Sonoluminescence and the probability of isothermal bubble collapse

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Abstract Computations of air bubble collapse dynamics usually neglect thermal conduction, but recent computations show about a 3-fold reduction in bubble gas temperature if thermal conduction is included. However, an isothermal collapse at ambient temperature is even more likely because the air molecules collide with and stick to the bubble walls during bubble expansion and are not available for compression heating during collapse. The probability of isothermal collapse is shown to depend on the mean free path of the air molecules moving through the H_2O vapor molecules within the bubble during bubble expansion and is sensitive to the lowering of ambient temperature to the freezing point.

Keywords Sonoluminescence, Bubble collapse, Thermal conduction, Cold fusion

1 Introduction

The effect of thermal conduction (TC) on air bubble dynamics in liquid H_2O near the sonoluminescence (SL) threshold was studied^[1] using data^[2,3] for light emitting and non-light emitting bubbles. Using picosecond SL (PSL) to designate light emitting bubbles, PSL computed with TC shows about a 3-fold reduction in the bubble air temperature from that computed without TC. A similar reduction was found for the non-light emitting bubble. During bubble collapse, the peak bubble air temperature for PSL and non-light emitting bubbles computed with TC was found to be about 2000 and 500 K respectively.

For both PSL and non-light emitting bubbles, the number of air bubble gas molecules in the computation^[1] changed only negligibly because the diffusion of air in and out of the liquid H₂O wall was insignificant. However, if during bubble expansion the air molecules collide with and stick to the bubble walls, the number of air molecules available to be compressed to high temperatures during bubble collapse would be drastically reduced. In effect, bubble expansion tends to evacuate^[4] the bubble of gases other than H₂O vapor and precludes any subsequent temperature increase of the bubble gases during bubble collapse, i.e. the bubble gas molecules within the bubble are not available to be compressed or to propagate shock waves dur-

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ing bubble collapse. Alternatively, the air temperatures for PSL and non-light emitting bubbles computed^[1] with and without TC would reduce to an isothermal bubble collapse at ambient temperature.

A simple way to assess the probability of an isothermal bubble collapse in SL is to estimate the probability of the air molecules sticking to the liquid H₂O bubble walls during bubble expansion. The sticking coefficients of NO and SO₂ gases on a liquid H₂O surface were computed^[5] using molecular dynamics and found to be about 0.65 and 0.85. rcspectively. Desorption was not considered, but like diffusion^[1] during SL bubble expansion is expected to be insignificant. The sticking coefficients were shown to be simply estimated by assuming an elastic collision of the gas molecule with a liquid H_2O molecule and only depend on the molecular weight ratio of the gas to H_2O . Hence, the sticking coefficient for air $(O_2 \text{ and }$ N_2 molecules) is estimated for the purposes here as about 0.65 corresponding to NO.

The probability of an isothermal collapse increases with the number of air molecule and bubble wall collisions. Scattering of air molecules by H_2O vapor molecules within the bubble delays the time between collisions with the bubble walls thereby lowering the probability of an isothermal bubble collapse. Hence, the probability of isothermal collapse delayed by scattering may be assessed by comparing the mean free path mfp of the air molecule with the bubble radius R after bubble expansion just prior to collapse. If mfp > R, the air molecules are not scattered giving the maximum number of wall collisions possible per unit time and a high probability of isothermal collapse. However, if mfp < R, the air molecules are scattered giving a reduced number of wall collisions per unit time and a lower probability of isothermal collapse. The mfp is

$$mfp = \frac{K_{\rm b}T}{\pi\sqrt{2}(P_{\rm air} + P_{\rm vap})d^2} \tag{1}$$

where, $K_{\rm b}$ is Boltzmann's constant, T is the absolute temperature, d is the diameter of the air molecule, $P_{\rm air}$ is the pressure of the air, and $P_{\rm vap}$ is the H₂O vapor pressure. The vapor pressure $P_{\rm vap}$ only depends on the temperature T_0 of the liquid H₂O bubble walls and is constant during bubble expansion, i.e., at 10 and 20°C, $P_{\rm vap} \sim 1228$ and 2339 Pa. At the freezing point of liquid H₂O, $P_{\rm vap} \sim 611$ Pa. In contrast, the air pressure $P_{\rm air}$ decreases during bubble expansion. Bubble expansion is an isothermal process because the temperature T of the air molecules after numerous collisions with the H₂O vapor molecules tends to remain at the ambient temperature T_0 of the bubble walls. In the classical isothermal process, the gas pressure decreases at constant gas mass. But during bubble expansion, the air pressure $P_{\rm air}$ decreases more rapidly than the isothermal process because mass is lost as the air molecules stick to the bubble walls. Since the mfp is inversely proportional to the air pressure $P_{\rm air}$, a conservative estimate of the mfp is found by assuming the air pressure $P_{\rm air}$ decreases in the manner of the classical isothermal expansion. For a spherical bubble, $P_{\rm air} = (P_{\rm atm} - P_{\rm vap}) (R_0/R)^3$, where P_{atm} is atmospheric pressure, R_0 and Rare the initial and final bubble radii, respectively. Combining,

