# MODELLING OF VAPOUR-GAS BUBBLE OSCILLATION USING LINEAR WAVE EQUATION

**Dr. Abbas Z. Al-Asady**

Mechanical Engineering Department, Engineering College, Basrah University, Iraq

## Abstract

By using linear wave equation a new model of bubble dynamics in acoustic field is constructed including effects of thermal conduction both inside and outside a bubble, and non-equilibrium evaporation and condensation of water vapour at bubble wall. The liquid temperature at bubble wall is numerically calculated by solving the heat conduction equation (without assuming a profile of liquid temperature). It is including effect of the latent heat of non-equilibrium evaporation and condensation at bubble wall. It is concluded that the liquid temperature increases to the same order of magnitude with that of the maximum temperature attained in the bubble at strong collapses. It is caused by the latent heat of intense vapour condensation and by the thermal conduction from the heated interior of the bubble to the surrounding liquid. The intense vapour condensation takes place at strong collapses because the pressure inside the bubble increases. The comparison is given between the calculated result and the experimental data of radius-time curve for one acoustic cycle. The calculated result fits well with the experimental data.

## نمذجة ذبذبات فقاعة بخارية-غازية باستخدام المعادلة الموجية الخطية

*د. عباس زكي الأسدي*

قسم الهندسة الميكانيكية – كلية الهندسة – جامعة البصرة – العراق

الخلاصة

باستخدام المعادلة الموجية الخطية، تم بناء نموذج جديد لحركة الفقاعة في وسط صوتي متضمناً تأثيرات التوصيل الحراري داخل وخارج الفقاعة والتبخير والتكثيف غير المنتظم لبخار الماء على سطح الفقاعة. احتسبت درجة حرارة السائل عند سطح الفقاعة عددياً بواسطة حل معادلة التوصيل الحراري (بدون فرض توزيع لدرجة حرارة السائل). تتضمن تأثير الحرارة الكامنة للتبخير والتكثيف غير المنتظم عند سطح الفقاعة. استنتج أن درجة حرارة السائل تزداد لنفس الدرجة من المقدار لدرجة الحرارة العظمى في الفقاعة. يحدث هذا بسبب الحرارة الكامنة للتكثيف الشديد لبخار الماء عند الانهيارات الشديدة بسبب زيادة الضغط داخل الفقاعة. أجريت مقارنة بين النتيجة محسوبة وبيانات تجريبية لمنحني القطر – الزمن لدورة صوتية واحدة. لوحظ تطابق تام للنتيجة المحسوبة مع البيانات التجريبية.

## 1. Introduction

A number of complex and often quite striking phenomena take place in a liquid subject to a sufficiently intense sound field. In view of their intimate connection with the presence of bubbles, or cavities, in the liquid, they are collectively known as Acoustic Cavitation. The mixture of permanent gases and liquid vapour contained in the bubbles gives rise to a restoring force when they expend and contract under the action of the sound field. Under strong excitation during the expansion half-cycle the effect of the restoring force becomes negligible compared to the acoustic pressure and the inertia of the liquid the bubble can grow by orders of magnitude and then implode. This process is characterized by an impressive violence with internal temperatures reaching thousands of degrees and internal pressures thousands of atmospheres. This behavior is known as stable cavitation [1].

In many theories of bubble dynamics in acoustic field [2-4], it is assumed that the partial pressure of vapour inside a bubble is always identical to the saturated vapour pressure of the surrounding liquid. In addition, in many theories [2-4], the liquid temperature at bubble wall is assumed to be always identical to the ambient liquid temperature. In order to investigate the validity of these assumptions, the kinetic equation of evaporation and condensation at the bubble wall is numerically solved and the liquid temperature at the bubble wall is calculated as a function of time. It is assumed that the temperature profile in the liquid near bubble wall is parabolic [4]. While the profile of liquid temperature assumed to be exponential [6,8]. However, for more accuracy, the heat conduction equation (energy equation) should be solved numerically without assuming a profile of liquid temperature.

In this paper, a new model of bubble dynamics in acoustic field is constructed including effect of variable of liquid temperature at bubble wall (energy equation is solved numerically), of non-equilibrium evaporation and condensation of water vapour at bubble wall, and that of thermal conduction inside a bubble.

It should be noted that the liquid temperature near bubble wall has already been calculated in some theoretical studies of bubble dynamics in acoustic field [9, 10]. However, in these studies, the latent heat of intense vapour condensation is completely neglected. Some researches [11,12] have already constructed models of bubble dynamics including effect of the latent heat of evaporation and condensation. However, the new model constructed in this paper differs from these models [11,12] in many points. It is assumed that the vapour pressure inside a bubble ($P_v$) is at the equilibrium vapour pressure ($P^*_v$) at the temperature of the bubble wall, while in the present study non-equilibrium effect of evaporation and condensation is taken into account by the kinetic theory [11].

## 2. Model

The physical situation is a single spherical bubble in water irradiated by an ultrasonic wave. The contents of the bubble are non-condensable gas (air) and water vapour. In the present study, pressure ($P_g$) inside a bubble is assumed to be spatially uniform. The temperature inside the bubble ($T_g$) is assumed to be spatially uniform except for a thin boundary layer near the bubble wall even at the collapse of the bubble. The thickness of the boundary layer is assumed to be ($\delta = n\lambda$) where n is a constant and λ is the mean free path of a gas molecule [13,14]. It is assumed that the temperature in the boundary layer changes linearly with radius (r): from $T_g$ at $r = R-\delta$ to $T_B$ at $r=R$, (the origin of the radius (r) is the bubble center) [6].

Figure (1) Schematic diagrams depicting the temperature profile both inside and outside the bubble.

