Strong compression of bubbles in water, acetone and benzol

To cite this article: A A Aganin and D Yu Toporkov 2018 J. Phys.: Conf. Ser. 1058 012068

View the article online for updates and enhancements.
Strong compression of bubbles in water, acetone and benzol

A A Aganin, D Yu Toporkov

Institute of Mechanics and Engineering - Subdivision of the Federal State Budgetary Institution of Science "Kazan Scientific Center of the Russian Academy of Sciences" (IME - Subdivision of FIC KazanSC of RAS) 2/31, Lobachevsky str., Kazan 420111 Russia

E-mail: top.dmtr@gmail.com

Abstract. Strong compression of the medium in cavitation bubbles in water, acetone and benzol realizing in the final stage of their collapse in the initially motionless liquid at a temperature of 293 K is considered. At the beginning of the collapse, the radius of the bubbles is 500 μm, the vapor in the bubbles is in its saturation state at the temperature of the surrounding liquid. The pressure of water and benzol is varied in the range $1 \leq p_0 \leq 100$ bar to determine its values at which the degree of compression of the medium inside the cavitation bubbles in these liquids is close to that achieved inside the cavitation bubble in acetone at the pressure $p_0 = 15$ bar. It is shown that in the case of the bubble in benzol such a degree of the vapor compression can be achieved at $p_0 = 4$ bar, whereas in the case of the bubble in water, even $p_0 = 100$ bar is not enough.

1. Introduction

One important feature of bubble dynamics in a liquid is the possibility of reaching high densities, pressures and temperatures in the final stage of the bubble collapse [1, 2]. The strong compression of the vapor-gas medium in a bubble can be gained by nearly homogeneous compression, by radially-converging isentropic (shockless) waves and by radially-converging shock waves [2, 3]. The greatest effect is achieved with compression by shock waves [2]. In particular, it was shown in [4] that the temperatures of the order of $10^7$ K, the densities of the order of 1 g / cm$^3$ can be obtained at a liquid pressure of 15 bar and its temperature of 273 K in a small central region (200 nm in diameter) of the collapsing cavitation bubble in deuterated acetone.

This paper investigates the possibility of realizing the cavitation bubble collapse in water and benzol with attaining the same high degree of the vapor compression inside the bubble that is achieved in the case of the bubble in acetone collapsing at the room temperature (293 K) and the 15 bar pressure. At that, the room temperature of water and benzol is also taken, and their pressure is varied in the range of 1÷100 bar so that the maximum values of the temperature and density inside their cavitation bubbles are close to those achieved in the case of the bubble in acetone. Water and benzol are considered due to the fact that they are widely used in various technologies. According to the criterion of [5], for producing shock waves inside a cavitation bubble, water (benzol) is less (more) suitable than acetone.
2. Problem statement

Collapse of a single cavitation bubble in an unlimited volume of liquid (acetone, water and benzol) is considered. At the beginning of the collapse (at time \( t = 0 \)) the bubble is at rest, its radius is \( R = R_0 = 500 \mu m \), the vapor and liquid temperature is \( T = T_0 = 293 \) K, the liquid pressure far from the bubble is \( p = p_0 \), the vapor pressure is equal to the saturation pressure \( p_s \) at temperature \( T_0 \). The pressure of water and benzol is varied in the range \( 1 \leq p_0 \leq 100 \) bar so that the achieved compression degree of the medium inside the cavitation bubbles in these liquids is close to the degree achieved inside the cavitation bubble in acetone at \( p_0 = 15 \) bar. The initial bubble radius \( R_0 = 500 \mu m \) and the compressive liquid pressure \( p_0 = 15 \) bar are taken in accordance with the estimates [4] of the experimental data on bubble supercompression [1]. The main characteristics of the vapor compression degree inside a bubble are the levels of the maximum temperature and density values at the boundary of a small central region of the bubble with \( r \leq 0.25 \mu m \) (the central super-hot core). This small area is excluded from consideration because the model of the present work is not adequate in this area since it does not take into account the effects of dissociation, ionization, nonsphericity, etc. However, these characteristics seem acceptable for the purposes of the present work.

The dynamics of the vapor and liquid is described by the equations [4, 6]:

\[
\begin{align*}
\frac{\partial}{\partial t} (pr^2) + \frac{\partial}{\partial r} (pwr^2) &= 0, \\
\frac{\partial}{\partial t} (pwr^2) + \frac{\partial}{\partial r} (pw^2r^2 + pr^2) &= 2pr, \\
\frac{\partial}{\partial t} (pr^2) + \frac{\partial}{\partial r} [wr^2(p_e + p)] &= \frac{\partial}{\partial r} \left( r^2 \kappa \frac{\partial T}{\partial r} \right).
\end{align*}
\]

Here \( \rho \) is the density, \( w \) is the radial velocity, \( e = U + \frac{w^2}{2} \) is the specific total energy, \( U \) is the specific internal energy, and \( \kappa \) is the thermal conductivity. The boundary conditions have the form [4, 6]:

\[
\begin{align*}
& r \rightarrow \infty: \quad p = p_0, \quad T = T_0, \\
& r = R(t): \quad \dot{R} = w_i + \frac{J}{\rho_i} = w_g + \frac{J}{\rho_g}, \quad \rho_i = \rho_g = \frac{4\mu_i w_i}{R} - \frac{2\sigma}{R}, \\
& \kappa_i \left( \frac{\partial T}{\partial r} \right)_i - \kappa_g \left( \frac{\partial T}{\partial r} \right)_g = j(l(p_g)), \quad T_i = T_g.
\end{align*}
\]

Here \( \mu_i \) is the dynamic viscosity of the liquid, \( \sigma \) is the surface tension, \( l \) is the heat of vaporization, \( j \) is the evaporation and condensation velocity per unit surface area (determined by the Hertz-Knudsen-Langmuir formula [6]). The subscripts \( l \) and \( g \) indicate the correspondence to the liquid and the vapor, respectively.

