J. At. Mol. Sci.
doi: 10.4208/jams.041813.070613a

Vol. **5**, No. 1, pp. 1-8
February 2014

The effect of shock wave and bubble coalescence in spherical cloud of cavitation bubbles on maximum temperature inside central bubbles

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Received 18 April 2013; Accepted (in revised version) 6 July 2013
Published Online 18 November 2013

Abstract. We present a theoretical analysis of the influence of shock wave propagating in bubble cluster and bubble combining in expansion phase on maximum temperature inside central bubbles. By using adiabatic model and assumptions for simplifying the problem we find that these parameters have significant effects on temperature rising in compression phase. In particular, the shock wave, in comparison to bubble combining, has a greater impact on the maximum temperature.

PACS: 47.35.Rs, 47.11.-j, 47.10.-g

Key words: shock wave, adiabatic model, compression phase, bubble combining

1 Introduction

Single-bubble sonoluminescence (SBSL) was discovered in 1989 by Felipe Gaitan [1]. It is a light emission phenomenon from a single bubble in liquid irradiated by an ultrasonic wave. Although the driving pressure is usually a simple harmonic wave, the evolution of the radius of the bubble is complicated (slowing growth and rapid collapse). The bubble expands up to nearly ten times of its initial radius, then collapses extremely quickly and results in adiabatic heating of the gas inside the bubble. The collapse is followed by afterbounces with roughly the eigenfrequency of the bubble. Indeed after the expansion phase of the bubble in the first half cycle, severe collapse takes place in the second half-cycle and at the end of collapse light pulse is emitted. The pulse width of the light has been experimentally measured to be less than 50 ps [2,3]. It was shown that the light pulse is emitted periodically with the frequency of the ultrasonic wave [3]. The spectrum

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is broadband and can be fitted by a black-body formula with the effective temperatures ranging from 6000 to 25000 K [4-7].

Many different theories have been developed to explain sonoluminescence, but most researchers now agree that the observed light pulses are due to shock wave and compressive heating of the gas/vapor plasma to incandescent temperatures. Sonoluminescence has been studied a lot in the literature and has been attracted a great deal of attention for both multiple bubble sonoluminescence (MBSL) and single bubble sonoluminescence (SBSL). For a good review see [8,9]. Particle density, temperature and pressure during the implosion of cavitation bubbles depend on the experimental conditions. It seems that by choosing a suitable liquid and optimization of the effective parameters such as initial radius, acoustic pressure amplitude, initial temperature of the liquid and acoustic wave frequency the temperature and pressure can be greatly enhanced.

In 2002 Taleyarkhan optimized the experimental conditions and claimed that, in his experiment, the temperature and pressure in bubble center was so high that fusion has occurred. In fact, the goal of Taleyarkhan experiments was to create a suitable condition to have thermonuclear fusion during the compression of cavitation bubbles, and this means that the maximum temperature of Taleyarkhan experiment raises 100 times in comparison to typical sonoluminescence experiments [10].

In order to get this result a fundamental change in experimental technique was made, which allowed one to increase the kinetic energy of the liquid, accelerated toward the bubble's center, several times. Thus the effect of shock wave compression was enhanced drastically. They increased the amplitude of standing acoustic wave up to 10 times. It is worth to mention that in most of liquids cavitation can be occurred, when they are under the high tension as above. The test liquid used in experiments was a well-degassed organic liquid. Because of the high molecular weight $(M=64)$ and lower adiabatic constant $(\gamma=1.125)$ the speed of sound in acetone ($C_G=\sqrt{(R\gamma/M)T}$, R is the universal gas constant) is less than other common liquids that could be utilized. This leads to the formation of stronger shock waves. In recent years, the result of this experiment have been confirmed or challenged by many researchers [11-17].