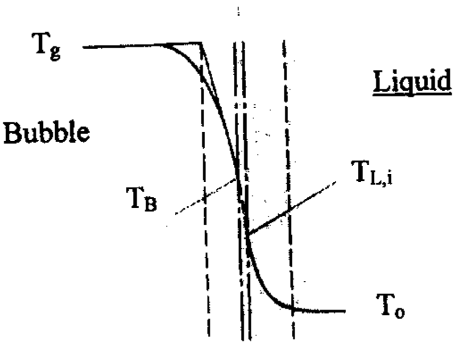


**Fig. (1) The model**

Thus

$$\left.\frac{\partial T_g}{\partial r}\right|_R = \frac{T_B - T_g}{\delta} \qquad \ldots(1)$$

As a well-known result of the kinetic theory of gases, temperature jump ($\Delta T$) exists at the bubble wall [15]

$$T_B = T_{L,i} + \Delta T \qquad \ldots(2)$$

where $T_{L,i}$ is the liquid temperature at the bubble wall. Temperature jump ($\Delta T$) is given by [6]:

$$\Delta T = -\frac{1}{2Kn'}\sqrt{\frac{\pi m}{2kT_B}}\,\frac{2-a'\alpha_e}{\alpha_e}\,k_g \left.\frac{\partial T_g}{\partial r}\right|_R \qquad \ldots(3)$$

where K is the Boltzman constant and $a'$ is a constant ($a' = 0.827$).

In the model, the number of water molecules in the bubble ($n_{H2O}$) changes with time due to evaporation or condensation at the bubble wall:

$$n_{H2O}(t+\Delta t) = n_{H2O}(t) + 4\pi R^2 \Delta t \dot{m} \quad \text{...(4)}$$

The rate of evaporation per unit area and unit time ($\dot{m}$) is calculated by the following kinetic equations [13]

$$\dot{m} = \dot{m}_{eva} - \dot{m}_{con} \quad \text{... (5)}$$

$$\dot{m}_{eva} = \frac{10^3 N_A}{M_{H2O}} \frac{\alpha_M}{(2\pi R_v)^{\frac{1}{2}}} \frac{P_v^*}{T_{L,i}^{\frac{1}{2}}} \quad \text{... (6)}$$

$$\dot{m}_{con} = \frac{10^3 N_A}{M_{H2O}} \frac{\alpha_M}{(2\pi R_v)^{\frac{1}{2}}} \frac{\Gamma P_v}{T_B^{\frac{1}{2}}} \quad \text{... (7)}$$

Eq. (5) means that the net rate of evaporation ($\dot{m}$) is the difference between the actual rate of evaporation and that of condensation. $P_v$ is the actual vapour pressure:

$$P_v = \frac{n_{H2O}}{n_t} P_g \quad \text{...(8)}$$

The correction factor ($\Gamma$) in eq. (7) is expressed as [12]

$$\Gamma = \exp(-\Omega^2) - \Omega\sqrt{\pi}\left(1 - \frac{2}{\sqrt{\pi}} \int_0^{\Omega} \exp(-x^2)\, dx\right) \quad \text{... (9)}$$

in which

$$\Omega = \frac{\dot{m}}{P_v}\left(\frac{R_v T_g}{2}\right)^{\frac{1}{2}} \quad \text{... (10)}$$

The derivation of an equation of bubble radius starts from the following two equations [16]:

$$\frac{\partial^2 \phi}{\partial r^2} + \frac{2}{r}\frac{\partial \phi}{\partial r} - \frac{1}{c^2}\frac{\partial^2 \phi}{\partial r^2} = 0 \quad \text{... (11)}$$

$$\frac{\partial \phi}{\partial t} + \frac{1}{2}\left(\frac{2\phi}{\partial r}\right)^2 + \frac{P_L - P_\infty}{\rho_{L,\infty}} = 0 \quad \text{... (12)}$$

with the boundary condition [12]

$$\rho_{L,i}\left[\left(\frac{\partial \phi}{\partial r}\right)_R - \dot{R}\right] = -\dot{m} \quad \text{... (13)}$$

where eq. (11) is called Linear Wave Equation, $\Phi$ is the velocity potential of the liquid, and u is the velocity of the liquid. The general solution of linear wave equation (eq. (11)) under the spherical symmetry is given by [17].

$$\phi = -\frac{1}{r} f(t - \frac{r}{c}) - \frac{1}{r} g(t + \frac{r}{c}) \quad \text{... (14)}$$

Yasui [6] used eqs. (11), (12), (13) and (14) to derive the following equation (eq. (15)) of bubble radius, in which compressibility of liquid, effect of evaporation and condensation of water vapour at the bubble wall, and effect of variation of liquid temperature near the bubble wall are taken into account.

$$R\ddot{R}\left[1-\frac{\dot{R}}{c}+\frac{\dot{m}}{c\,\rho_{L,i}}\right]+\frac{3}{2}\dot{R}^2\left[1-\frac{\dot{R}}{3c}+\frac{2\dot{m}}{3c\rho_{L,i}}\right]=$$

$$\frac{\left(1+\frac{\dot{R}}{c}\right)}{\rho_{L,\infty}}\left[P_B-P_s(t+\frac{R}{c})-P_\infty\right]+$$

$$\frac{\ddot{m}R}{\rho_{L,i}}\left[1-\frac{\dot{R}}{c}+\frac{\dot{m}}{c\rho_{L,i}}\right]+\frac{\dot{m}}{\rho_{L,i}} \qquad ...(15)$$

$$\left[\dot{R}+\frac{\dot{m}}{2\rho_{L,i}}+\frac{\dot{m}\dot{R}}{2c\rho_{L,i}}-\frac{R}{\rho_{L,i}}\frac{d\rho_{L,i}}{dt}-\frac{\dot{m}R}{c\,\rho_{L,i}^2}\frac{d\rho_{L,i}}{dt}\right]$$

$$+\frac{\dot{m}}{\rho_{L,i}}\left[\frac{R\dot{R}}{c\rho_{L,i}}\frac{d\rho_{L,i}}{dt}\right]+\frac{R}{c\rho_{L,\infty}}\frac{dP_B}{dt}$$

where the dot denotes the time derivative ($\frac{d}{dt}$), $P_B$ is the liquid pressure on the external side of the bubble wall and $P_s(t)$ is a no constant ambient pressure component such as a sound field. $P_B$ is related to the pressure inside the bubble by [18]

$$P_B(t)=P_g-\frac{2\sigma}{R}-\frac{4\mu}{R}\left(\dot{R}-\frac{\dot{m}}{\rho_{L,i}}\right)-\dot{m}^2\left(\frac{1}{\rho_{L,i}}-\frac{1}{\rho_g}\right) \qquad ...(16)$$

when a bubble is irradiated by an acoustic wave the wavelength of which is much larger than the bubble radius.

$$P_s(t)=-P_m\sin\omega t \qquad ...(17)$$

In order to calculate $P_g$ (t), the van der Waals equation of state is employed [19].

$$\left[P_g(t)+\frac{a}{\upsilon^2}\right](\upsilon-b)=R_g\,T_g \qquad ...(18)$$

In this model, the van der Waals constants (a and b) change with time due to the change of $n_{H2O}$. Equations of the van der Waals constants are described [13] as a function of $n_{H2O}$ and $n_{air}$.

