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Laser induced sonofusion: A new road toward thermonuclear reactions

Rasoul Sadighi-Bonabi^{1,a} and Maryam Gheshlaghi^{2,3}

¹Sharif University of Technology, P.O. Box 11365-91, Tehran, Iran

²Payame noor University, P.O. Box 19395-3697, Tehran, Iran

³Laser and optics research school, Nuclear Science and Technology Research Institute (NSTRL), P.O. Box 14155-1339, Tehran, Iran

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The Possibility of the laser assisted sonofusion is studied via single bubble sonoluminescence (SBSL) in Deuterated acetone (C_3D_6O) using quasi-adiabatic and hydro-chemical simulations at the ambient temperatures of 0 and $-28.5^\circ C$. The interior temperature of the produced bubbles in Deuterated acetone is $1.6 \times 10^6 K$ in hydro-chemical model and it is reached up to $1.9 \times 10^6 K$ in the laser induced SBSL bubbles. Under these circumstances, temperature up to $10^7 K$ can be produced in the center of the bubble in which the thermonuclear D-D fusion reactions are promising under the controlled conditions. © 2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). [<http://dx.doi.org/10.1063/1.4945343>]

I. INTRODUCTION

“Sonofusion- fact or fiction?” was the title of Taleyarkhan’s article reported in 2005.¹ He and his colleagues claimed that they measured sufficient sonofusion neutrons experimentally by imploding cavitation bubbles in the chilled Deuterated acetone.² This idea was initially presented by Moss in 1994 claimed that adding a pressure spike to the periodic driving amplitude may create temperatures that are sufficient to generate a very small number of thermonuclear D-D fusion reactions in the bubble.³ Following the first experimental observations, some positive, negative and mixed comments were provided about this important measurement.⁴⁻⁷ It was claimed that an experimental search for the nuclear fusion inside the imploding bubbles of degassed Deuterated acetone at $0^\circ C$ driven by a 15 atm sound field and seeded with a neutron generator reveals an upper bound that is a factor of 10000 less than the signal reported by Taleyarkhan et al. The strength of their upper bound was limited by the weakness of the sonoluminescence flash, which they blamed on the relatively high vapor pressure of acetone.⁸ Based on the earlier reports the range of the required temperatures is about 10^6 - $10^8 K$ and the dense plasma pressure should be more than 10^7 atm for sonofusion in Deuterated acetone as a host fluid.^{8,9} More recently, a sonofusion simulation in poor quasi-adiabatic model in Deuterated acetone (C_3D_6O) was presented.¹⁰ In spite of very useful discussions the presented results were only rough estimates due to using violent adiabatic model and ignoring many events in this model. In addition, temperatures were calculated for pressures up to 7 atm due to the instability of the used computer code, so the results were extra plotted up to fifteen atmospheres to be able to compare with the reported experiment.¹⁰ Furthermore, due to a variety of techniques presented for SBSL, presentation of an optimum approach for achieving the highest possible temperature was neglected. Therefore, a comprehensive and complete investigation is required to present proper results to answer too many ambiguities in this important subject in order to represent a proper experimental arrangement exhibiting thermonuclear reaction.

In this work the simulation results are presented based on quasi-adiabatic and the most progressed hydro-chemical model for the reported experimental conditions.⁴ Then, quasi-adiabatic

^aE-mail: Sadighi@sharif.ir

model is employed for a transient cavitation bubble induced by laser in the presence of the sound field. Due to the laser presence, the liquid is assumed to behave as a compressible fluid. Some simulation results for laser-induced single cavitation bubble luminescence (LI-SCBL) plus SBSL have been published in water and sulfuric acid.^{11,12} In this paper, the outcomes for LI-SCBL and SBSL are reported in Deuterated acetone at two ambient temperatures. This matter can fulfill the old dream of sonofusion more properly by achieving the temperatures up to 10⁷ K by performing some manipulation tasks explained in detail. To prove the authenticity of these model water, as a reported usual buffer liquid, is used.