In this work, the effects of various parameters including shock wave in cluster and coalescence of bubbles in expansion phase on maximum temperature inside the bubble are numerically investigated. This was done by using adiabatic model and applying some assumptions for simplifying the problem. It is important to note that the effects of these parameters are investigated theoretically and for full analysis of the problem and also comparing the results with experimental data we need to consider the other effects such as mass and heat diffusion, shock wave propagation inside the bubble in compression phase and chemical reactions among the particles inside the bubble.

2 Model

We use adiabatic model to study the influences of effective parameters in temperature and pressure rising inside the central bubble in bubble cluster. In this model bubble oscillation cycle is divided into two parts: First, the expansion phase, in which the wall velocity is low in comparison to the speed of sound in gas/vapor inside bubble, and we can use isothermal approximation. Second, the compression phase, in which the wall velocity is high and we can use adiabatic approximation. Also, during the full cycle the pressure and temperature inside the bubble are assumed uniform.

The dynamics of the bubble wall is described by the Rayleigh-Plesset (RP) equation:

$$\left(1-\frac{\dot{R}}{C}\right)R\ddot{R}+\frac{3}{2}\dot{R}^2\left(1-\frac{\dot{R}}{3C}\right)=\left(1+\frac{\dot{R}}{C}\right)\frac{1}{\rho}(P_g-P_{ac}-P_0)+\frac{P\dot{P}_g}{\rho C}-\frac{4v\dot{R}}{R}-\frac{2\sigma}{\rho R} \tag{1}$$

where P_g is the uniform gas pressure inside the bubble, $P_{ac}=iP_a\sin$ is the acoustic forcing pressure with angular frequency ω, P_0 is the ambient pressure valid during the measurements and the remaining parameters are material constants of the host liquid, e.g. C is the speed of sound, ρ is its density, and v is the kinematic viscosity. The gas pressure P_g can be related to R (t) through the equation of the state.

We use the modified polytropic van der Waals equation of state, which includes the effects of surface tension σ

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

Here h is the hard core van der Waals radius of the gas, R_0 is the initial radius of bubble and γ is the ratio of specific heats and should be considered as function of radius and velocity of the bubble [18]

$$\gamma(R,t)=1+(\gamma-1)\exp(-\frac{A}{(P_e)^B}) \tag{3}$$

A and B are the constant parameters and P_e is peclet number and describes the radial motion of the bubble:

$$P_e(t)=\frac{R(t)|\dot{R}(t)|}{\chi(R,t)} \tag{4}$$

where $\chi(R,t)$ is the thermal conductivity of the gas inside the bubble and is related to effective atomic mass and molecular weight of particles inside the bubble [19, 20].

In most of the acoustic period, except the final phases of the collapse and after-bounces, the gas can be considered isothermic, thus one has $\gamma=1$.

The evolution of temperature inside the bubble is given as follows [21]

$$\dot{T}=-[\gamma(R,\dot{R},T)-1]\frac{3R^2\dot{R}}{R^3-h^3}T \tag{5}$$

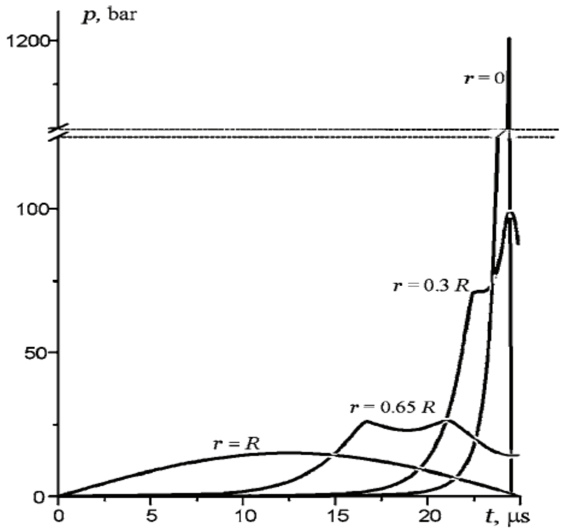

Figure 1: The evolution of liquid pressure intensification within an imploding bubble cluster at different radii, r, for a cluster with 1000 bubbles subjected to a 15 bar compression pressure on the boundary of the bubble cluster $(r=R)$[22].

