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NUMERICAL INVESTIGATION OF AN OSCILLATING GAS BUBBLE IN AN ULTRASONIC FIELD

Alhelfi A.* and Sunden B.
*Author for correspondence
Department of Energy Sciences, Faculty of Engineering,
Lund University,
Lund, 221 00,
Sweden,
E-mail: ali.alhelfi@energy.lth.se

ABSTRACT

The discovery of acoustic cavitation phenomenon is an important role in the design of a wide range of devices handling liquids and it has led to a renewed interest in the bubble dynamics in a sound field. In this study, the nonlinear behaviour of individual gas bubble in liquid under the action of ultrasound fields has been analysed, and simulated results of formation and collapse of a bubble have been provided.

The characterization of acoustic cavitation bubbles under the influence of periodic pressure field, e.g., the motion of the bubble surface, pressure, temperature and density fields inside the bubble have been investigated and the results are compared with experimental data. The numerically calculated results reveal that the assumption of polytropic approximation inside the bubble predicts that a radius-time curve does not fit to the observed data. Also, the results indicate that the pressure gradient and the heat transfer inside the bubble and across the bubble surface play a major role to predict the extreme conditions associated with the bubble collapse.

INTRODUCTION

The study on dynamics of the acoustic cavitation phenomenon, by means of numerical investigations or via experimental studies, is important for the development of many applications, and is considered to have significant role in different areas of science and technology including various industrial processes, sonochemistry acoustics, hydraulics and medicine. Several experimental techniques have been tested and various numerical models have been developed to characterize the dynamics of bubble oscillation in an ultrasonic acoustic field [1,2]. The purpose is to improve the understanding of interaction between the various physical processes involved.

In many cases, the shapes of the cavitation bubbles are believed to be spherical in an acoustic field in liquid because they are very tiny and the effect of surface tension plays an important role [3]. In particular, Kameda and Matsumoto [4] observed experimentally the radial motion of a spherical air bubble in acoustic fields where highly viscous silicon oil was used.

Fujiwara [5], analyzed theoretically the nonlinear oscillation of a bubble in compressible hydraulic oils subjected to a periodic pulsating pressure. According to the numerical calculations, the effect of compressibility of the liquid on the oscillation of a bubble was clarified. The effect of compressibility is appreciable when the amplitude is large.

Kwak et al. [6,7], studied Sonoluminescence (SL), i.e., the phenomenon associated with the collapse of bubbles oscillating under an ultrasonic pressure field, by solving the continuity, momentum, and energy equations for the gas inside the bubble analytically. Heat transfer in the liquid layer adjacent to the bubble surface was considered in their analysis. For Sonoluminescence (SL), the gas temperature after the shock focusing had been found to be 7000-44000 K, depending on the equilibrium bubble radius and the driving amplitude of ultrasound.

Sochard et al. [8], studied the dynamics of a gas-vapor bubble in a liquid subjected to an ultrasound field. A simulation was carried out assuming pressure uniformity of the internal pressure and perfect gas law for the gas-vapour mixture. At the maximum compression of the bubble, all the reactions of dissociation which can occur are assumed to be at thermodynamic equilibrium. It was proved that, in order to predict the extreme conditions associated with a collapse, the bubble dynamics must take into account the heat transfer inside the bubble and across the interface.

Yasui [9], created a new model of bubble dynamics in order to investigate the single bubble sonoluminescense. The physical situation was that of a single spherical bubble in liquid water irradiated by an ultrasonic wave. The contents of the bubble were non-condensable gas (air) and water vapor. The pressure inside the bubble was assumed to be spatially uniform. The calculated results from the numerical simulation of bubble oscillations revealed that the liquid temperature at the bubble surface increase considerably at the collapse due to thermal conduction from the heat in the interior of the bubble.

Hisanobu et al. [10], investigated numerically the radial motion of a spherical gas-vapor bubble in an acoustic field. The model includes the effect of spatial distribution of temperature inside the bubble and assumes uniform pressure for the bubble content. The small amplitude bubble oscillation in a hydrothermal system was simulated. The results showed that, for small amplitudes the spatial uniformity of pressure was valid.