II. THE MODELS

The available models for simulation of SBSL are quasi-adiabatic, and hydro-chemical codes, and quasi-adiabatic model for a set of LI-SCBL and SBSL. 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.^{13,14} Another one is hydro-chemical model which is used to study SBSL.¹⁵⁻¹⁷ In this model effects of heat and mass transfer at the bubble wall have been considered.

A. The quasi-adiabatic model

Using the Rayleigh-Plesset equation, the oscillations of a transient cavitation bubble induced by an acoustic field are obtained and a complete dynamics and acoustic cycles of single bubble oscillations and their after bounces in C₃D₆O are shown. The bubble expands slowly till reaching its maximum radius. Then, it implodes intensively and emits a flash of light with a spectrum extending from IR to UV.¹⁸

$$\left(1 - \frac{\dot{R}}{C}\right) R \ddot{R} + \frac{3}{2} \left(1 - \frac{\dot{R}}{3C}\right) \dot{R}^2 = \left(1 - \frac{\dot{R}}{C}\right) \frac{1}{\rho} (P_l - P_a - P_0) + \left(\frac{R}{\rho C}\right) \frac{d}{dt} (P_l - P_a) \quad (1)$$

R , \dot{R} , \ddot{R} , ρ and C are the bubble radius, the bubble wall velocity, the bubble wall acceleration, the density of the liquid and the speed of sound on the bubble wall, respectively. P_0 , P_a and P_l are the initial ambient pressure, the driving pressure and the fluid pressure at the bubble wall, respectively. P_l is given by:

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

Where μ is the fluid kinematic viscosity and P_g is the gas pressures:¹¹

$$P_g = (P_0 + 2\sigma/R_0) \left(\frac{R_0^3 - a^3}{R(t)^3 - a^3} \right)^\gamma \quad (3)$$

Also R_0 is the initial radius of bubble which is induced by the acoustic field, σ is the surface tension, $a = R_0/8.36$ indicates a hard-core van der Waals term for Deuterated acetone vapor,¹⁰ and γ is the polytropic exponent which describes the degree of adiabaticity during the bubble oscillation cycle.²⁰ The driving pressure of the acoustic field, $P_a(t)$ is assumed to be a sinusoidal sound field as a function of time (t), applied in the liquid very far from the bubble as:

$$P_a(t) = P_a \sin(2\pi ft) \quad (4)$$

where P_a and f are the amplitude and the frequency of the driving acoustic field, respectively. The bubble temperature is obtained from an excluded volume Van der Waals equation of state:

$$P_g \frac{4\pi}{3} (R^3 - a^3) = \frac{4\pi}{3} R_0^3 \nu_m \alpha T \quad (5)$$

v_m , α and T are the gas specific molar volume, ideal gas constant and gas temperature, respectively.²⁰ Regarding the thermal cooling of the gas in the boundary layer, T is obtained by:¹⁴

$$\dot{T} = -[\gamma(Pe) - 1] \frac{3R^2\dot{R}}{R^3 - a^3} T - \chi_{gas} \frac{T - T_\infty}{R^2} \quad (6)$$

where T_∞ holds for the fluid temperature at infinity, and In (6) we have:

$$\chi_{gas}(R, T) = \frac{25}{48} \Gamma^{-1} \left(\frac{\pi(a_{gas})^2 \alpha T}{\delta_{gas}} \right)^{0.5} G(g) \quad (7)$$

a_{gas} and δ_{gas} are the gas effective atomic diameter and the gas molecular weight, correspondingly. $G(g)$ is defined as:

$$G(g) = \frac{1}{g} \left(\frac{1}{1 + c_1 g + c_2 g^2 + c_3 g^3} + 1.2g + 0.755g^2(1 + c_1 g + c_2 g^2 + c_3 g^3) \right) \quad (8)$$

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

$$g = \frac{2\pi N_a a_{gas}^3 R_0^3}{3K_B \tau_m R^3} \quad (9)$$

where N_a and K_B are the Avogadro number and the Boltzmann constant.