3 Results and discussion

In the experiments of Taleyarkhan, spherical cluster of 1000 bubbles were exposed to an acoustic field. The measured pressure amplitude of the acoustic field on the periphery of the bubble cluster was same as the amplitude of the applied acoustic field. This was not the same as the pressure on the bubbles near the center of the cluster. The bubbles in the central region of the cluster may be subjected to a much higher compression pressure than the peripheral bubbles because of multibubble dynamics. These dynamics induces an amplification of the compression wave. For a spherical bubble cluster the focusing and intensification of compression waves was investigated numerically in [22-24]. Fig. 1 shows the evolution of liquid pressure intensification within an imploding bubble cluster at different distances from cluster center. As it can be seen the bubbles in the central region of the cluster may be subjected to a much higher compression pressure than the peripheral bubbles also it may be subjected to a lower pressure in expansion phase than the peripheral bubbles. So we expect that the compression in central bubbles be more powerful than the ones in far distances.

3.1 The effect of shock wave on wall velocity and maximum temperature inside bubble

We consider single bubble near the center of cluster exposed to a sinusoidal acoustic wave with the assumption that the evolution of acoustic wave is sinusoidal and the amplitude

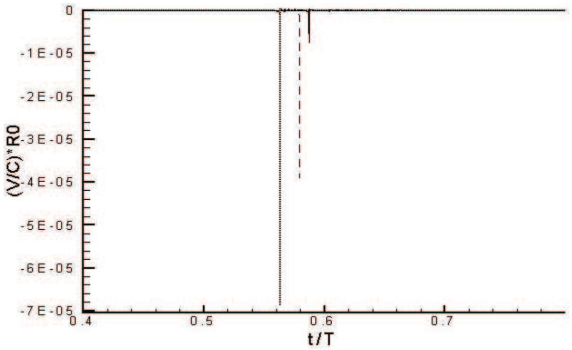

Figure 2: Variation of the bubble wall velocity versus time in different p_c. Solid: $p_c = 5$ atm, dashed: $p_c = 12$ atm and dotted: $p_c = 28$ atm.

of acoustic wave in compression phase, according to figure1, is higher than the expansion phase. So we can assume a bubble under the influence of acoustic wave with variable amplitude in two phases

$$P_{ac} = p(t)\sin(\omega t) \quad p(t) = p_e, p_c \tag{6}$$

where p_e and p_c are the amplitude of acoustic, wave in expansion and compression phase respectively. We can study the effect of pressure increasing in the compression phase (Due to the shock wave propagation in cluster) by replacing p_e with p_c in second phase. All of the calculations have been performed for a driving frequency of 19 kHz, pressure amplitude of $p_e = 1.4$ atm and the initial bubble radius of $R_0 = 3\mu$m .The physical and chemical properties of the deuterated acetone at 20°C are given in Table 1.

Table 1: Physical properties of deuterated acetone at 20°C.

C(ms^{-1})	ρ(kgm^{-2})	υ($\mathrm{m}^2\mathrm{s}^{-1}$)	σ(Nm^{-1})
1189	921	4.59	0.029

In Fig. 2 the effect of amplitude increase of acoustic pressure in compression phase on wall velocity has been shown. We see that the increase in the pressure amplitude in compression phase leads to increase in bubble wall velocity and peaks shift to the right. In the second stage, bubble sees more positive pressure and ultimately the velocity of wall reaches to its maximum value. Temperature inside the bubble is directly proportional to wall velocity, which is due to the increase in the strength of the bubble collapse, so peak temperature of the bubble has been increased (Fig. 3).