Kim et al. [11], estimated the temperature and pressure fields generated by a collapsing bubble of microsize in a liquid under the action of an acoustic field and considering the heat transfer through the bubble surface neglecting mass transfer. An analytical model used for the simulation consists of solution for the Navier-Stokes equations inside the bubble and for the liquid adjacent to the bubble. The model was used to study the oscillation of a Xenon bubble in a sulfuric acid solution. The results showed that, high temperature and pressure appeared due to the collapsing micro bubbles.

Kim and Kwak [12], predicted the motion of a bubble under ultrasound field by an analytical model consisting of a set of Navier-Stokes equations for the gas inside a spherical bubble and Navier-Stokes equations for the liquid surrounding the bubble. The results showed that, the heat transfer inside the bubble and in the liquid layer plays a major role in the bubble behavior. Also, the results showed that the mass transfer through the interface does not affect the bubble motion. The calculations were performed for an argon bubble of 13 μm driven by an acoustic field with a frequency of 28.5 kHz and a pressure amplitude of 1.42 bar in an aqueous solution of sulfuric acid. Around the collapse point, the maximum bubble surface acceleration was 1.2×10^{10} m/s^2, the temperature at the bubble center was 9300 K and the pressure at the bubble center was 1034 bar.

Kawashima and Kameda [13], developed a mathematical model to simulate the radial motion of cavitation bubbles. The model contained non-condensable gas and vapor. The temperature and gas concentration distribution of bubble interior as well as exterior were considerd, and the Rayleigh-Plasset equation was used to describe the time-dependent bubble radius. The pressure in the bubble was assumed to be uniform in space. The results showed that, the growth rate was very sensitive to the initial bubble radius, ambient pressure and liquid temperature.

Lim et al. [14], the dynamics of a Xenon bubble with initial radius R=15 μm driven by an ultrasonic waves with a frequency 37.8 kHz and amplitude of 1.5 bar in aqueous sulfuric acid solution was investigated, taking into account the heat transfer inside the bubble and through the bubble surface. In their studied, a set of solutions of the Navier-Stokes equations for the gas inside the bubble and for the liquid adjacent to the bubble surface was used to treat properly the heat transfer process for the oscillating bubble under ultrasound. The results showed that, the polytropic relation, which has been used for the process of pressure change cannot properly treat heat transfer involving the oscillating bubble under ultrasound.

In this work, an enhanced numerical model is developed to study the acoustic cavitation phenomenon and the enhancement concerns taking both the pressure and temperature gradients inside the bubble as well as heat transfer through the bubble surface into account. This is very important to obtain the temperature of the liquid surrounding the bubble surface.

NOMENCLATURE

c	[m/s]	Speed of sound in the liquid
D	[m^2/s]	Thermal diffusivity
F	[kHz]	Acoustic frequency
H	[J/kg]	Enthalpy at the bubble surface
P	[bar]	Pressure
r	[m]	Radial distance from the center of the bubble
R	[m]	Radius of the bubble
t	[s]	Time
T	[K]	Temperature
u	[m/s]	Gas Velocity inside the bubble

Special characters

γ	[-]	Specific heat ratio
λ	[W/m.K]	Thermal conductivity
μ	[N.s/m^2]	Viscosity
ρ	[kg/m^3]	Density
σ	[N/m]	Surface tension
ω	[rad/s]	Angular frequency
∞	[-]	Ambient liquid medium

Superscripts

.	Refer to first time derivatives
..	Refer to second time derivatives

Subscripts

A	Acoustic
bo	The values at the bubble center
g	Gas
L	Liquid
o	Equilibrium values

PROBLEM DESCRIPTION

A single bubble which has a spherical geometry with initial radius R_o containing a gas is considered to interact with an acoustic wave within a static, infinite, viscous and compressible liquid. The bubble and the liquid are originally in equilibrium at a temperature T_o and pressure P_o at the interface of the bubble, and then the bubble begins to oscillate under ultrasound wave action.

Due to the applied acoustic pressure the bubble motion becomes nonlinear [15], as represented in Figure 1.

