperatures inside the bubble (Hilgenfeldt et al., 1999a, b). Based on this model, the emitted intensity of Xe bubble is almost of the same order of which is reported experimentally (Didenko et al., 2000; Flannigan and Suslick, 2005b; Gaitan et al., 1996; Hilgenfeldt et al., 1999a). Various features of SBSL in He, Ar and Xe bubbles are investigated in water (Brenner et al., 2002; Moshaii et al., 2008).

In this work, by using the Bremsstrahlung model, the influence of all rare gas solutions on SBSL radiation is investigated in water. The time variations of the bubble interior pressure and temperature due to the presence of the He, Ne, Ar, Kr and Xe, are compared. The emitted intensity, which depends on a bubble temperature according to the Bremsstrahlung model are also investigated and compared for the noble gas bubbles. It is noticed that the bubble characteristics strongly depend on the gas type and in the same conditions; the interior gas affects on the bubble interior pressure and temperature. These achievements are discussed in detail.
MATERIAL AND METHODS

a. Radial Oscillations

The Rayleigh-Plesset equation in association with an appropriate boundary equation governs the radial oscillations of the bubble (Löfstedt et al., 1995):

\[
\left(1 - \frac{R}{C}\right) R \frac{\partial R}{\partial t} + \frac{3}{2} \left(1 - \frac{R}{C}\right) \frac{R^2}{C} R = \left(1 + \frac{R}{C}\right) \left(\frac{P_1 - P_\infty}{\rho} + \frac{R}{\rho C} \frac{dP_1}{dt}\right)
\]  

(1)

Where \(R, R, \dot{R}, C, \) and \(C\) are the bubble radius, the bubble wall velocity, the bubble wall acceleration, the density of fluid and the speed of sound in the host fluid, respectively. \(P_1\) is the fluid pressure at the bubble wall (Imani et al., 2012) and \(P_\infty\) is the fluid pressure far enough from the bubble:

\[
P_1 = P_g - 2 \frac{a}{R} - 4 \mu \frac{R}{R} \dot{R}
\]

(2)

\[
P_\infty = P_0 + P_e(t)
\]

(3)

Where \(P_g, a\) and \(\mu\) in Eq. (2) are the gas pressure at the bubble wall, the surface tension, and the fluid shear viscosity, respectively.

In Eq. (3), \(P_0 = 1.031\) atm is an ambient pressure and \(P_e(t)\) is an acoustic driving pressure as follows (Toegel et al., 2006):

\[
P_e(t) = P_0 \sin(\omega t) \left(1 - \frac{\pi^2 |X|^2}{6 R_\ell^4}\right)
\]

(4)

In Eq. (4), \(P_e\) is the driving pressure amplitude, \(\omega\) is the frequency, \(|X|\) is the bubble distance from the center of the resonator and \(R_\ell = 3\) cm is the resonator radius.

Interior gas pressure, \(P_g\) is defined as:

\[
P_g[R(t)] = \left(\frac{P_0 + 2 \mu}{R_0} \left(\frac{R_0^2 - h^2}{R(t)^2 - h^2}\right)^\gamma\right)
\]

(5)

Where \(R_0\) is the bubble initial radius, \(h = \frac{R_0}{\sqrt[3]{\pi}}\) is the Van der Waals hard core radius for Ar and \(\gamma\) is the effective polytropic exponent (Hilgenfeldt et al., 1999a, b). To calculate the Van der Waals hard core radius for other gases, we have estimated this number by atomic gas. Away from collapse, the heat conduction is faster than the bubble wall motion, so that the bubble is (nearly) isothermal, with \(\gamma = 1\). For the strong collapses of SL bubbles, using a time-dependent, instantaneous Pe’clet number \(\gamma\) is a function of \(\hat{R}, R\) and the gas temperature (Kwak and Na, 1996; Löfstedt et al., 1993; Sadighi-Bonabi et al., 2009; Yasui, 1997) T:

\[
\gamma(\text{Pe}) = 1 + (\Gamma - 1) \exp\left(-\frac{A}{\text{Pe}^B}\right)
\]

(6)

\(A \approx 5.8, B \approx 0.6\) and \(\text{Pe}\) is the instantaneous Péclet number:

\[
\text{Pe} = \text{Pe}(t) = \frac{R(t) \dot{R}(t)}{\chi_{\text{gas}}(R,T)}
\]

(7)

Where \(\gamma(\text{Pe} \to 0) \to 1\) (isothermal behavior, where thermal diffusion is dominant) and \(\gamma(\text{Pe} \to \infty) \to \Gamma = \frac{5}{3}\) (adiabatic behavior, where advection is dominant) (Hilgenfeldt et al., 1999b). In Eq. (7):

\[
\chi_{\text{gas}}(R,T) = \frac{25}{48} \Gamma^{-1} \left(\frac{\pi a_{\text{gas}} \alpha T}{\delta_{\text{gas}}}\right)^{0.5}
\]