B. The hydro-chemical Model

In the hydro-chemical model, the bubble dynamic is described by the Rayleigh-Plesset (1) along with the van der Waals equation as the equation of state. The Rayleigh-Plesset equation is coupled with the gas pressure in this model is described by.²¹

$$P_g = \frac{N_{tot} K_B T}{V - N_{tot} B} \quad (10)$$

In this equation N_{tot} , B , T and V are the total number of particles inside the bubble, the hard core parameter, the gas temperature and the bubble volume, respectively. And $N_{tot} = N_{Ar} + N_{liquid}$ is the total number of particles inside the bubble.

The hard core parameter, B is assumed to be equal for all particles inside the bubble.²¹ The value of N_{tot} changes with time because of evaporation and condensation of the host liquid (water or Deuterated acetone) molecules at the bubble interface. The rate of change can be modeled as:

$$\dot{N}_{tot} = 4\pi R^2 D \left(\frac{n_0 - n}{l_d} \right) \quad (11)$$

Where l_d is thickness of diffusive boundary layer obtained from:

$$l_d = \min \left(\frac{R}{\pi}, \sqrt{\frac{RD}{|\dot{R}|}} \right) \quad (12)$$

Where n and n_0 are the instantaneous and equilibrium concentration of the host liquid molecules, respectively.²² And D is the diffusion constant given by:

$$D = D_0 \left[\frac{n_0}{n_{tot}} \right] \quad (13)$$

Where $D_0 = 23.55 \times 10^{-6} m^2/s$, n_{tot} and n_0 are the instantaneous total number density and the equilibrium concentration of the bubble, respectively.²³

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:

$$\dot{Q} = 4\pi R^2 \kappa \frac{T_0 - T}{l_{th}}, \quad l_{th} = \min \left(\frac{R}{\pi}, \sqrt{\frac{R\chi}{\dot{R}}} \right) \quad (14)$$

T and T_0 are the gas temperature and the ambient liquid temperature, respectively. Also, κ is the thermal conductivity coefficient of the gas content, l_{th} is thickness of the thermal boundary layer and χ is the thermal diffusivity coefficient given by:

$$\chi = \kappa/c_p \quad (15)$$

With c_p as heat capacity at constant pressure per unit volume of the gas.¹⁶

In this model, chemical reactions in the bubble, particle diffusion from the bubble wall, evaporation and condensation of molecules, heat conduction, and the bubble stabilities are considered.

C. The quasi-adiabatic model for LI-SCBL+ SBSL (in short is said LI-SCBL model)

The same quasi-adiabatic model is used with some changes in the Rayleigh-Plesset equation (1) appropriate for a situation which the oscillations of a transient cavitation bubble induced by laser in the presence of the sound field. In this state, C and P_g are replaced by C_l and P_l , so that the sound velocity is $C_l = \sqrt{dP_l/d\rho}|_{r=R}$, and the interior gas pressure is given by (2).¹⁹ Also, surface tension σ as a result of variation of the compressibility are shown as follow:²⁴⁻²⁶

$$\sigma = \int_{\rho_0}^{\rho} \frac{C_l}{\rho} d\rho \quad (16)$$

ρ_0 is the ambient density of the liquid and ρ is the liquid density that is affected by the fluid compressibility.

In the presence of a laser, the surrounded liquid acts as a compressible fluid, so the pressure of the liquid, P_l , as a function of density is shown by:

$$\frac{P_l + \beta}{P_0 + \beta} = (\rho/\rho_0)^n \quad (17)$$

where n and β are constants and depend on the type of fluids.²⁷ To induce bubbles, in addition to a sound field with the mentioned frequencies in Table IV, a Nd:YAG laser pulse with FWHM of 8 ns at a wavelength of 1064 nm is used. The pulse energy for nanosecond pulses is between 1.8-3 mJ.²⁰

III. NUMERICAL RESULTS

As it was mentioned, two models of quasi-adiabatic, and hydro-chemical for SBSL and a modified quasi-adiabatic model for LI-SCBL+ SBSL are used to investigate the effects of the acoustic pressures on the interior temperatures, in water at room temperature (20 °C) and Deuterated acetone at 0 °C and -28.5 °C. Due to very high vapor pressure of Deuterated acetone at 20 °C, the ambient temperatures are selected to be 0 °C and -28.5 °C, where the former relates to the reported experimental measurements.⁵ Under these conditions, the physical properties of water and Deuterated acetone are given in Table I, where some of them are measured in this work, including vapor pressure and the speed of sound for Deuterated acetone. The bubble parameters for three simulation codes are also denoted in Table II to IV.

