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ARTICLE

# EFFECT OF ACOUSTIC PRESSURE ON THE PROPERTIES OF SINGLE BUBBLE SONOLUMINESCENCE

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## ABSTRACT

*By using two computer simulations (quasi-adiabatic and hydro-chemical simulations), the relative radius, the bubble interior temperature and the emitted intensity inside a single bubble sonoluminescence in water due to different acoustic pressures were measured and compared. It was found that with increasing the acoustic pressure, the bubble relative radius and the bubble interior temperature rises, and thus increases the intensity of the emitted light. By changing the acoustic pressure in the quasi-adiabatic simulations of 1.313 to 2.02 bar, the bubble interior temperature changed about 4×103 to 34×103 K and the emitted intensity changed about of 1.52×10-5 to 2.21 W/m2. And by changing the acoustic pressure in the hydro-chemical simulations of 1.111 to 1.616 bar, the bubble interior temperature changed about 8.01×103 to 38.18×103 K and the emitted intensity changed about of 6.73×10-3 to 3.096 W/m2.*

**KEY WORDS**
*acoustic pressure; hydro-chemical simulation; quasi-adiabatic simulation; sonoluminescence*

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## INTRODUCTION

For many years, a phenomenon known as sonoluminescence (SL) has attracted the attention of researches. Identifying various aspects and parameters of this cavitation bubble has been an interest of SL scholars [1, 2]. Stabilizing an oscillating bubble and achieving extremely high pressures and temperatures during collapse has motivated scientists to perform numerous experimental and theoretical investigations [3, 4]. 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 [5, 6]. The SL bubble is investigated in two major categories: single bubble sonoluminescence (SBSL) and multi bubble sonoluminescence (MBSL) [7]. Effective forces acting on the MBSL bubbles, including interacting forces between bubbles are reported in various host liquids [8]. 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 [4, 9]. 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 available models of SBSL are quasi-adiabatic, hydro-chemical ones. The quasi-adiabatic model (adiabatic behavior only near the minimum radius and isothermal for the rest of the cycle) is very simple, so many parameters of the bubble cannot be found and some parameters of the host fluid and the bubble parameters, such as chemical reactions, are ignored [10, 11]. Another one is hydro-chemical model which is used to study SBSL that is more complete [12]. In this work, changes of parameters of SBSL in water were studied for different acoustic pressures by the quasi-adiabatic and the hydro-chemical simulations.

## MATERIALS AND METHODS

The The Rayleigh-Plesset equation in association with an appropriate boundary equation governs the radial oscillations of the bubble [13]:

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

Where $R, \dot R, \ddot R, \rho$ 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. $P_l$ is the fluid pressure at the bubble wall[9] and $P_m$ is the fluid pressure [14] far enough from the bubble:

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

$$P_m = P_0 + P_a(t) \quad (3)$$

Where $P_g$, $\sigma$ and μ in (2) are the gas pressure at the bubble wall, the surface tension, and the fluid shear viscosity, respectively.

In (3), $P_0 = 1\ bar$ is an ambient pressure and $P_a(t)$ is an acoustic driving pressure as follows [15]:

$$P_a(t) = -P_a\sin(\omega t)\left(1-\frac{\pi^2|\chi|^2}{6R_{fl}^2}\right) \quad (4)$$

In (4), $P_a$ is the driving pressure amplitude, $\omega$ is the frequency, $|\chi|$ is the bubble distance from the center of the resonator and $R_{fl} = 3cm$ is the resonator radius. Interior gas pressure, $P_g$ in quasi-adiabatic model, is defined as:

$$P_g[R(t)] = \left(P_0+\frac{2\sigma}{R_0}\right)\left(\frac{R_0^3-h^3}{R^3(t)-h^3}\right)^{\gamma} \quad (5)$$