The temperature inside the bubble ($T_g$) is calculated by solving eq. (19).

$$E=\frac{n_{air}}{N_A}\int_0^{Tg}C_{V,air}(T')\,dT'+\frac{n_{H2O}}{N_A}\int_0^{Tg}C_{V,H2O}(T')\,dT'-\left(\frac{n_t}{N_A}\right)^2\frac{a}{V} \qquad ...(19)$$

where ($n_t = n_{air} + n_{H2O}$), and $C_{V,air}$(T) and $C_{V,H2O}$ (T) are the molar heat of air and vapour at constant volume at temperature T, respectively. Explicit form of the functions $C_{V,air}$(T) and $C_{V,H2O}$ (T) are given [13].

The change of the internal energy of a bubble is expressed by eq. (20) [13].

$$\Delta E(t)=-P_g(t)\,\Delta V(t)+4\pi R^2\,\Delta t(\dot{m}_{eva}\,e_{eva}-\dot{m}_{con}\,e_{con})+4\pi R^2\,\Delta t\,k_g\left.\frac{\partial T_g}{\partial r}\right|_R \qquad ...(20)$$

where

$$e_{eva} = \frac{1}{N_A} \int_0^{T_{L,i}} C_{V,H2O}(T')\, dT' \qquad \text{... (21)}$$

and

$$e_{con} = \frac{1}{N_A} \int_0^{T_B} C_{V,H2O}(T')\, dT' \qquad \text{... (22)}$$

The description of solution of the heat conduction (energy equation) of the liquid near the bubble are:

Continuity of energy flux at the bubble wall is given by:

$$k_L \left.\frac{\partial T_L}{\partial r}\right|_R = k_g \left.\frac{\partial T_L}{\partial r}\right|_R + \dot{m}L + (\dot{m}_{eva} e_{eva} - \dot{m}_{con}\, e_{con}) \qquad \text{... (23)}$$

The boundary conditions are:

$$T_L (r \to \infty) = T_\infty \qquad \text{... (24-a)}$$

$$T_{L,i} = T_L|_{r=R} \qquad \text{...(24-b)}$$

$$\left.\frac{\partial T_L}{\partial r}\right|_{r \to \infty} = 0 \qquad \text{... (25)}$$

The temperature distribution in liquid water can be calculated by solving the energy equation [20].

$$\rho_{L,i}\, Cp_L \left[\frac{\partial T_L}{\partial t} + \frac{R^2 \dot{R}}{r^2} \frac{\partial T_L}{\partial r}\right] = \frac{1}{r^2}\frac{\partial}{\partial r}\left[k_L\, r^2 \frac{\partial T_L}{\partial r}\right] \qquad \text{...(26)}$$

in the domain $R \leq r \leq \infty$

Variation of the liquid temperature at bubble wall is calculated by solving eq. (26). Physical quantities of liquid depend on liquid temperature ($T_L$) and the liquid pressure ($P_L$). Equations of the quantities employed in the calculations are described [13].

Therefore, eq. (15) is solved numerically [21] coupling with the energy equation of liquid water (eq. (26)), which is solved using finite difference method [22].

## 3. Results and Discussion

Physical quantities employed in the calculations are listed in Table 1. The ambient liquid temperature ($T_o$) and the ambient pressure ($P_o$) are chosen to be 20 °C and 1 bar, respectively. The accommodation coefficient for evaporation or condensation ($\alpha_m$) is assumed to be $\alpha_m$ =0.04 [12]. The thermal accommodation coefficient ($\alpha_e$) is assumed to be $\alpha_e$ = 1 [12]. At the condition, the speed of sound in liquid water (c) and the liquid density ($\rho_\infty$) are 1483 (m/s) and 9.982 x $10^2$ (kg/m$^3$), respectively. The specific heat of liquid water at constant pressure ($Cp_L$) is $Cp_L$=4.2 (kJ/kg.K). n=3 is assumed, which determines the thickness of the thermal boundary layer inside a bubble ($n\lambda$).

Calculations start from the time t=0 (μs) with the initial conditions that:

$$R = R_o, \dot{R} = 0, T_g = T_B = T_{L,i} = T_o$$

$$P_B = P_o, \frac{dP_B}{dt} = 0$$

and

$$\dot{m} = \ddot{m} = 0, \frac{d\rho_g}{dt} = 0, P_s(0) = 0$$

The initial number of water vapour molecules ($n_{H2O,\ o}$) and that of air molecules ($n_{air,\ o}$) in a bubble are listed in Table 1.

**Table 1. Quantities of Study**

| | |
|---|---|
| f (kHz) | 26.5 |
| $P_m$ (bar) | 1 |
| $R_o$ (μm) | 10.5 |
| $n_{air,o}$ | 1.351945 x $10^{11}$ |
| $n_{H2O,o}$ | 2.8012 x $10^9$ |

Results of the calculation under the above conditions are shown in Figs. 1~10 for three acoustic cycles. The time axes (the horizontal axes) in the figures are the same. All the physical quantities of a bubble except $n_{air}$ change with time periodically with the frequency of the acoustic field applied on the bubble. The pressure, number of molecules and density axis (the vertical axis) are logarithmic.

In Fig. 1, the bubble radius (R) is shown as a function of time. In Fig. 2, the bubble wall velocity ($\dot{R}$) is shown as a function of time with linear vertical axis. In Fig. 3, the temperature inside the bubble ($T_g$) is shown as a function of time. At the slow expansion phase in a bubble oscillation, the temperature inside the bubble ($T_g$) is almost identical to the liquid temperature ($T_o$). At collapse of a bubble, the temperature ($T_g$) increases suddenly, followed by small oscillations due to the small bounces of bubble radius.