TABLE I. The physical properties of various host liquids.

Host liquid	Surface tension σ (N.m ⁻¹)	Liquid viscosity μ (Pa.s)	Speed of sound C (m.s ⁻¹)	Vapor pressure P_{vap} (psi)
H ₂ O (20 °C)	0.038	1.307×10^{-3}	1660	0.338
C ₃ D ₆ O (0 °C)	0.029	4.42×10^{-3}	1004.32	1.25
C ₃ D ₆ O (-28.5 °C)	0.034	47.3×10^{-3}	865.79	0.293

TABLE II. The bubble parameters for various host liquids in the Quasi-adiabatic model.

Host liquid	Ambient temperature T_0 (°C)	Initial radius R_0 (μm)	Frequency of acoustic field f(kHz)	Amplitude of acoustic field P_a (bar)	Maximum of relative radius R/R_0	Maximum of interior temperature T(K)
H ₂ O	20	6.0	30	1.3	4.6	1.0×10^4
C ₃ D ₆ O	0	6.0	19	1.4	8.6	1.9×10^4
C ₃ D ₆ O	-28.5	2.0	19	1.4	10.8	2.1×10^4

The bubble parameters in various host liquids achieved by the Quasi-adiabatic model are denoted in Table II. Figs. 1(a) and 1(b) show the bubble relative radius and the bubble interior temperature at the collapse time, respectively, as a function of time for water, Deuterated acetone at two temperatures of $T_0 = 0$ °C and -28.5 °C, in achieved by quasi-adiabatic simulation. It is noteworthy that in Figs. 1, 4, and 5, the horizontal axis (t/τ) is normalized to one driving period, where t and τ are time and the period of the driving pressure, respectively.

Table I denotes that at -28.5 °C the Deuterated acetone vapor pressure is fairly below water vapor pressure at 20 °C and it is decreased significantly with decreasing temperature where the pressure should be increased to maintain the bubble stability. Therefore, we suggest this temperature as an optimum temperature for sonofusion by using Deuterated acetone as a host liquid, which will be discussed in detail. Using hydro-chemical simulation, the acoustic pressures and initial radii are derived from the phase diagrams (refer to Fig. 2). Fig. 2(a) demonstrates the stable points of phase space for Deuterated acetone at 0 °C are below $P_a = 16$ atm. Fig. 2(b) denotes the stable points of phase space for Deuterated acetone at -28.5 °C and they should be less than $P_a = 14.5$ atm. Further decreasing of the ambient temperature results in lower pressure in order to have a stable bubble and departs from strong light flashes. Therefore, we can conclude that -28.5 °C can be around the optimum ambient temperature. This can be noticed in Fig. 3 by showing the interior temperature of the bubble in the collapse time for Deuterated acetone as a function of acoustic pressure at $T_0 = -28.5$ °C and $T_0 = 0$ °C. Fig. 3 denotes that the interior temperature of the bubble in Deuterated acetone has the maximum amounts at 0 °C and -28.5 °C for acoustic pressures of $P_a = 15.5$ atm and $P_a = 14.4$ atm, respectively.

The bubble parameters in various host liquids are indicated in Tables III and IV for hydro-chemical and LI-SCBL models, respectively.