Where $R_0$ is the bubble initial radius, $h = \frac{R_0}{8.86}$ is the Van der Waals hard core radius for Ar and γ is the effective polytrophic exponent [16]. To calculate the Van der Waals hard core radius for other gases, we have estimated this number by $\frac{\text{gas atomic radius}}{\text{Ar atomic radius}} \times 8.86$ instead of 8.86 for Ar. The temperature changes due to the bubble dynamics and the thermal conduction are described through the definition of γ. If the time it takes the bubble wall to oscillate is faster than the time scale of heat conduction through the bubble wall, the collapse will be (nearly) adiabatic and $\gamma \approx \Gamma$, where Γ=5/3 is the adiabatic exponent for mono-atomic gas. Away from collapse, the heat conduction is faster than the bubble wall motion, so that the bubble is (nearly) isothermal, with γ=1. For the strong collapses of SL bubbles, using a time-dependent, instantaneous Pe´clet number $\gamma$ is a function of $\dot{R}, R$ and the gas temperature [17] *T*:

$$\gamma(\mathrm{Pe}) = 1 + (\Gamma - 1)exp\left(-\frac{A}{Pe^B}\right) \quad (6)$$

$A \approx 5.8, B \approx 0.6$ and *Pe* is the instantaneous Peclet number:

$$Pe = Pe(t) = \frac{R(t)|\dot{R}(t)|}{\chi(R,T)} \quad (7)$$

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

$$\chi_{gas}(\mathrm{R,T}) = \frac{45}{16}\Gamma^{-1}\left(\frac{\pi a_{gas} ...}{...}\right) \quad \mathrm{G(g)} \quad (8)$$

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

$$G(g) = \frac{1}{...}\left(\frac{1}{...} + 1.2g + 0.755g^2(1 + c_1g + c_2g^2 + c_3g^3)\right) \quad (9)$$

In which $c_1 = 0.625, c_2 = 0.2869, c_3 = 0.115$ and:

$$g = \frac{2\pi N_a a^3_{gas} R_0^3}{...} \quad (10)$$

$N_a$ is Avogadro number and $\tau_m$ is a gas specific molar volume.

The bubble temperature is obtained from an excluded volume van der Waals equation of state:

$$\mathrm{P_g}\frac{4\pi}{3}(R^3 - h^3) = \frac{4\pi}{3}R_0^3\tau_m\alpha\mathrm{T} \quad (11)$$

And regarding the thermal cooling of the gas in the boundary layer, it is given by:

$$\dot{T} = -[\gamma(Pe) - 1]\frac{3R^2\dot{R}}{R^3 - h^3}T - \chi_{gas}\frac{T - T_\infty}{R^2} \quad (12)$$

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

The emitted intensity of the electron-ion and electron-atom Bremsstrahlung collisions can be presented as follows [18]:

$$P_{Br,ion} = 1.57 \times 10^{-40}q^2N^2T^{0.5}\frac{4}{3}\pi R^3 \quad (13)$$

$$P_{Br,atom} = 4.6 \times 10^{-44}qN^2T\frac{4}{3}\pi R^3 \quad (14)$$

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

$$\frac{q^2}{1-q} = 2.4 \times 10^{21}T^{3/2}e^{-\epsilon_{gas}/K_BT}\frac{1}{N} \quad (15)$$

Where $\epsilon_{gas}$ and $K_B$ are the ionization potential of gas and the Boltzmann constant, respectively. In (13) - (15), all of the quantities are expressed in SI units.

The emitted intensity yields:

$$I = r_e(r_\gamma h_{\mathrm{plank}}\bar{\mathrm{v}} + P_{Br,ion} + P_{Br,atom}) \quad (16)$$

In this equation $r_e, r_\gamma, h_{\mathrm{plank}}\bar{\mathrm{v}}$ are the escape rate of emitted photon from SL bubble, the rate of radiative recombination and the mean energy of the photons emitted by radiative recombination, respectively.

And in the hydro-chemical model, the Rayleigh-Plesset equation is coupled with gas pressure. The gas pressure in this model is described by [12]:

$$P_g = \frac{N_{tot}K_BT}{V - N_{tot}B} \quad (17)$$

In this equation $N_{tot}$, *B* and *V* are the total number of particles inside the bubble, the hard core parameter and the bubble volume, respectively.

Also the boundary layer formalism is used to consider heat transfer between the bubble and its surrounding liquid. The heat loss is estimated to be:

$$\dot{Q} = 4\pi R^2\kappa\frac{T_0 - T}{l_{th}}, \; l_{th} = \min\left(\frac{R}{\pi}, \sqrt{\left|\frac{R\chi}{\dot{R}}\right|}\right) \quad (18)$$

$T_0$ is the initial bubble temperature, and $\kappa, \chi$ are the thermal conductivity and thermal diffusivity for the gas mixture [12]. Chemical reactions in the bubble, particle diffusion from the bubble wall, evaporation and condensation of molecules, heat conduction, and the bubble stabilities are considered in this model.