In Fig. 4, the liquid-temperature at the bubble wall ($T_{L,i}$) is shown as a function of time. It is concluded from Fig. 3 that $T_{L,i}$ is almost identical to $T_o$ during bubble oscillations except at strong collapses. At strong collapses, $T_{L,i}$ increases dramatically. It is caused by the thermal conduction from the heated interior of the bubble to the surrounding liquid, and the latent heat of intense condensation. At strong collapses, intense vapour condensation takes place at bubble wall because the pressure inside the bubble increases dramatically as seen in Fig. 5 and Fig. 6.

Strictly speaking, the boundary between gas-phase and liquid-phase may be ambiguous at the final stage of the strong collapse because the density of gas is very high as seen in Fig. 7. In Fig. 8, the number of molecules in the bubble is shown as a function of time with logarithmic vertical axis. It is seen that the number of vapour molecules ($n_{H2O}$) decreases dramatically by the intense condensation at the strong collapses. In Fig. 9, the internal energy of the bubble (E) is shown as a function of time with logarithmic vertical axis. At the expansion phase in a bubble oscillation, the internal energy increases because evaporating vapour molecules carry their own energy into the bubble and heat flows from the surrounding liquid into the bubble by thermal conduction. At collapse, the internal energy decreases because condensing vapour molecules carry their own energy from the bubble into the surrounding liquid and heat flows from the bubble to the surrounding liquid.

In Fig. 10, comparison is given between the calculated result and the experimental data [23] of radius-time curve for one acoustic cycle. The calculated result fits well with the experimental data.

## 4. Conclusions

In order to calculate the liquid temperature at bubble wall ($T_{L,i}$) a new model of bubble dynamics in acoustic field is constructed including effects of thermal conduction both inside and outside a bubble and that of non-equilibrium evaporation and condensation of water vapour at bubble wall. Calculated results fit well with the experimental data of radius-time curve. The results reveal that the liquid temperature at bubble wall ($T_{L,i}$) is almost identical to the ambient liquid temperature during bubble oscillations except at strong collapses. At strong collapses, $T_{L,i}$ increases to the same order of magnitude with that of the maximum temperature attained in the bubble. It is caused by the latent heat of intense vapour condensation and by the thermal conduction from the heated interior of the bubble to the surrounding liquid. At strong collapses, intense vapour condensation takes place because the pressure inside the bubble increases dramatically.

## 5. Nomenclature

**Subscripts**

a: Refers to air

H2O, V : Refers to water vapor

g: Refers to the bubble content (air and vapor)

L: Refers to liquid

L,i: Refers to liquid at bubble wall

o: Refers to the equilibrium state

∞: Refers to conditions at a great distance from the bubble

| Symbol | Definition | Units |
|---|---|---|
| a | van der Walls constant | $J.m^3 /mol^2$ |
| b | van der Waals constant | $m^3/mol$ |
| c | Sound speed in liquid at infinity | m/s |
| $C_V$ | Heat capacity at constant volume | J/kg. K |
| $C_p$ | Heat capacity at constant pressure | J/kg. K |
| E | Internal energy of a bubble | J |
| $\Delta E$ | Change of internal energy of a bubble | J |
| $e_{eva}$ | Energy carried by evaporation | J/molecule |
| $e_{con}$ | Energy carried by condensation | J/molecule |
| f | Acoustic field frequency | Hz |
| k | Thermal conductivity | W/m.K |
| K | Boltzman constant | J/K |
| L | Latent heat of evaporation or condensation | J/kg |
| m | Mean mass of a molecule in a bubble | kg |
| $\dot{m}$ | Net rate of evaporation and condensation | $kg/m^2.s$ |
| $\dot{m}_{eva}$ | Actual rate of evaporation | $kg/m^2.s$ |
| $\dot{m}_{con}$ | Actual rate of condensation | $kg/m^2.s$ |
| M | Molar weight | g/mol |
| $n'$ | Number density of air and water vapor in a bubble | $molecule/m^3$ |
| $n_t$ | Total number of molecules in a bubble | molecule |
| $N_A$ | Avogadro number | Molecule/mol |
| P | Pressure | Pa |
| $P_m$ | Acoustic pressure amplitude | Pa |
| $P^*_v$ | Saturated liquid pressure | Pa |
| r | Radial distance from bubble center | m |
| R | Bubble radius | m |
| $\dot{R}$ | Bubble wall velocity | m/s |
| $R_g$ | Universal gas constant | J/mol. K |
| $R_v$ | Gas constant of water vapor | J/kg. K |
| t | Time | s |
| $\Delta T$ | Change of temperature at bubble wall | K |
| $T_B$ | Temperature inside a bubble at boundary layer | K |
| $\alpha_e$ | Thermal accommodation coefficient | |
| $\alpha_M$ | Evaporation or condensation accommodation coefficient | |
| $\delta$ | Thickness of boundary layer | m |
| $\lambda$ | Mean free path of a molecule in a bubble | m |
| $\mu$ | Liquid viscosity | $N.s/m^2$ |
| $\rho$ | Density | $kg/m^3$ |
| $\sigma$ | Surface tension | N/m |
| $\nu$ | Molar volume | $m^3/mol$ |
| $\omega$ | Angular frequency ($\omega=2\pi f$) | rad/s |

## References

[1] A. Prosperetti, "Physics of acoustic cavitation", Physical Acoustic, XCIII corso, Italy, (1986).

[2] C. E. Brennen, "Cavitation and bubble dynamics", Oxford University Press, New York, (1995).

[3] F. R. Young, "Cavitation", McGraw-Hill, London, (1989).

[4] M. A. Margulis," Sonochemistry and Cavitation", Gordon and Breach, Amsterdam, (1995).

[5] A. Shima and Y. Tomita, "The effects of heat transfer on the behaviour of bubble and impulse pressure in a viscous compressible liquid", ZAMM 59, (1979).

[6] K. Yasui," Variation of Liquid temperature at bubble wall near the sonoluminescence threshold", J. Phys. Soc. Jap., vol. 65, No.9, Sep. 1996.