The diagrams in Figs. 4(a), 4(b) show the bubble relative radius and the bubble interior temperatures at the collapse time, respectively, as a function of time for water and Deuterated acetone at $T_0 = 0$ °C and -28.5 °C, in hydro-chemical simulation. In this simulation, the maximum bubble

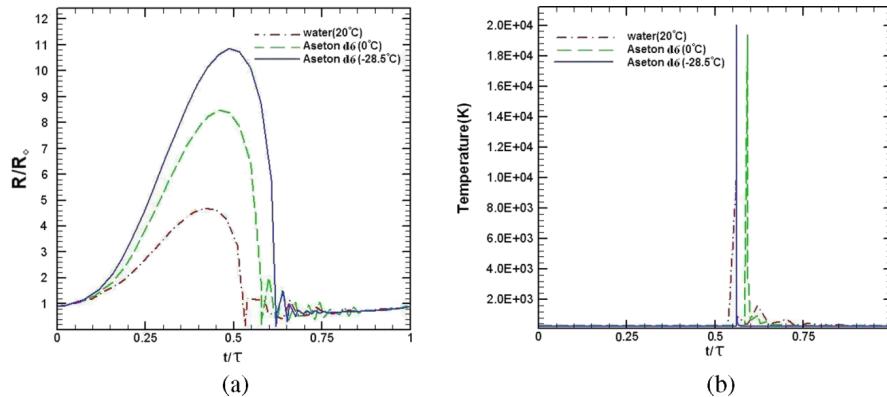
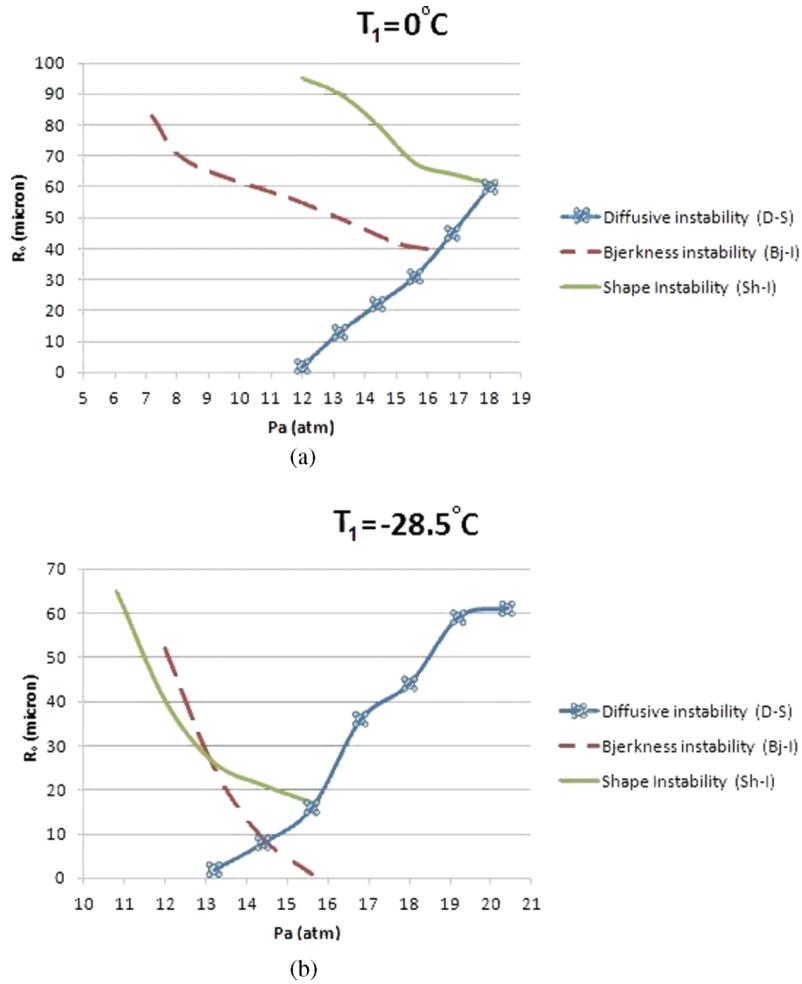


FIG. 1. (a) Comparison of the bubble relative radius, (b) Comparison of the bubble interior temperatures at the collapse time as a function of time for two fluids: water at $T_0 = 20$ °C, Deuterated acetone at $T_0 = 0$ °C and $T_0 = -28.5$ °C, in quasi-adiabatic simulation.