## RESULTS

At first, the quasi adiabatic simulation of the single bubble sonoluminescence was presented and compared for various acoustic pressures in water $20\,^{\circ}C$. The physical properties of water in $20\,^{\circ}C$ are summarized in [**Table 1**]. The bubble relative radius as a function of time, the bubble interior temperature and the emitted intensity at the collapse time, were calculated and compared for the acoustic pressures from P1 to P5. The amounts of the acoustic pressures from P1 to P5 are given in [**Table 2**].

Table 1.The physical properties of water in $20\,^{\circ}C$

| | $\rho(kg.m^{-3})$ | $\sigma(N.m^{-1})$ | $\mu(Pa.s)$ | $C(m.s^{-1})$ | | $T(^{\circ}C)$ |
|---|---|---|---|---|---|---|
| $H_2O$ | 1000 | 0.073 | $1.307\times10^{-3}$ | 1660 | 0.338 | 20 |

To ensure the required conditions for SBSL, the driving frequency is 30 KHz, and the bubble initial radius is 6 micron [19]. The calculated results are shown in [Fig. 1,2,3].

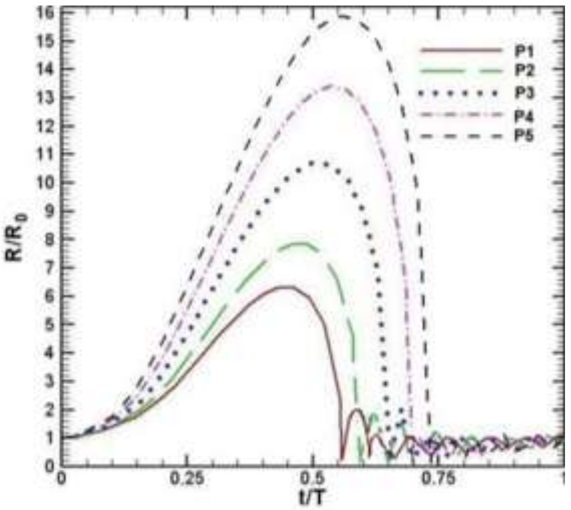


**Fig: 1.** Comparison of the bubble relative radius as a function of time for different acoustic pressures at the first cycle (in the quasi adiabatic simulation)

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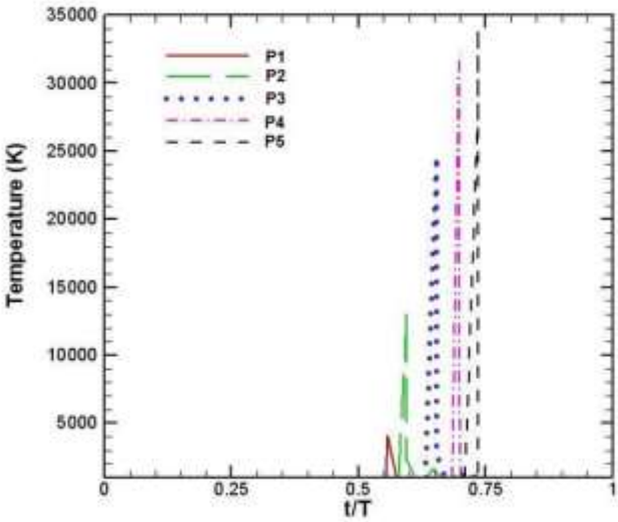


**Fig: 2.** comparison of the bubble interior temperature for different acoustic pressures at the collapse time (in the quasi adiabatic simulation)

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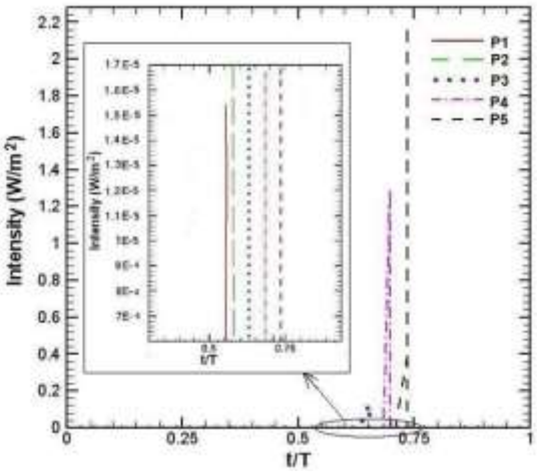