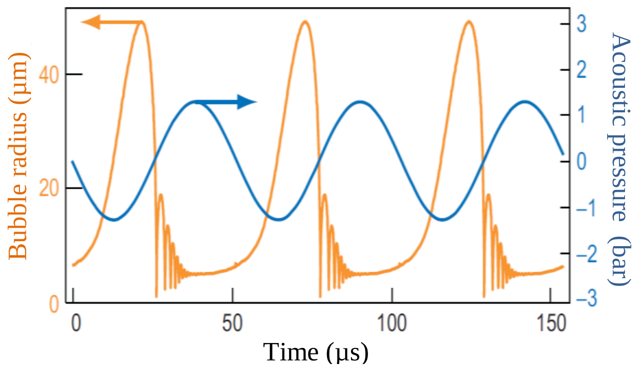

Figure 1 Radius-time curve of a cavitating bubble. The bubble is driven by a sinusoidal acoustic field [16]

MATHEMATICAL FORMULATIONS

The most common approach to understand the radial motion of a bubble within a static, infinite, viscous and compressible liquid is to solve the well-known Keller-Kolodner equation.

$$R\ddot{R}\left(1-\frac{\dot{R}}{c}\right)+\frac{3}{2}\dot{R}^{2}\left(1-\frac{\dot{R}}{3c}\right)=\left(1+\frac{\dot{R}}{c}\right)H+\frac{R}{c}\frac{dH}{dt} \tag{1}$$

where:

$$H=\frac{1}{\rho_{L}}\left[P_{L}(R)-P_{\infty}(t)\right]$$

where R is the bubble radius, c speed of sound in the liquid, $\dot{R}$ is the bubble surface velocity, $\ddot{R}$ is the bubble surface acceleration, P_L is the liquid pressure at the bubble surface and P_∞ is pressure far from the bubble.

A force balance on the bubble surface is now considered. The pressure $P_L(R)$ is written as taking the surface tension and the liquid viscosity into account [17]:

$$P_{L}=P_{g}-2\left(\frac{\sigma}{R}\right)-4\mu\left(\frac{\dot{R}}{R}\right) \tag{2}$$

At infinity the pressure far from the bubble is denoted by P_∞ and is given by,

$$P_{\infty}=P_{o}-P_{A}\sin\omega t \tag{3}$$

where

$$\omega=2\pi F$$

where P_o is the hydrostatic pressure, P_A is the time dependent acoustic pressure, ω is the angular frequency, and F is the acoustic frequency.

1. CASE 1: POLYTROPIC APPROXIMATION

There are many investigations based on this polytropic approximation. A usual simplification is carried out by assuming uniform pressure and temperature inside the bubble.
In this case study, the governing equations for the gas inside the bubble are replaced by the polytropic relations for pressure and temperature as follows;

The uniform internal pressure is then linked to the bubble radius by,

$$P=P_{go}\left(\frac{R_{o}}{R}\right)^{3k} \tag{4}$$

where R_o is the initial bubble radius, k is the polytropic exponent, and P_{go} is the initial internal pressure of the gas inside the bubble.

$$P_{go}=P_{o}+2\sigma/R_{o} \tag{5}$$

where P_o hydrostatic pressure in the liquid, σ is the surface tension.
The internal temperature inside the bubble is given by,

$$T=T_{o}\left(\frac{R_{o}}{R}\right)^{3(k-1)} \tag{6}$$

Kameda and Matsumoto [4] showed significant discrepancies between the polytropic theory and experimental data for an oscillating bubble under the action of ultrasound. They stated that "*the polytropic approximation has a serious limitation for many problems, because it cannot correctly describe the thermal behavior of the bubble interior. Indeed, we have a considerable spatial non-uniformity of the temperature in the bubble, which needs to be taken into account*".

Consequently, different models have been proposed for more accurate calculations of the bubble content by replacing the polytropic model, as highlighted below.