[7] K. Yasui," Single-bubble dynamics in liquid nitrogen", Phys. Rev. E., 58, 1,1998.

[8] K. Yasui, "Effect of liquid temperature on sonoluminescence", Phys. Rev. E. 64, 2001.

[9] K. S. Suslick, R. E. Cline, Jr. and D. A. Hammerton, "Determination of local temperature caused by acoustic cavitation", IEEE Ultrasonic Symposium Proceedings, vol. 2, 1985.

[10] V. Kamath, A. Prosperetti and F.N. Egolfopoulos, "A theoretical study of sonoluminescence", J. Acoustic. Soc. Am., 94, 1, July 1993.

[11] T. Wang, "Rectified heat transfer", J. Acoustic Soc. Am., 56, 4, Oct. 1974.

[12] S. Fujikawa and T. Akamatsu, "Effect of non-equilibrium condensation of vapour on the pressure wave produced by the collapse of bubble in a liquid", J. Fluid Mech., 97, 3, 1980.

[13] A. Z. AL-Asady," Modelling oscillation of an acoustic bubble using nonlinear wave equation", Ph.D. Thesis, Engineering College, Basrah University, Iraq, 2002.

[14] K. Yasui, "Effect of non-equilibrium evaporation and condensation on bubble dynamics near the sonoluminescence threshold", Ultrasonic, 36, 1998.

[15] M. N. Kogan, "Rarefied gas dynamics", Plenum Press, New York,(1969).

[16] A. Prosperetti and A. Lezzi," Bubble dynamics in a compressible liquid. Part 1. First-Order Theory", J. Fluid Mech., 168,1986.

[17] J. B. Keller and M. Miksis, "Bubble oscillations of large amplitude", J. Acoust. Soc. Am., 68, 2, Aug. 1980.

[18] S. Sochard, A. M. Wilhelm and H. Delmas, "Gas-Vapour bubble dynamics and homogeneous sonochemistry, Chem. Eng., 51, 1997.

[19] K. Yasui," Effect of surfactants on single-bubble sonoluminescence", Physical Review E, vol. 58, No. 4, Oct. 1998.

[20] M. S. Plesset and A. Prosperetti, " Bubble dynamics and cavitation", Ann. Rev. Fluid Mech., 1977.

[21] J. L. Buchana and P. R. Turner," Numerical methods and analysis", McGraw-Hill, Inc., 1992.

[22] B. Carnahan, H. A. Luther and J. O. Wilkes, "Applied numerical methods", John Wiley and Sons, New York, (1969).

[23] B. P. Barber and S. J. Putterman, Physical Review letters, Vol. 69, No. 26, Dec. 1992.