**Fig: 3.** Comparison of the emitted intensity for different acoustic pressures at the collapse time (in the quasi adiabatic simulation)

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In [Fig. 1] the bubble relative radius as a function of time in one cycle (T is period of the acoustic pressure and t/T is no dimension time) was compared for various acoustic pressures. It is noticed that as the acoustic pressures increases the bubble relative radius increases. [Fig. 2] shows the bubble interior temperature of five different acoustic pressures. It is shown that the increment of the acoustic pressures induces an increment in the bubble interior temperature at the collapse time. A time variation of the emitted intensity in one cycle is compared in [Fig. 3]. It is shown that the increment of the acoustic pressures induces an increment in the emitted intensity at the collapse time. Maximum of the bubble interior temperature, the emitted intensity and the bubble relative radius in the quasi adiabatic simulation are given in [**Table 2**]. These results have been achieved from [Figs. 1,2,3].

**Table 2:** Results of SL in the quasi adiabatic simulation for different acoustic pressures

| | $P_a$ (bar) | $R/R_0$ | $(K)_{..}$ | $(W/m^2)_{..}$ |
|---|---|---|---|---|
| P1 | 1.313 | 6.43 | $4 \times 10^3$ | $1.52 \times 10^{-5}$ |
| P2 | 1.414 | 7.84 | $1.3 \times 10^4$ | $3.50 \times 10^{-4}$ |
| P3 | 1.616 | 10.84 | $2.4 \times 10^4$ | 0.13 |
| P4 | 1.818 | 13.56 | $3.2 \times 10^4$ | 1.32 |
| P5 | 2.020 | 16.06 | $3.4 \times 10^4$ | 2.21 |

At next step, the hydro chemical simulation of SL was presented and compared for various acoustic pressures in water $20\,^{\circ}C$. The bubble relative radius as a function of time, the bubble interior temperature and the emitted intensity at the collapse time were calculated and compared for acoustic pressures from P6 to P10. The pressures from P6 to P10 are given in [**Table 3**]. Also the calculated results are shown in [Figs. 4,5,6].

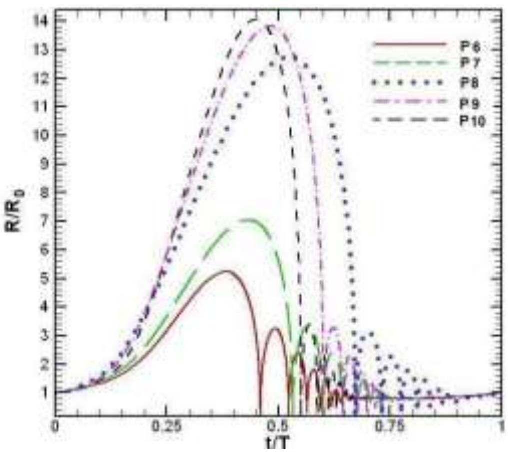


**Fig. 4:** Comparison of the bubble relative radius as a function of time for different acoustic pressures at the first cycle (in the hydro chemical simulation)