2. CASE 2: UNIFORM PRESSURE MODEL

The model studied is based on two main assumptions, the pressure gradient inside the bubble is neglected $(\partial P/\partial r)=0$ and the gas inside the bubble behaves as a perfect gas. By using these assumptions, the continuity and energy equations are combined to obtain an exact expression for the gas velocity distribution inside the bubble in terms of the temperature gradient and this is given as [18,19],

$$u(r,t)=\frac{1}{\gamma P}\left((\gamma-1)\lambda\left(\frac{\partial T}{\partial r}\right)_{R}-\frac{1}{3}r\frac{dP}{dt}\right) \tag{7}$$

By applying the velocity boundary condition ($u=\dot{R}$ at $r=R$) for equation (7) the time dependent pressure term is obtained as,

$$\frac{dP}{dt}=\frac{3}{R}\left[(\gamma-1)\lambda\left(\frac{\partial T}{\partial r}\right)_{R}-\gamma P\dot{R}\right] \tag{8}$$

The energy equation inside the bubble with spherical symmetry is written in the following form [19],

$$\frac{\gamma}{\gamma-1}\frac{P}{T}\left[\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial r}\right]-\frac{dP}{dt}=\frac{1}{r^{2}}\frac{\partial}{\partial r}\left(r^{2}\lambda\frac{\partial T}{\partial r}\right) \tag{9}$$

where r is the radial distance from the center of the bubble, T, P are the gas temperature and pressure respectively, u is the gas velocity, γ is the specific heat ratio, λ is the thermal conductivity of the gas inside the bubble.

The thermal conductivity of the gas inside the bubble is assumed to follow [20]:

$$\lambda = AT + B \tag{10}$$

where the constants in equation (10) for air are,
A=5.528×10^{-5} W/m K^2 and B=0.01165 W/m K

In this case the heat transfer between the bubble and the surrounding liquid is considered, so the energy equation of the liquid is required, and is given as [21],

$$\frac{\partial T_L}{\partial t} + \frac{R^2 \dot{R}}{r^2}\frac{\partial T_L}{\partial r} = \frac{D_L}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial T_L}{\partial r}\right) \tag{11}$$

where D_L is the liquid thermal diffusivity, and T_L is the temperature of the liquid at a distance r from the bubble center.

3. CASE 3: VARIABLE PRESSURE MODEL

The dynamics of a gas bubble in a liquid is strongly related to the pressure of the gas inside it. Basically, this quantity must be calculated from the solutions of the conservation equations inside and outside the bubble coupled together by suitable boundary conditions at the bubble-liquid interface. This task is very complex and can only be solved analytically for small-amplitude motion in which the equations can be linearized [22].

In introduction section, different models were presented to improve and give more comprehensive understanding of the bubble dynamics. Furthermore, Wu and Robert, [23] and Moss et al. [24] performed numerical simulations of the energy equation in addition to the mass and momentum equations for the gas inside the bubble with spherical symmetry. However, the heat transfer inside the bubble and in the liquid layer at the bubble surface was not considered in their study. In the recent study by Kwak [25] an analytical model was developed consisting of a set of Navier-Stokes equations for the gas inside a spherical bubble and an analytical treatment for the Navier-Stokes equations for the liquid surrounding the bubble.

In the present study an enhanced numerical model is developed to study the acoustic cavitation phenomenon and the enhancement takes into account the pressure and temperature gradient inside the bubble, as well as heat transfer through the bubble surface. This is very important to obtain the temperature of the liquid surrounding the bubble surface.

The gas density and the radially dependent velocity distribution inside the bubble imposed in Ref. [25] are given as,

$$\rho_g = \rho_{bo} + \rho_r \tag{12}$$

$$u = \frac{\dot{R}}{R} r \tag{13}$$

where ρ_g is the gas density inside the bubble, ρ_{bo} is the gas density at the bubble center , and ρ_r the radially dependent gas density.

The gas pressure inside the bubble can be obtained by solving the momentum equation for the gas inside the bubble with the density and velocity profiles given above.

$$P_g = P_{bo} - \frac{1}{2}\left(\rho_{bo} + \frac{1}{2}\rho_r\right)\frac{\ddot{R}}{R} r^2 \tag{14}$$

where P_{bo} is the gas pressure at the bubble center.