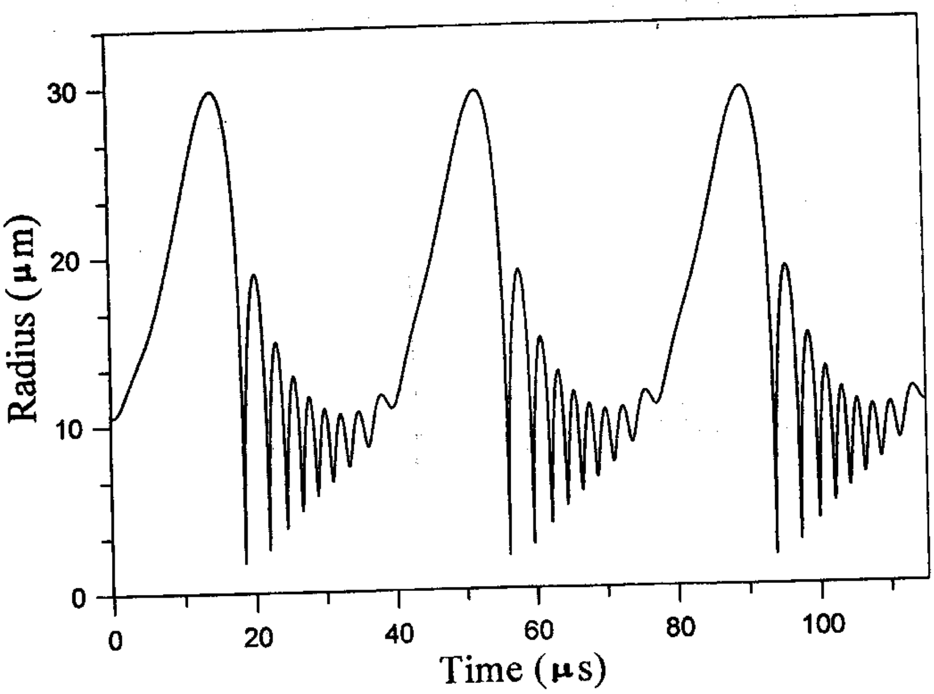


**Fig. 1. The bubble radius (R) as a function of time.**

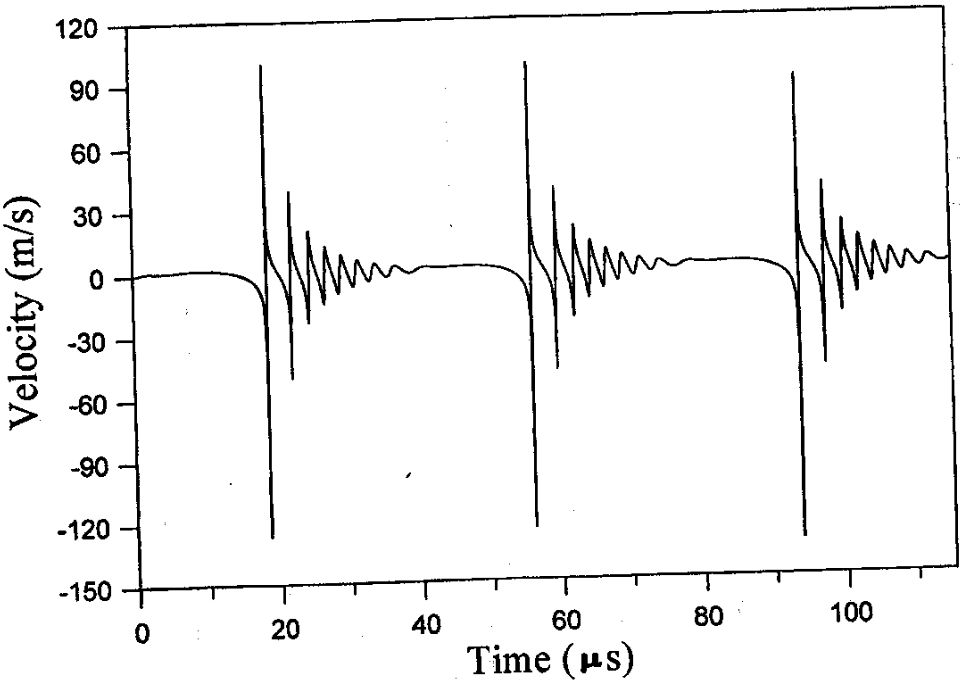


**Fig. 2. The bubble wall velocity ($\dot{R}$) as a function of time.**

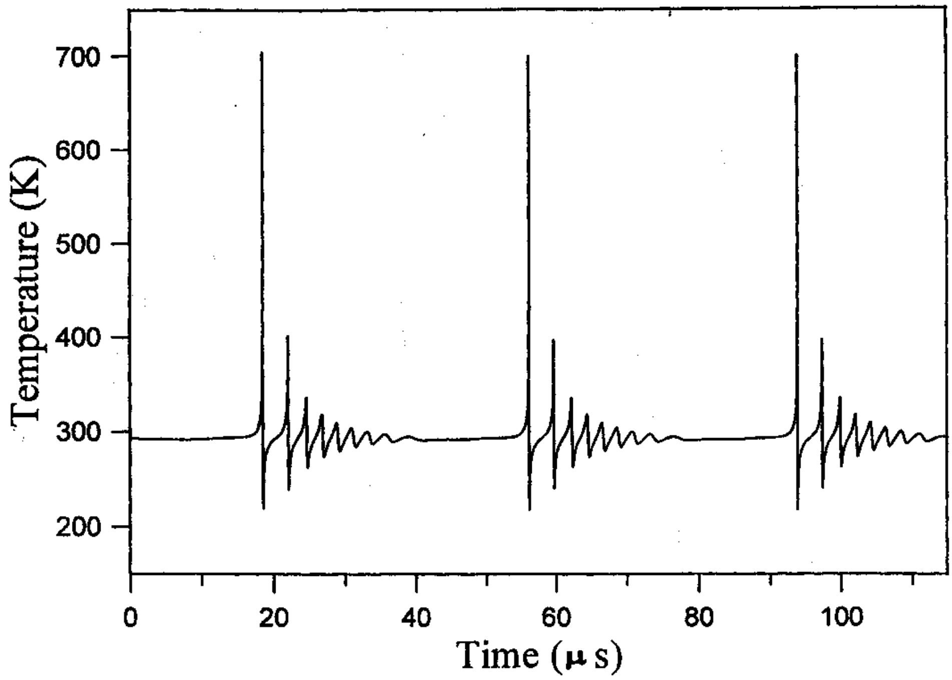


**Fig. 3. The temperature inside the bubble ( $T_g$) as a function of time.**

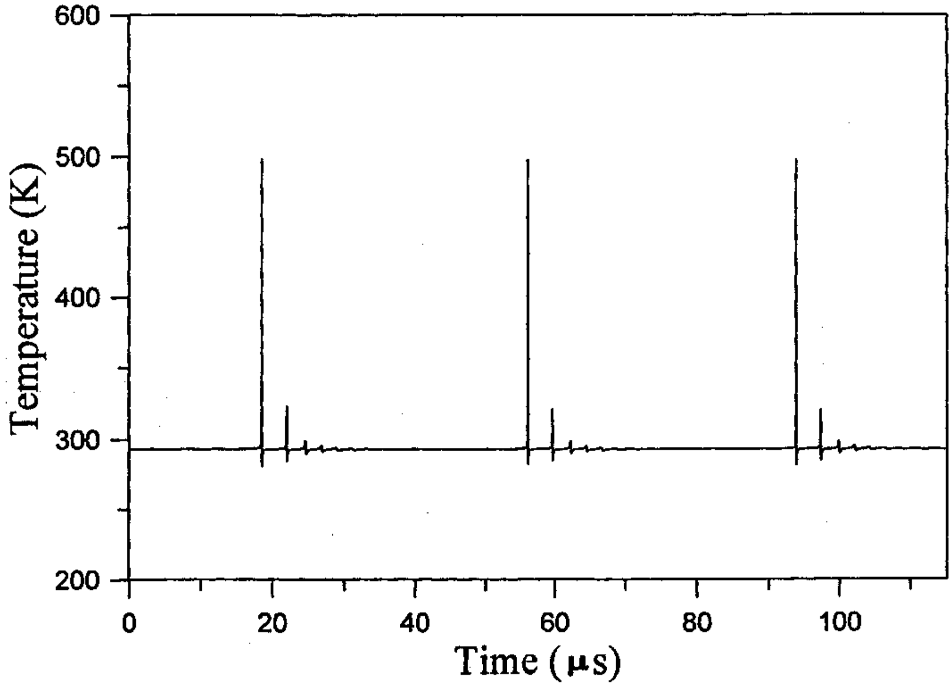