(8)

\(a_{\text{gas}}, \alpha, T\) and \(\delta_{\text{gas}}\) are gas effective atomic diameter, ideal gas constant, gas temperature and gas molecular weight, respectively. \(G(g)\) is defined as:

\[
G(g) = \frac{1}{g} \left(1 + c_1 g + c_2 g^2 + c_3 g^3 + 1.2 g + 0.755 g^2(1 + c_1 g + c_2 g^2 + c_3 g^3)\right)
\]

(9)

In which \(c_1 = 0.625, c_2 = 0.2869, c_3 = 0.115\) and:

\[
g = \frac{2\pi N_a a_{\text{gas}}^3 R_0^3}{3 K T m R^3}
\]

(10)

\(N_a\) is Avogadro number and \(T_m\) is a gas specific molar volume (Hirschfelder et al., 1954). The bubble temperature is obtained from an excluded volume van der Waals equation of state:

\[
P_g \frac{4\pi}{3} (R^3 - h^3) = \frac{4\pi}{3} R_0^3 T m \alpha
\]

(11)

and regarding the thermal cooling of the gas in the boundary layer, it is given by (Hilgenfeldt et al., 1999b):
\[ T = -[\gamma(Pe) - 1] \frac{3R^2 \dot{R}}{R^2 - h^2} T - \chi_{gas} \frac{T - T_\infty}{R^2} \]  

(12)

Where \( T_\infty \) holds for the fluid temperature at infinity.

**b. Bremsstrahlung Model**

It is assumed that the radiation is a result of three different processes: electron-ion Bremsstrahlung (the light emission from an electron accelerating in the coulomb field of a positive ion), electron-atom Bremsstrahlung (the light emission from an electron accelerating in the coulomb field of a neutral atom) and the radiative recombination of electrons and ions (the process in which an electron is captured in one of the ionic bound states and the emitted photon takes away the excess energy and momentum) which is the inverse process of photoionization (Rybicki and Lightman, 1979).

In this model, it is assumed that the pressure and temperature are spatially uniform inside the bubble except at the thermal boundary layer near the bubble wall (Yasui, 1997). All the effects of thermal conduction between the bubble and the fluid, and also the presence of the water vapor as a result of chemical reactions at the bubble wall, are also taken into account.

The emitted intensity of the electron-ion and electron-atom Bremsstrahlung collisions are (Yasui, 1997):

\[ P_{Br,ion} = 1.57 \times 10^{-40} q^2 N^2 T^{0.5} \frac{4}{3} \pi R^3 \]  

(13)

\[ P_{Br,atom} = 4.6 \times 10^{-44} q N^2 T^{4} \frac{4}{3} \pi R^3 \]  

(14)

\( q, N \) and \( T \) are degree of ionization, number density of atoms and interior temperature of the bubble, respectively. The degree of ionization, \( q \) is:

\[ \frac{q^2}{1 - q} = 2.4 \times 10^{21} T^{3/2} e^{-\epsilon_{gas}/K T} \frac{1}{N} \]  

(15)

With \( \epsilon_{gas} \) as an ionization potential of the gas and \( K \) as the Boltzmann constant. In Eqs. (13)-(15), all the quantities are expressed in SI units.

The emitted intensity yields:

\[ I = r_e (r_r h_{plank} v + P_{Br,ion} + P_{Br,atom}) \]  

(16)

In Eq. (16) \( r_e, r_r, h_{plank} \) are escape rate of the emitted photon from the bubble, rate of radiative recombination and mean energy of the photon emitted by radiative recombination, respectively.

By calculating the above equations, the bubble properties, such as; the interior pressure and temperature, the emitted intensity and the bubble trajectory in the space are compared for solution of five noble gases that are presented in the next section.

**RESULTS AND DISCUSSION**

In this paper, a computer simulation of the gas bubble radiation is presented and is compared for various noble gas solutions in water. The SL bubble is filled with noble gases and the bubble interior pressure and temperature and the emitted intensity are compared for He, Ne, Ar, Kr and Xe. The gases’ parameters are summarized in Table 1 (Flannigan and Suslick, 2005a, b; Tsui, 1999).