Continuity and momentum equations for the bubble content are replaced by Eqs. (13) and (14), respectively.
The energy equation of the gas inside the bubble may be written in the following form [13],

$$\frac{\gamma}{\gamma - 1}\frac{P}{T}\left[\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial r}\right] - \left(\frac{dP}{dt} + u\frac{dP}{dr}\right) = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \lambda \frac{\partial T}{\partial r}\right) \tag{15}$$

where r is the radial distance from the center of the bubble, u is the gas velocity, T temperature of the gas inside the bubble, P pressure of the gas inside the bubble, λ is the thermal conductivity of the gas inside the bubble expressed by Eq. (10), and γ is the specific heat ratio.

To complete the system of equations, the bubble surface motion equation is required, i.e., Eq. (1). Also, the liquid temperature on the external side of the bubble surface is assumed to vary during the oscillations, so the energy equation for the liquid surrounding the bubble, i.e., Eq. (11) as modified previously, is required to complete the set of equations.

NUMERICAL SOLUTION METHOD

In the present work, a numerical solution method is performed for the systems of equations modified previously. The systems of equations required to be solved consist of ordinary and partial differential equations, which are both nonlinear and time dependent equations. A fourth order Runge-Kutta algorithm is applied to solve the ordinary differential equations, and more details regarding this method can be found in Ref. [26]. One the other hand, the Finite Difference Method (FDM) is employed to solve the partial differential equations. This method has been one of the most widely used to solve several physical problems [27].

In order to determine a radius versus time behavior and other characteristics of the bubble, the constants c, ω, P_A, P_o, T_o, F, μ, and σ must be known. Numerical calculations are performed for a gas (air) bubble with an equilibrium radius R_o of 8.5µm driven by an acoustic field with a frequency of 26.5 kHz and amplitude of 1.075 bar, in a liquid (water) at the conditions T_o=20°C and P_o=1 bar. The calculations start from time t = 0 s with the initial condition that $R = R_o$ and $\dot{R} = 0$, for a gas bubble in liquid with physical properties ρ = 998.2 kg/m^3, c=1482 m/s, σ =7.275E-02 N/m and μ=1.003E-03 Ns/m^2.

RESULTS AND DISCUSSION

The present bubble dynamics model and a simpler adiabatic one are compared.

From the graphs in Figure 2 it is clearly illustrated that the acoustic pressure amplitude has a great influence on the bubble dynamics. It is observed that the bubble starts to grow immediately and begins to oscillate in a nonlinear manner due to the action of periodic acoustic pressure. Also, it can be seen that, during the rarefaction phase of the sound field the bubble grows. As the sound field turns compressive, the bubble may oscillate. Subsequently, the bubble can oscillate with low amplitude on a very short time scale.

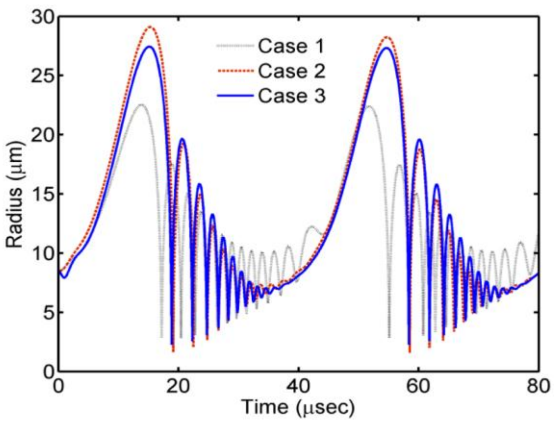

Figure 2 Comparison of radius-time behavior for the three cases of study
Case 1: Polytropic approximation
Case 2: Uniform pressure model
Case 3: Variable pressure model

The major variables in the acoustic cavitation phenomenon are the temperature and pressure produced by the collapsing bubble of microsize in the liquid in the ultrasonic field. So, the temperature-time variation and pressure-time variation for the three cases are given in Figures 3 and 4.