FIG. 2. Phase diagrams of Deuterated acetone at (a) $T_0 = 0^\circ\text{C}$, (b) $T_0 = -28.5^\circ\text{C}$.

interior temperature in the collapse time for Deuterated acetone at $T_0 = -28.5^\circ\text{C}$ is 1.6×10^6 K. This amount has increased more than 15% in LI-SCBL simulation as illustrated in Fig. 5. In this simulation the interior temperature of bubble at the collapse time for Deuterated acetone at $T_0 = -28.5^\circ\text{C}$ is 1.9×10^6 K. This is because the bubble relative radius in LI-SCBL method is more

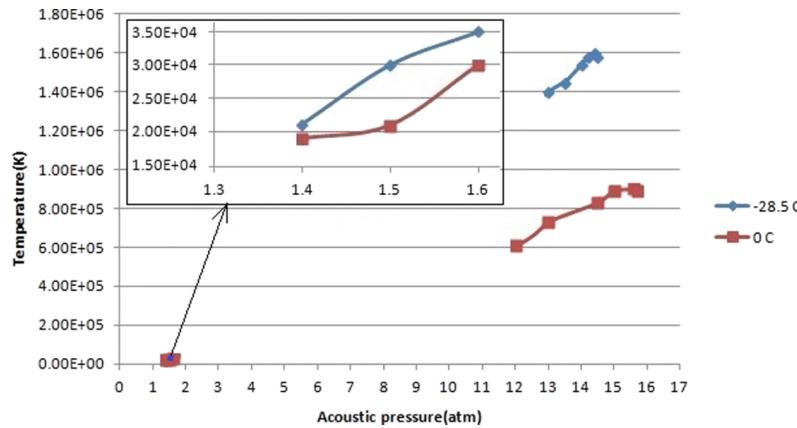
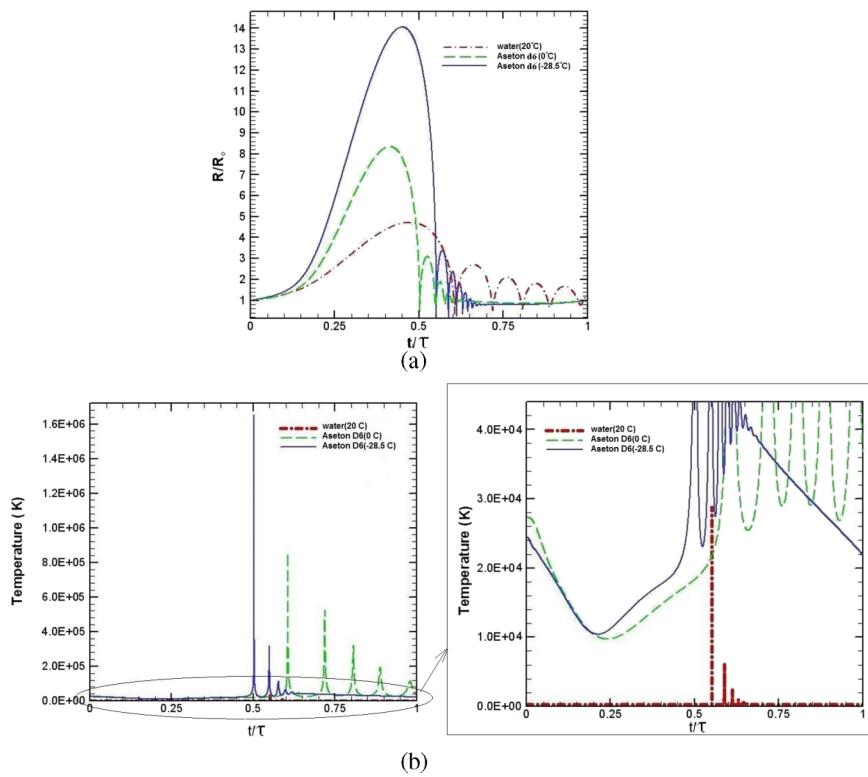
FIG. 3. The maximum bubble interior temperature at the collapse time for Deuterated acetone as a function of acoustic pressure at $T_0 = -28.5^\circ\text{C}$ and $T_0 = 0^\circ\text{C}$.