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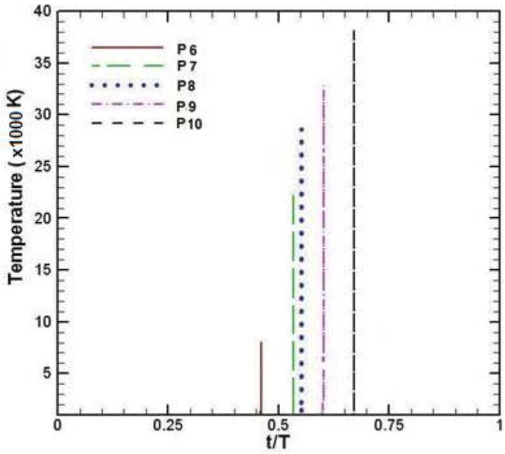
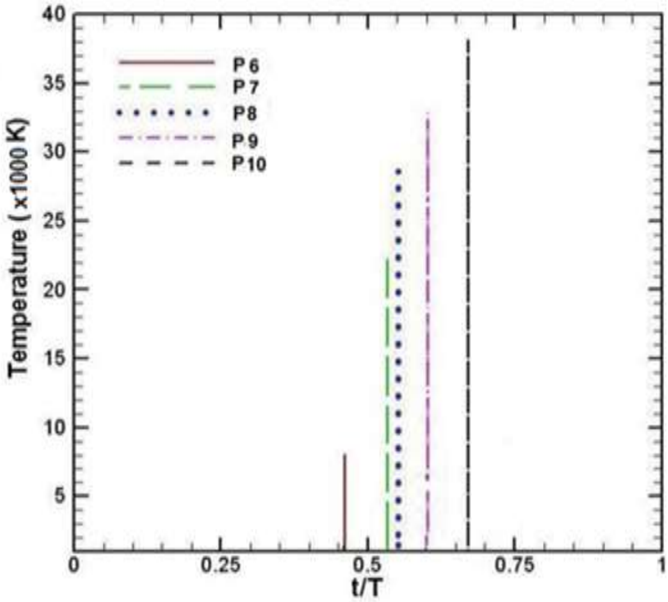



Fig. 5: Comparison of the bubble interior temperc
(in the hydro chemical simulation)



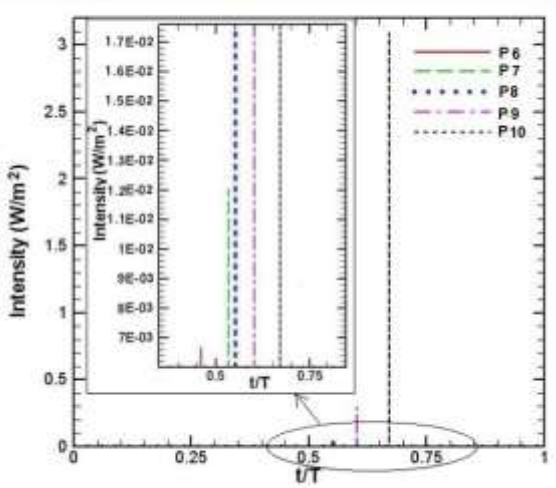




**Fig. 6:** Comparison the emitted intensity of the SL bubble for different acoustic pressures at the collapse time (in the hydro chemical simulation)

[Fig. 4,5,6] are same [Fig. 1,2,3] except that type of simulation has been changed. Maximum of the bubble interior temperature, the emitted intensity and the bubble relative radius in the hydro chemical simulation are given in **Table-3**. These results have been achieved from [Fig. 4,5, 6].

**Table 3:** Results of SL in the hydro chemical simulation for different acoustic pressures

| | $R_0$ (μm) | $P_a$ (bar) | $R/R_0$ | (K) | (W/m²) |
|---|---|---|---|---|---|
| P6 | 3.5 | 1.111 | 5.24 | $8.07 \times 10^3$ | $6.73 \times 10^{-3}$ |
| P7 | 4.5 | 1.212 | 7.05 | $22.23 \times 10^3$ | 0.012 |
| P8 | 2.45 | 1.313 | 12.77 | $28.73 \times 10^3$ | 0.033 |
| P9 | 3.45 | 1.414 | 13.83 | $33.07 \times 10^3$ | 0. 295 |
| P10 | 5.5 | 1.616 | 14.07 | $38.18 \times 10^3$ | 3.096 |

at the [**Table 3**], in the hydro chemical simulation, the initial radius was not same for each simulation by changing the acoustic pressures. The initial radius should be chosen such that bubble stability is maintained. The initial radius and the acoustic pressure of a stable bubble, at diagram phase is selected. That this issue is fully discussed in other articles [20]. [Fig. 7,8,9] that are obtained from [**Tables 2 and 3**], show the relative radius, the interior temperature and the emitted intensity changes in terms of the acoustic pressure respectively, in the quasi adiabatic and hydro chemical simulations.