**Fig. 4. The liquid temperature at the bubble wall ( $T_{L,i}$) as a function of time.**

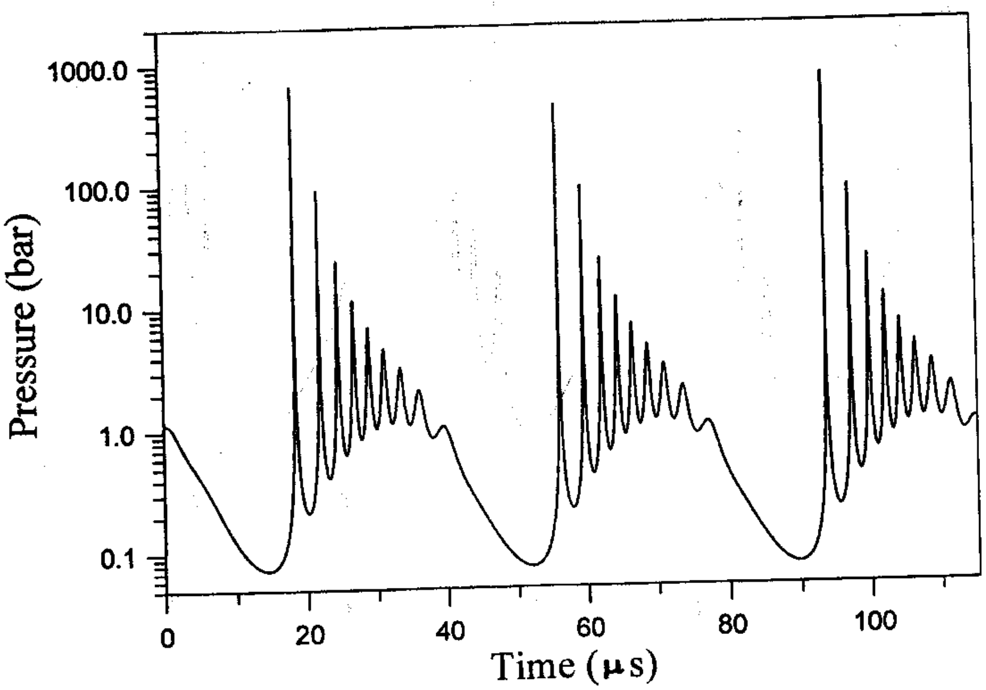


**Fig. 5. The pressure inside the bubble ($P_g$) as a function of time with logarithmic vertical axis.**

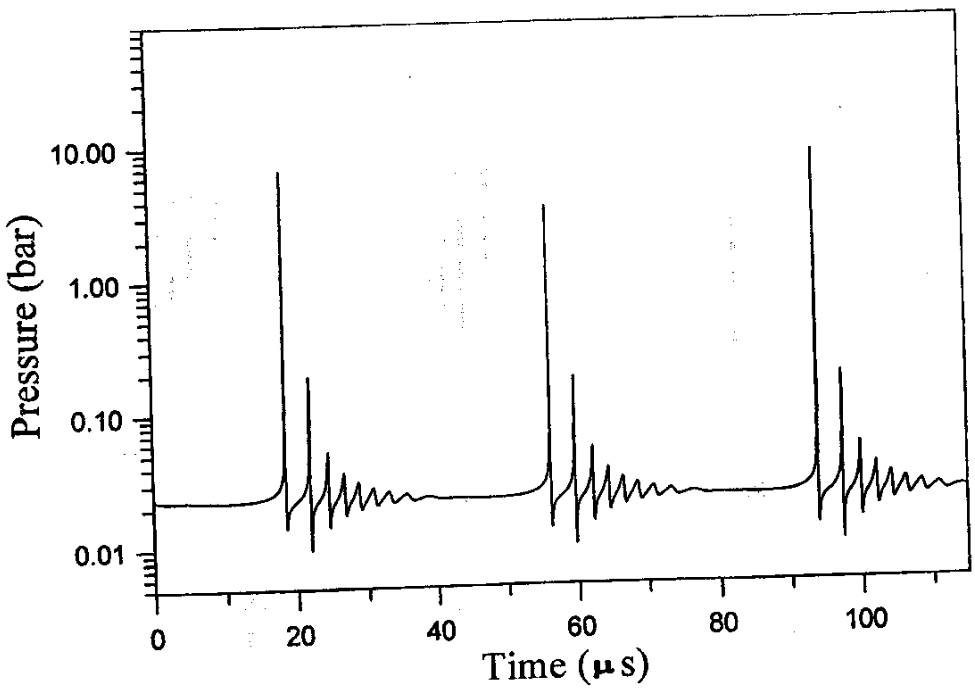


**Fig. 6. The partial pressure of water vapour ($P_V$) as a function of time with logarithmic vertical axis.**

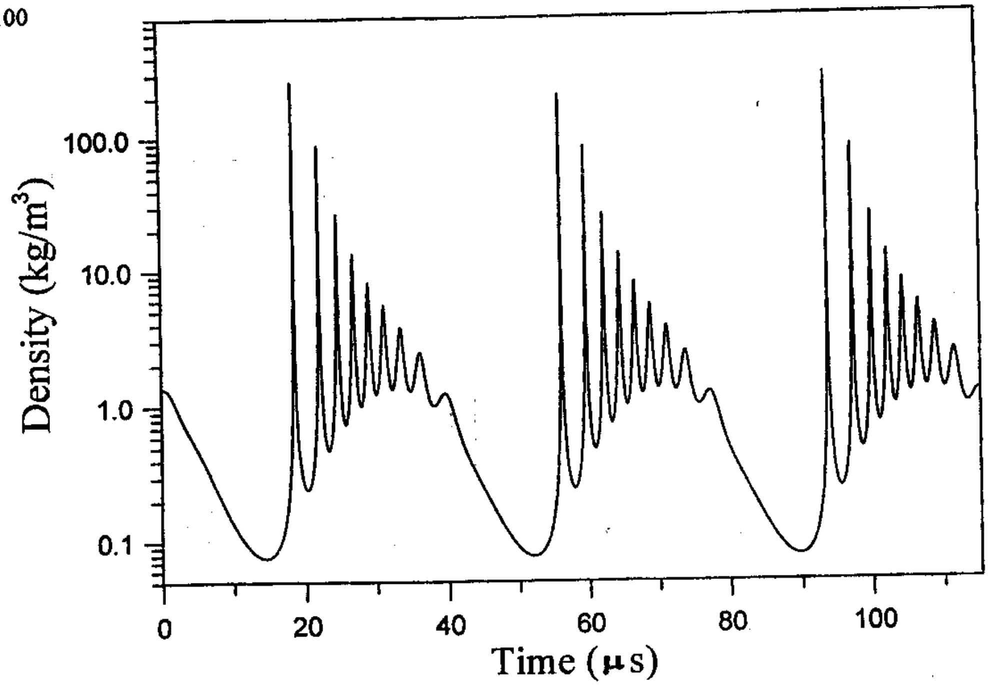


**Fig. 7. The density of the gas inside the bubble ($\rho_g$) as a function of time.**

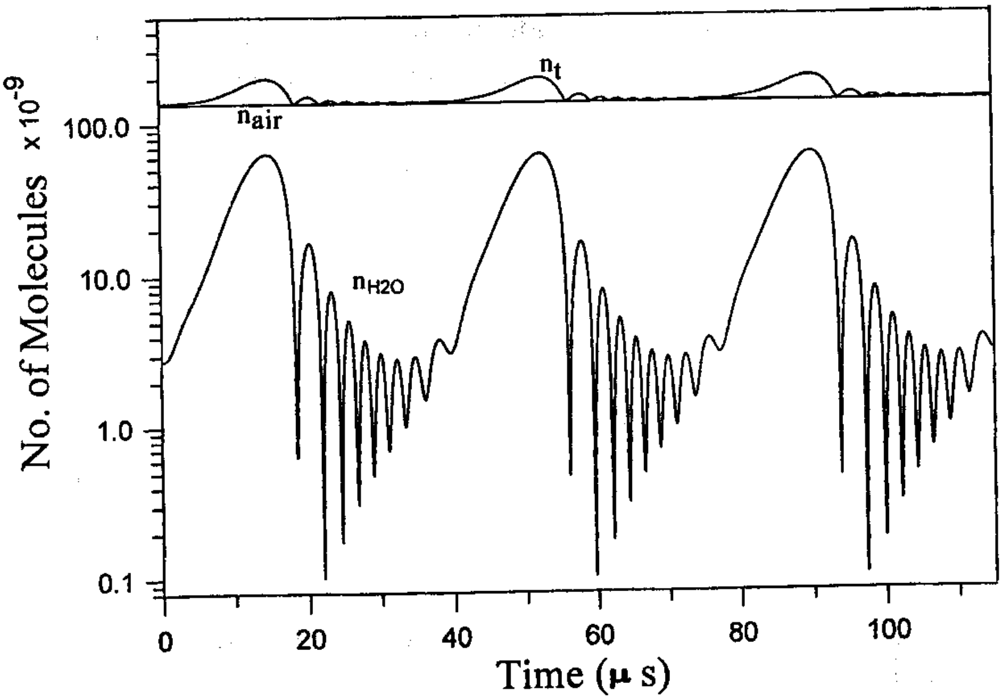