For all cases high temperatures and pressures are predicted during compression as can be seen in the figures above. In case 1, the assumption of polytropic behavior of the gas inside the bubble at the minimum bubble radius predicts maximum values of pressure and temperature of 122 bar and 1065.2 K, respectively. In case 2, the assumption of uniform pressure and variable temperature inside the bubble at minimum bubble radius predicts pressure and temperature maximum values of 1042 bar and 3075.5 K, respectively, while in case 3 for the assumption of variable pressure and temperature inside the bubble, the pressure and temperature reach the maximum values of 398 bar and 2234.5 K, respectively.

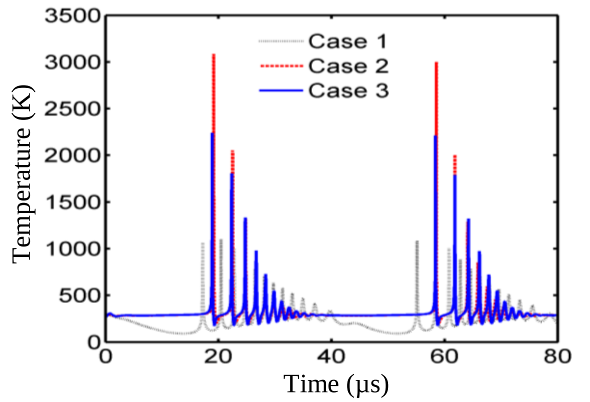

Figure 3 The temperature inside the bubble as a function of time

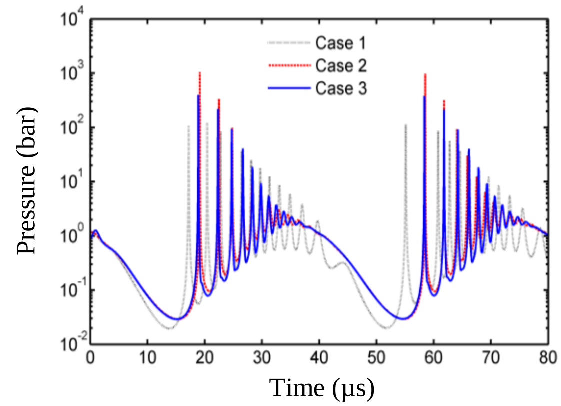

Figure 4 The pressure inside the bubble as a function of time (logarithmic vertical axis)

Several factors affect the pressure of the gas inside the bubble, and the dominating forces in the liquid near the bubble surface are the surface tension, the viscous force, the hydrostatic pressure, and the time dependent acoustic pressure. Thus the velocity of the bubble surface plays an important role in the bubble dynamics. The velocity and acceleration of the bubble surface for the three cases are given in Figures 5 and 6.

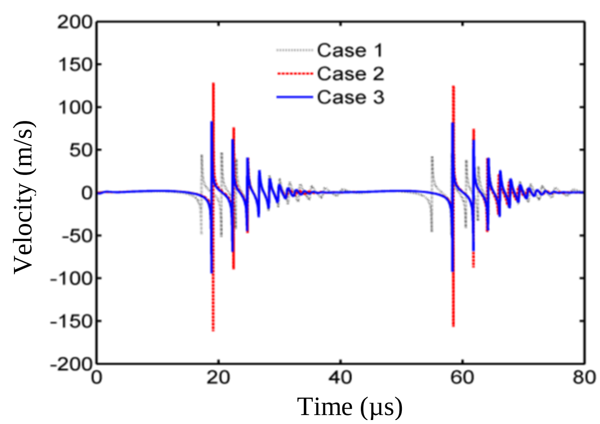

Figure 5 The bubble surface velocity as a function of time

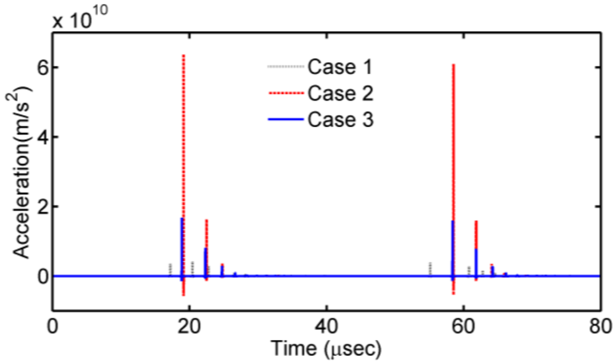

Figure 6 The bubble surface acceleration as a function of time

The physical properties of the bubble content are assumed to be variable with time so the gas density behaviour inside the bubble shown in Figure 7.