TABLE III. The bubble parameters for various host liquids in the hydro-chemical model.

Host liquid	Ambient temperature T_0 (°C)	Initial radius R_0 (μm)	Frequency of acoustic field f(kHz)	Amplitude of acoustic field P_a (bar)	Maximum of relative radius R/R_0	Maximum of interior temperature T(K)
H ₂ O	20	6.0	30	1.3	4.8	2.7×10^4
C ₃ D ₆ O	0	41.0	38	15.5	8.2	9.0×10^5
C ₃ D ₆ O	-28.5	8.0	38	14.4	14	1.6×10^6

TABLE IV. The bubble parameters for various host liquids for the LI-SCBL.

Host liquid	Ambient temperature T_0 (°C)	Initial radius R_0 (μm)	Frequency of acoustic field f(kHz)	Amplitude of acoustic field P_a (bar)	Maximum of relative radius R/R_0	Maximum of interior temperature T(K)
H ₂ O	20	1.5	30	1.4	5.4	3.1×10^4
C ₃ D ₆ O	0	6.5	30	1.2	11.2	1.5×10^6
C ₃ D ₆ O	-28.5	4.5	30	1.5	25.6	1.9×10^6

FIG. 4. (a) Comparison of the bubble relative radius, (b) Comparison of the interior temperature of bubble in collapse as a function of time for three fluids: water, Deuterated acetone at $T_0 = 0^\circ\text{C}$ and Deuterated acetone at $T_0 = -28.5^\circ\text{C}$, in hydro-chemical simulation.

compared to hydro-chemical simulation. In the bubble center the temperature exceeds greatly these average temperatures inside the bubble.¹¹

Fig. 6 summarizes the maximum interior temperatures of the bubble in the collapse time in different models for water and Deuterated acetone. The results reveal that the maximum interior temperatures of the bubble for Deuterated acetone in 0°C and -28.5°C is about 100 times larger than the ones for water, in both hydro-chemical and LI-SCBL simulations.

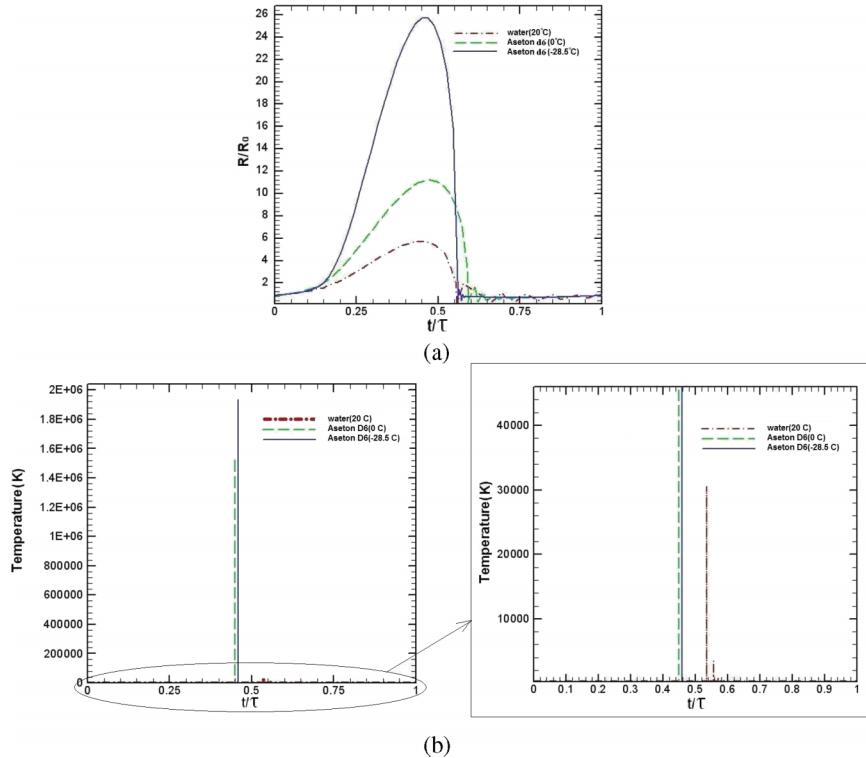


FIG. 5. (a) Comparison of the bubble relative radius, (b) Comparison of the bubble interior temperatures in the collapse situation as a function of time for two fluids at three temperatures: water, Deuterated acetone at $T_0 = 0^\circ\text{C}$ and Deuterated acetone at $T_0 = -28.5^\circ\text{C}$, in LI-SCBL simulation.