**Fig. 8. The number of molecules in the bubble as a function of time with logarithmic vertical axis.**

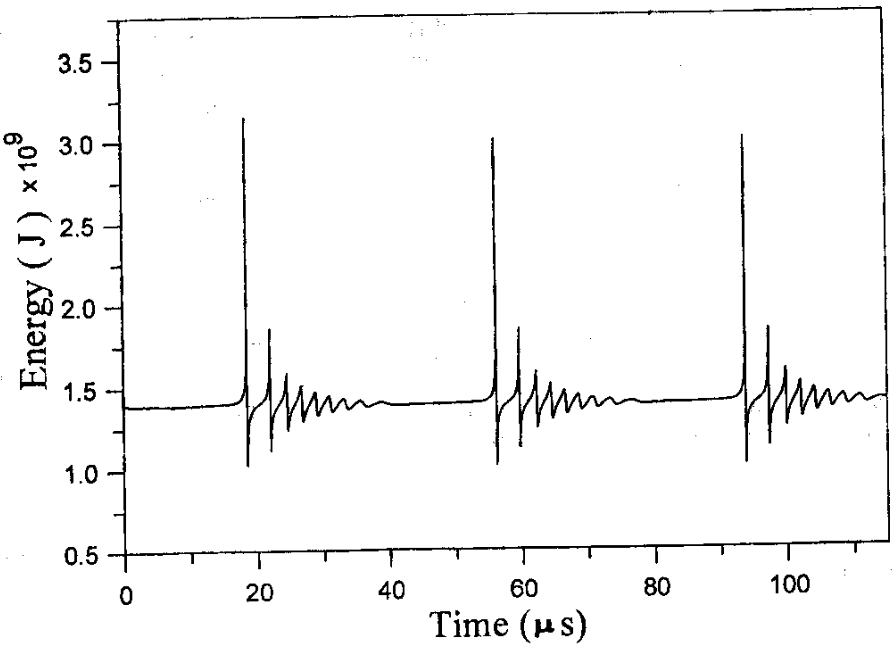


**Fig. 9. The internal energy of the bubble (E) as a function of time.**

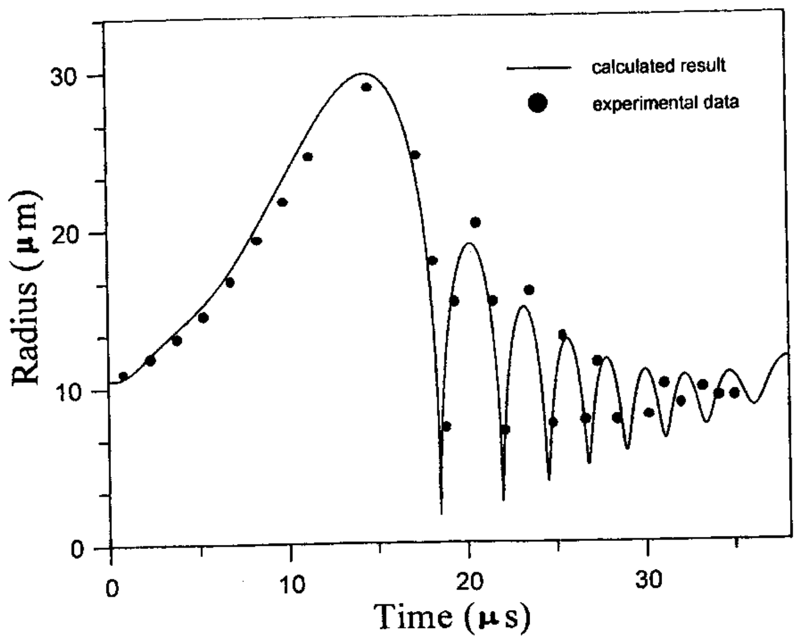


**Fig. 10. Comparison between the calculated result and the experimental data[23] of radius-time curve for one acoustic cycle.**