3.2 The effect of coalescence of bubbles in expansion phase on maximum temperature

During the expansion phase, bubbles are combined together and bigger bubbles are created. The bubble coalescence process within the expanding bubble clusters is mainly con-

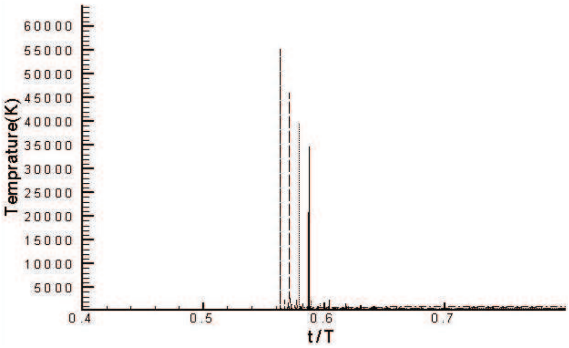

Figure 3: Temperature inside the bubble versus time in different p_c. Solid: $p_c = p_e$, dashed: $p_c = 12$ atm, dotted: $p_c = 5$ atm and long dashed: $p_c = 28$ atm

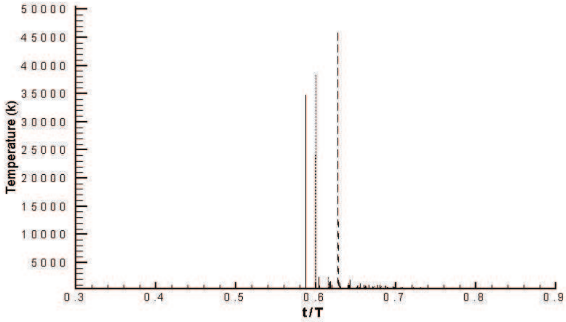

Figure 4: Variation of the temperature inside the bubble versus time in compression phase. Solid: $R_0 = R_{\max}$, dashed: $R_0 = 4R_{\max}$ and dashed: $R_0 = 11R_{\max}$.

trolled by liquid film drainage dynamics between adjacent bubbles. The film drainage is driven by surface tension forces and is limited by liquid inertia. Calculations show that the time, which is needed for bubbles to coalesce, is about 2-3 μs. So bubbles within an expanding bubble cluster have sufficient time to coalesce. The effect of maximum bubble size, R_{max}, on the intensification of gas compression was confirmed experimentally in [25].

In this stage we increase the Rmax, depending on the number of combined bubbles, and run the adiabatic code in compression phase. Fig. 4 shows the effect of coalescence of bubbles in expansion period on temperature evolution in compression phase. Combining bubbles in expansion phase causes the bubble to be accelerated and get higher speed in a longer path and as a result intense compression takes place.

Finally we have considered the effects of these two factors and performed the code in compression stage. As it is obvious from the Fig. 5 the maximum temperature increases intensively.

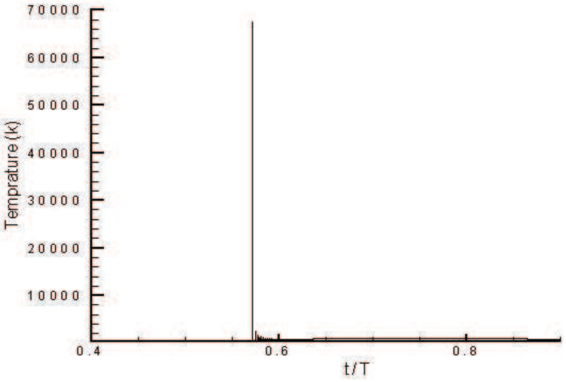

Figure 5: Variation of the bubble radius versus time with considering both the shock wave and bubble combining in expansion stage. $(P_c = 28$ atm, $R_0 = 11R_{\max})$.