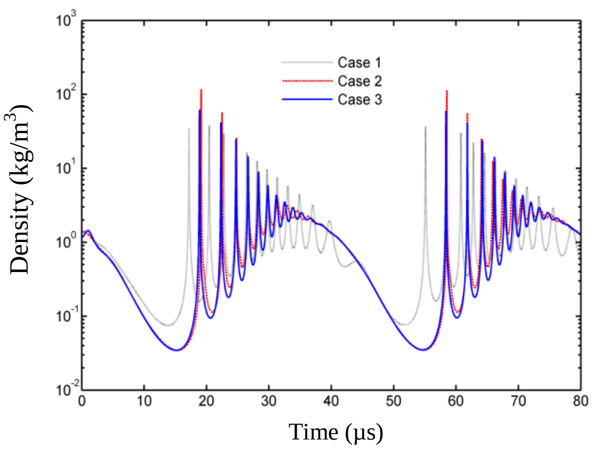

Figure 7 The gas density inside the bubble as a function of time

For polytropic approximation presented in case study 1, a general simplification is adapted by assuming no heat transfer inside the bubble as well as no heat transfer between the bubble and the surrounding liquid. Additionally, incorporation of an energy balance enables a study of the effect of liquid temperature as shown in Figure 8 for case 2 and 3.

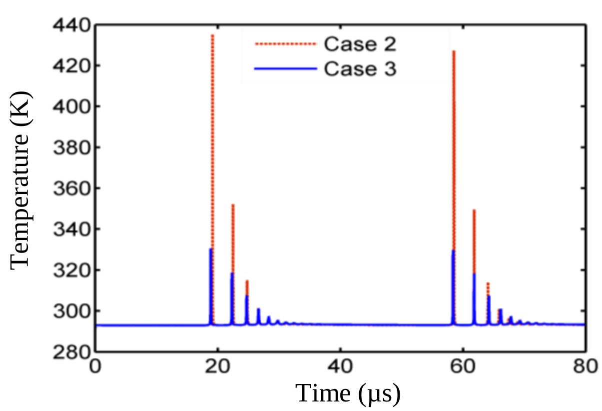

Figure 8 The liquid temperature at the bubble surface as a function of time

VALIDATION OF NUMERICAL MODELS

Comparing the results of case 1, case 2 and case 3 along with the observed one reveals that, the assumption of uniform pressure and temperature inside the bubble to predict the radius-time behavior is not close to the experimental results.

Figure 9 shows the calculated radius-time behavior for the three case studies for an air bubble of R_o=8.5 μm at P_A=1.075 bar and F=26.5 kHz in water along with the observed one obtained by Löfstedt et al. [28]. The experimental data of bubble radius behaviour under ultrasound were obtained by light scattering and the accuracy of the measurement was not indicated.

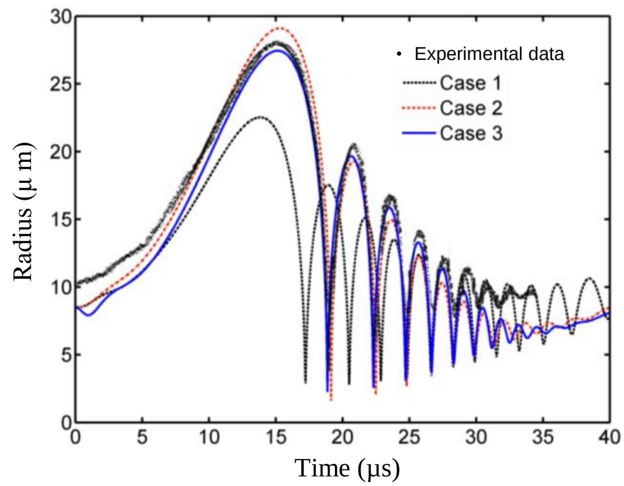

Figure 9 Comparison of calculated radius-time behaviour for the three cases of study with experimental data by Löfstedt et al. [28]