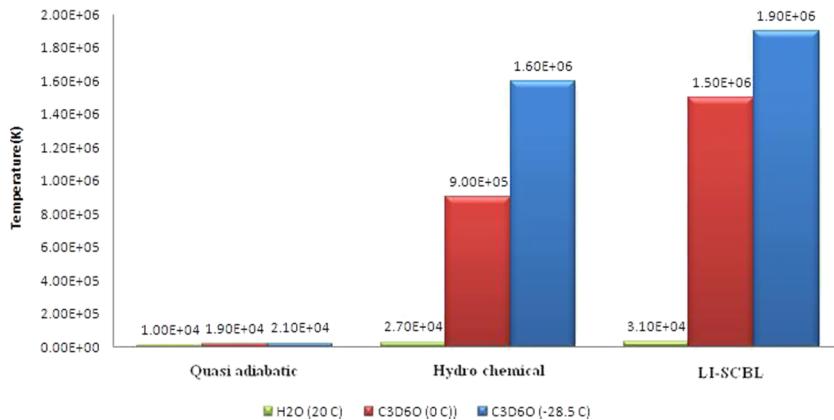


FIG. 6. The maximum interior temperature of the bubble in the collapse time in different models for water and Deuterated acetone.

IV. CONCLUSION

In this study, the interior temperatures of the single bubble sonoluminescence in water and Deuterated acetone liquid were calculated by different simulation models and they were compared. The interior temperatures of the single bubble sonoluminescence in Deuterated acetone liquid at ambient temperature of 0°C were obtained by three models of quasi-adiabatic, hydro-chemical model and LI-SCBL, as 1.9×10^4 , 9.0×10^5 and $1.5 \times 10^6\text{ K}$, respectively, at ambient temperature of 0°C and as 2.1×10^4 , 1.6×10^6 and $1.9 \times 10^6\text{ K}$, at ambient temperature of -28.5°C . By drawing phase diagrams, the bubble stable conditions were investigated separately in 0°C and -28.5°C .

The single bubble sonoluminescence in Deuterated acetone liquid is stabled under acoustic pressure of 16 atm at 0 °C and under acoustic pressure of 14.5 atm at -28.5 °C. The interior temperatures achieved by hydro-chemical model for Deuterated acetone liquid at 0 °C and -28.5 °C are related to the acoustic pressures of 14.4 atm and 15 atm, respectively. In general, the interior temperature in LI-SCBL was higher than hydro-chemical model for Deuterated acetone liquid.

More recently it has been noticed that in the presence of acoustic field, the laser causes the variable speed of sound, surface tension and density; and the host liquid acts as a compressible one and strongly affects the bubble's dynamics equations. This causes more than three times higher bubble interior temperature in their simulation conditions and it can improve these results considerably.¹²

The simulated results of the single bubble sonoluminescence in Deuterated acetone liquid indicate that the interior temperature of the bubble in the collapsing time is about the million degrees Kelvin in hydro-chemical and laser models. Based on the plasma core assumption inside the bubble, the temperature of the plasma core is about 3-6 times more than the temperature of the case of uniform bubble.¹¹ This was suggested earlier by Suslick et al. by observation of the Ar atomic lines due to production of optically opaque plasma at the center of the bubble during cavitation.²⁸⁻³⁰ This can increase the temperature to the orders close to the values of 10⁷ K or one can claim the temperature can be 10⁶ K < T < 10⁷ K. Therefore, in the mentioned proper conditions of confinement, the phenomenon of "bubble fusion" could be practical.

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