$$mfp > rac{K_{
m b}T_{
m 0}}{\pi\sqrt{2}d^{2}\left((P_{
m atm} - P_{
m vap})(rac{R_{
m o}}{R})^{3} + P_{
m vap}
ight)}_{(2)}$$

Taking O_2 as representative of air, the van der Waals diameter $d \sim 0.291$ nm. For a bubble expanding from atmospheric pressure $P_{\rm atm} \sim$ 1×10^5 Pa at ambient temperature $T_0 \sim 0$, 10 and 20°C, the mfp as a function of radius expansion ratio R/R_0 is shown in Fig.1.



Fig.1 Air mfp vs bubble expansion ratio

Experimental data^[2] give the initial R_0 and final radius R for PSL as 4.5 and 37.5 μ m giving $R/R_0 \sim 8.33$; whereas for a non-light emitting bubble the radii are 10.5 and 27.5 μ m giving $R/R_0 \sim 2.63$. From Fig.1, the mfp at 20°C for both PSL ($R \sim 37.5 \mu$ m) and non-light emitting bubbles ($R \sim 27.5 \mu$ m) is about 4.3 and



Fig.2 Delay time t_{avg} vs temperature

1.4 μ m. Since mfp < R, the air molecules are scattered before colliding with the bubble walls. However, scattering by H₂O vapor molecules may be reduced by lowering the ambient temperature. Fig.1 shows the mfp for the PSL bubble to be increased ~ 3× to about 13 μ m at the freezing point. But the mfp for non-light emitting bubbles with smaller expansion ratios increases only slightly to about 1.6μ m.

The delay time t_{delay} for the air molecule colliding with the bubble walls may be estimated by assuming a random walk between collisions with H₂O vapor molecules before reaching the bubble walls. The average time t_{avg} corresponds to the time for an air molecule at the center of the bubble to random walk a distance equal to the bubble radius R. For air molecules near the bubble wall, the delay time $t_{delay} \ll t_{avg}$. If the air molecule moves at the root mean square velocity V_{rms} between collisions, the average delay time t_{avg} is

$$t_{\rm avg} < \frac{R^2}{m f p V_{\rm rms}} \tag{3}$$

where

$$V_{\rm rms} = \sqrt{3K_{\rm b}T_0/m}$$

and m is the mass of the air molecule. Fig.2 shows the average time $T_{\rm avg}$ for an air molecule in a PSL bubble $(R \sim 37.5 \,\mu{\rm m})$ and non-light emitting bubble $(R \sim 27.5 \,\mu{\rm m})$ as a function of ambient temperature .

At 20°C, the PSL and non-light emitting bubbles have average delay times $t_{\rm avg} \sim 0.65$ and 1.04μ s. Over about 4μ s centered about the maximum bubble radius, the bubble radius at 37.5 μ m changes by only about 1μ m at 26.5 kHz. Hence, the air molecules in the PSL and non-light emitting bubbles before collapse have time to collide with the bubble wall more than about 6 and 4 times, respectively. For a sticking coefficient of 0.65, the air molecules in both the PSL and non-light emitting bubbles are likely stuck to the bubble walls before collapse. This means the SL photons observed for PSL occur with a high probability of isothermal bubble collapse. In contrast, the PSL and non-light emitting bubbles at the freezing point have average delay times $t_{\rm avg} \sim 0.22$ and $0.94\,\mu {\rm s}$ giving at least about 18 and 4 wall collisions, respectively. Given the sticking coefficient for air, an isothermal collapse is almost a certainty for the PSL bubble, but is still quite likely for the non-light emitting bubble near the freezing point.

In conclusion, an isothermal collapse is likely for both PSL and non-light emitting bubbles at ambient temperatures from 20° C to the freezing point. At 20° C, the number of wall collisions is about the same, but only the PSL bubble emits light. The reason why the PSL bubble emits light and not the non-light emitting bubble may be because of the higher drive pressure^[2] in PSL.

References

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