In order to give the model greater reliability, the previous comparisons were limited to the radius-time behavior only, while the pressure and temperature inside the bubble during collapse, which represent the most important parameters, were not considered. Thus, another comparison of the calculated results of case 2 and case 3 with experimental results is conducted but for an argon bubble of R_O=13 μm under the action of an acoustic field of P_A=1.42 bar and F=28.5 kHz in a sulfuric acid solution. The experimental results include the values of pressure and temperature inside the bubble during the collapse. The observed data was obtained originally by Flannigan et al. [29, 30] by standard tools of plasma diagnostics applied to the observed argon emission inside the cavitating bubble. The experimental error in the measured temperature was 5%. The temperature and pressure fields calculated as a function of time inside the bubble during the collapse phase are given in Figures 10 and 11.

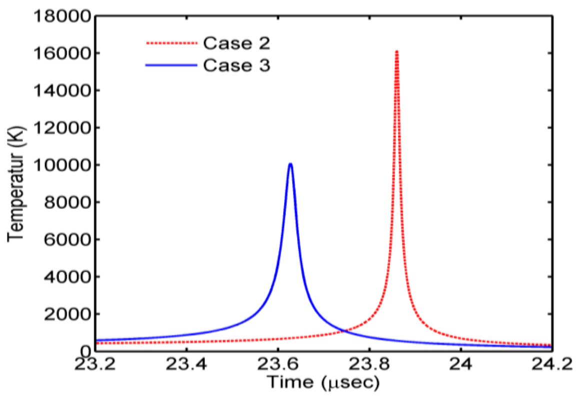

Figure 10 The time dependent gas temperature at the bubble center during the collapse phase

The value of the peak temperature during collapse for the case of variable pressure and temperature inside the bubble is 10085 K, which is closer to the observed value 10000 K. On the other hand the peak temperature for the case of uniform pressure and variable temperature inside the bubble is 16155 K, which is quite different from the observed values.

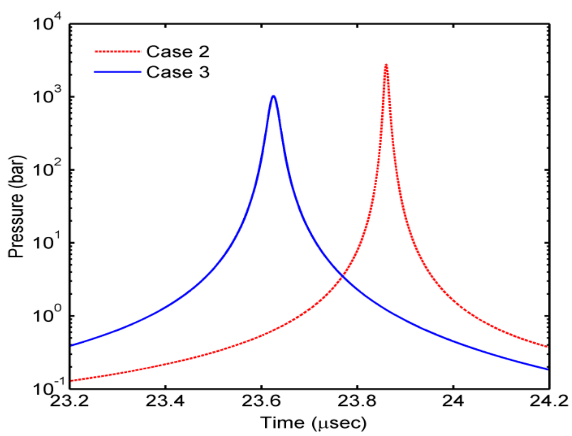

Figure 11 The time dependent gas pressure at the bubble center during the collapse phase

Also, there is a large difference in pressure predictions between the two cases. The value of the peak pressure inside the bubble during collapse for variable pressure model is 1023 bar, and that is not too far away from the observed value which is 1104 bar. The peak pressure for uniform pressure model is 2786 bar, which is far from the observed value.

The results reveal that, the predictions model based on the assumption of variable pressure inside the bubble are closer to the experimental results than those of a uniform pressure assumption. Accordingly this model represents the best assumption.

CONCLUSIONS

Models for the numerical calculations of bubble growth and collapse under the action of an acoustic field for different assumption of pressure and temperature inside the bubble are developed and implemented to study the bubble dynamics.

The calculated radius-time behavior based on the assumption of polytropic approximation does not fit to the experimental results and lead to the predictions of pressure, temperature, density, bubble surface velocity, and acceleration which are less than the predictions of the assumptions of uniform and variable pressure models. This means that neglecting the thermal conduction inside and outside the bubble has a considerable effect on the bubble dynamics.

Also, the results reveal that the pressure gradient inside the bubble has a considerable effect on bubble dynamics. Predictions of model based on the assumption of variable pressure inside the bubble are closer to the experimental results than those of uniform pressure assumptions.

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