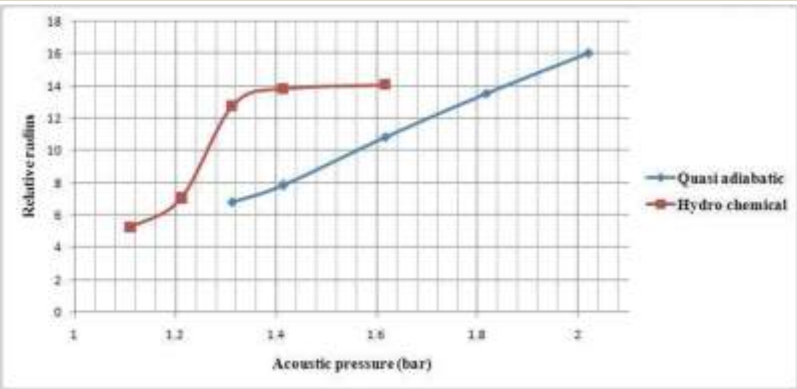



**Fig. 7:** The relative radius changes in terms of the acoustic pressure

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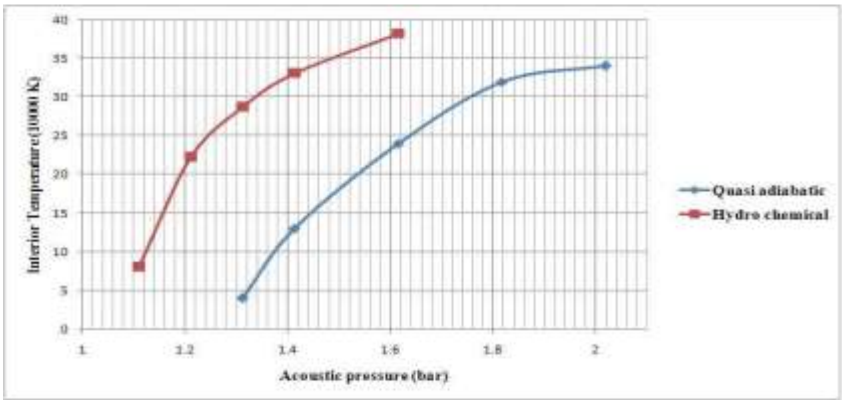


**Fig. 8:** The interior temperature changes in terms of the acoustic pressure.

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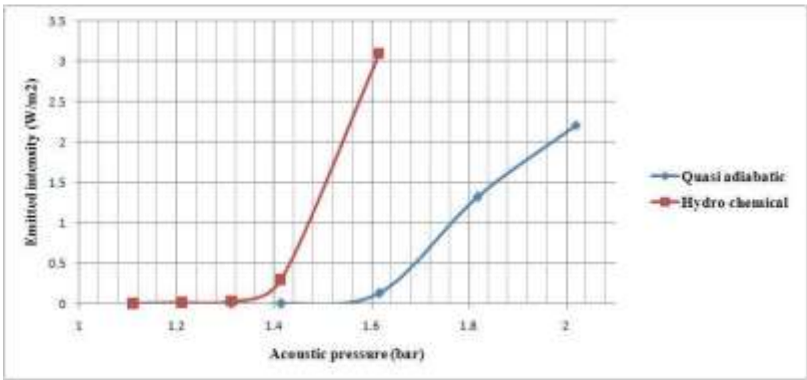


**Fig. 9:** The emitted intensity changes in terms of the acoustic pressure.

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## DISCUSSION

By studying of above results, it was found that parameters of SBSL such as the relative radius, the interior temperature and the emitted intensity, in the hydro chemical simulation are higher than ones in the quasi adiabatic simulation. Also the mentioned parameters increase with increasing the acoustic pressure. 54 percent increase in acoustic pressure leads to 149, 750 and 1454 percent increase in the relative radius, the interior temperature and the emitted intensity respectively at the quasi adiabatic simulation. And 45 percent increase in acoustic pressure leads to 168, 373 and 42902 percent increase in the relative radius, the interior temperature and the emitted intensity respectively at the hydro chemical simulation.

## CONCLUSION

The effect of the acoustic pressures on the bubble properties for SBSL in water is investigated. It is shown that for SBSL in water 20°C, by increasing the acoustic pressures, the bubble relative radius and the interior temperature and consequently the emitted intensity increase. Although, the increment of the acoustic pressures is small, it can induce a great difference in the emitted intensity profile. This is in agreement with the reported experimental measurements.

## CONFLICT OF INTEREST
There is no conflict of interest.

## ACKNOWLEDGEMENTS
None

## FINANCIAL DISCLOSURE
None

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