<table>
<thead>
<tr>
<th>Noble gas</th>
<th>Effective Atomic Radius (A)</th>
<th>Molecular Weight (Kg/mol)</th>
<th>Specific Molar Volume (mol/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>1.4</td>
<td>0.00400260</td>
<td>0.022424</td>
</tr>
<tr>
<td>Ne</td>
<td>1.54</td>
<td>0.0201797</td>
<td>0.02242</td>
</tr>
<tr>
<td>Ar</td>
<td>1.88</td>
<td>0.039948</td>
<td>0.022392</td>
</tr>
<tr>
<td>Kr</td>
<td>2.20</td>
<td>0.083798</td>
<td>0.02235</td>
</tr>
<tr>
<td>Xe</td>
<td>2.16</td>
<td>0.131293</td>
<td>0.0223</td>
</tr>
</tbody>
</table>

The physical properties of water in 20°C are summarized in Table 2.

<table>
<thead>
<tr>
<th>Sound velocity in water (C/m/s)</th>
<th>Kinetic viscosity (v) (m²/s)</th>
<th>Surface tension (σ) (N/m)</th>
<th>Density (ρ) (Kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1485</td>
<td>10⁻⁶</td>
<td>0.072</td>
<td>996</td>
</tr>
</tbody>
</table>

In the present calculation \( P_0 = 1.01325 \times 10^5 Pa \) is an ambient pressure. To ensure the required conditions for SBSL, the driving frequency is 30.0 KHz, the driving pressure is 1.3 Pa and the bubble initial radius is 6 micron (Sadighi-Bonab et al., 2011).
The calculated results are shown in Figs. 1-4. Figs. 1-4 are shown the various parameters of single bubble sonoluminescence in terms of dimensionless time for five cycles. $T$ is period of the acoustic pressure and $t/T$ is no dimension time.

Fig 1. The relative radius as a function of time for SBSL in the present of He, Ne, Ar, Kr and Xe for five cycles.
Fig 2. The bubble interior temperature at the collapse time for SBSL in the present of He, Ne, Ar, Kr and Xe for five cycles.

Fig 3. The bubble interior pressure at the collapse time for SBSL in the present of He, Ne, Ar, Kr and Xe for five cycles.
As seen in Fig. 1 the relative radius for SBSL in the present of He, Ne, Ar, Kr and Xe have no significant difference. In Fig. 2 it is seen that the bubble interior temperature maximum at the collapse time for SBSL for five cycles increase as the gas molecular weight increases. Also Fig. 3 shows the bubble interior pressure maximum increases with increasing the gas molecular weight. A big increment in the emitted intensity profile maximum is noticed with increasing the gas molecular weight in Fig. 4. As they are shown, the collapse duration depends highly on the gas type.

Table 3 shows maximum of the various parameters of SBSL in the present of noble gases.

<table>
<thead>
<tr>
<th>Relative radius</th>
<th>Interior temperature</th>
<th>Interior pressure</th>
<th>Emitted intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{R}{R_0}$</td>
<td>T(K)</td>
<td>P(atm)</td>
<td>I(W/m$^2$)</td>
</tr>
<tr>
<td>He</td>
<td>58.0</td>
<td>4100</td>
<td>850</td>
</tr>
<tr>
<td>Ne</td>
<td>58.2</td>
<td>6400</td>
<td>1150</td>
</tr>
<tr>
<td>Ar</td>
<td>58.3</td>
<td>6800</td>
<td>4600</td>
</tr>
<tr>
<td>Kr</td>
<td>58.5</td>
<td>11500</td>
<td>8500</td>
</tr>
<tr>
<td>Xe</td>
<td>58.9</td>
<td>16400</td>
<td>18500</td>
</tr>
</tbody>
</table>

Figs. 5 and 6 show the change in maximum interior temperature, interior pressure and the emitted intensity in terms of molecular weight respectively. Maximum interior temperature changes from 4100 to 16400K and maximum interior pressure changes from 850 to 18500 atm. Also maximum emitted intensity changes from 1.16E-11 to 3.1E-3.
Fig 6. The change in maximum emitted intensity in terms of molecular weight

According to the Bremsstrahlung model, the emitted intensity is proportional to the bubble interior temperature (Eq. (16)). The emitted intensity increment is of the order of $10^8$ as the gas molecular weight increases from He to Xe.

CONCLUSION

The effect of the gas solution on the bubble properties for SBSL in water is investigated. It is shown that for SBSL, by increasing the gas molecular weight, the bubble interior temperature, the bubble interior pressure and the emitted intensity increase. Although, the increment of the gas molecular weight is small, it can induce a great difference in the intensity profile. This is in agreement with the reported experimental measurements (Didenko et al., 2000).

Although these measurements are in agreement with the earlier experimental results of using a few noble gases for SBSL, the big difference in measurements proves the uncertainty of the Bremsstrahlung model, at least for the lighter atoms.

REFERENCES