4 Conclusion

A model of single-bubble sonoluminescence was constructed. In this model, the temperature and pressure was assumed to be spatially uniform inside the bubble. It was shown that the shock wave, propagating inside cluster and coalescence of bubbles during expansion phase, increases both the wall velocity and maximum temperature inside the bubble. Coalescence of bubbles during expansion phase causes the wall of bubble to be accelerated and get higher speed in a longer path and as the result intense compression takes place. Shock wave increases the amplitude of acoustic wave in compression phase and causes significant increase of temperature inside the bubble.

References

[1] D. F. Gaitan, Ph. D. Thesis (University of Mississippi, 1990).
[2] B. P. Barber and S. J. Putterman, Nature 352 (1991) 318.
[3] B. P. Barber, R. Hiller, K. Arisaka, H. Fetterman, and S. Putterman, J. Acoust. Soc. Am. 91 (1992) 3061.
[4] R. Hiller, S. J. Putterman, and B. P. Barber, Phys. Rev. Lett. 69 (1992) 1182.
[5] R. Hiller and S. J. Putterman, Phys. Rev. Lett. 75 (1995) 3549.
[6] R. Hiller, Ph. D. Thesis (University of California, 1995).
[7] D. F. Gaitan, A. A. Atchley, S. D. Lewia, J. T. Carlson, X. K. Maruyama, M. Moran, and D. Sweider, Phys. Rev. E 54 (1996) 525.
[8] L. A. Crum, J. Acoust. Soc. Am. 95 (1994) 559.
[9] S. J. Putterman and K. R. Weninger, Annu. Rev. Fluid Mech. 32 (2000) 445.
[10] R. P. Taleyarkhan, C. D. West, J. S. Cho, R. T. Lahey, R. I. Nigmatulin, and R. C. Block, Science 295 (2002) 1868.
[11] R. T Lahey, R. P Taleyarkhan, R. I Nigmatulin, and I. S. Akhatov, Advances in Heat Transfer 39 (2006) 4.
[12] R. Geisler, W. D. Schmidt, T. Kurz, and W. Lauterborn, Europhys. Lett. 66 (2004) 435.

[13] R. I. Nigmatulin and R. K. Bolotnova, Doklady Akademii Nauk. 52 (2007) 8.
[14] R. Nigmatulin, Nucl. Eng. Des. 235 (2005) 10.
[15] C. G. Camara, S. D. Hopkins, K. S. Suslick, and S. J. Putterman, Phys. Rev. Lett. 98 (2007) 6.
[16] R. T. Lahey, R. P. Taleyarkhan, and R. I. Nigmatulin, Nucl. Eng. Des. 237 (2007) 15.
[17] R. P. Taleyarkhan, J. Lapinskasa, Y. Xua, J. S. Chob, R. C. Blockc, R. T. Lahey, and R. I. Nigmatulin, Nucl. Eng. Des. 238 (2008) 27.
[18] R. Toegel and D. Lohse, J. Chem. Phys. 118 (2003) 4.
[19] A. Prosperetti, J. Acoust. Soc. Am. 61 (1997) 1.
[20] J. O. Hirschfelder, C. F. Curtiss, and R. B. Bird, Molecular Theory of Gases and Liquids (Wiley, New York, 1954).
[21] S. Hilgenfeldt, S. Grossmann, and D. Lohse, Phys. Fluids 11 (1999) 6.
[22] R. I. Nigmatulin, Dynamics of Multiphase Media (Hemisphere, New York, 1991).
[23] Y. Matsumoto, Bubble and bubble cloud dynamics. In: Nonlinear Acoustics at the Turn of the Millennium, Proceedings of the 15th International Symposium on Nonlinear Acoustics, Gottingen, Germany, 1-4 September 1999, edited by W. Lauterborn and T. Kurz (AIP, Melville, NY, 2000).
[24] M. Shimada, Y. Matsumoto, and T. Kobayashi, JSME Int. J., Ser. B 43 (2002) 3.
[25] G. Delgadino, F. Bonetto, and R. T. Lahey, Jr., Chem. Eng. Commun. 189 (2002) 786.