The equations of the liquid and vapor states are taken as sums of the potential \( (p^{(p)}, U^{(p)}) \) and thermal \( (p^{(T)}, U^{(T)}) \) components of the pressure \( p \) and the internal energy \( U \) with the addition of a constant \( U^{(ch)} \) in the equation for \( U \)

\[
p(\rho,T) = p^{(p)}(\rho) + p^{(T)}(\rho,T), \quad U(\rho,T) = U^{(p)}(\rho) + U^{(T)}(T) + U^{(ch)}.
\]

The density functions \( p^{(p)}, U^{(p)} \) are presented in the form of the generalized Born-Mayer potential, the functions \( p^{(T)} \) and \( U^{(T)} \) are expressed as \( p^{(T)}(\rho,T) = \rho \Gamma(\rho) U^{(T)}(T) \), \( U^{(T)}(T) = c_v T \) where \( \Gamma \) is the Grüneisen coefficient. The heat capacities \( c_v \) of the liquid and vapor are assumed to be constant. The model parameters for acetone are taken from [7], for water from [8] and for benzol from [9].
3. Results
A number of numerical experiments have been performed with various water and benzol pressure values in the range $1 \leq p_0 \leq 100$ bar, keeping the liquid temperature equal to 293 K. The results of those experiments have shown that to attain the vapor compression degree nearly as high as that achieved inside the cavitation bubble in acetone at $p_0 = 15$ bar, it is sufficient to take $p_0 = 4$ bar in the case of the bubble in benzol, and even $p_0 = 100$ bar is not enough in the case of the bubble in water.

Figure 1. Variation of the radius $R$ of the bubble during its collapse in acetone at $p_0 = 15$ bar (curve 1), in benzol at $p_0 = 4$ bar (curve 2) and in water at $p_0 = 100$ bar (curve 3). The circles indicate the minimum values of the bubble radii.

Figure 1 illustrates the change of the radii of the cavitation bubbles in acetone, water and benzol during their collapse at the pressure of acetone $p_0 = 15$ bar, water $p_0 = 100$ bar and benzol $p_0 = 4$ bar. It can be seen that duration of the bubble collapse in these three cases is very different. It is equal to 10.5 $\mu$s in the case of acetone, 4.8 $\mu$s in the case of water and 21.7 $\mu$s in the case of benzol. In the cases of water and benzol the bubble radii corresponding to the maximum values of the thermodynamic parameters attained inside the bubble are respectively 11 and 24 $\mu$m, which is significantly less than the similar radius (39 $\mu$m) in the case of acetone. The maximum velocities of collapse of the bubbles in acetone and benzol are approximately the same (about 600 m/s), whereas in the case of water it is much larger (3300 m/s).

Figure 2. Radial distributions of the temperature (a) and density (b) in the cavitation bubble (at $r \geq 0.25$ $\mu$m) and the surrounding liquid in the cases of: acetone at $p_0 = 15$ bar (curves 1), benzol at $p_0 = 4$ bar (curves 2) and water at $p_0 = 100$ bar (curves 3) at the moment of extreme compression of the medium in the bubble. The circles indicate the values of the parameters on the bubble surface.
Figure 2 shows the spatial distributions of the temperature and density at the moment of reaching the maximum values of the thermodynamic parameters in the bubbles at the pressure of acetone \( p_0 = 15 \) bar, benzol \( p_0 = 4 \) bar and water \( p_0 = 100 \) bar. In all the three cases, the maximum values are reached when the shock waves are focused in the central region of the bubble. The case of the bubble collapse in water differs significantly from the others by that in the case of water the converging shock wave turns out to be initially very weak. After focusing at the bubble center and reflection from it, it transforms into a divergent one, which then reaches the bubble surface. As a result of their interaction, two waves appear: a shock wave converging toward the bubble center and a divergent compression wave propagating in the liquid. At the moment of focusing of this second convergent shock wave in the central region of the bubble, the thermodynamic parameters reach their maximum values. In contrast, during the collapse of the bubbles in acetone and benzol, the initially-arising convergent shock wave is sufficiently intense, so that its focusing in the central region of the bubble leads to the attainment of the maximum values of the thermodynamic parameters.

One can see in Figure 2 that in the case of water at \( p_0 = 100 \) bar, the temperature in the central region of the bubble is noticeably lower than in the cases of acetone at \( p_0 = 15 \) bar and benzol at \( p_0 = 4 \) bar. This is explained by the fact that, in comparison with water, acetone and, especially, benzol are much more suitable for production of convergent shock waves in collapsing cavitation bubbles. For example, a quite intense shock waves arise in the cases of acetone and benzol, starting from \( p_0 \approx 3-4 \) and 0.5 bar, respectively. In contrast, in the case of water, an increase of \( p_0 \) up to 40-50 bar leads to only an increase of the intensity of the convergent isentropic (shockless) compression wave arising in the bubble. No shock waves appear in this case. As a result, in the case of water, a substantially different density variation takes place. For example, with increasing \( p_0 \) to 100 bar the water vapor density maximum reaches values of the order of 1450 kg/m\(^3\). In contrast, in the cases of acetone and benzol, due to the fact that the density increase on the shock wave is limited, the acetone and benzol vapor density maxima reach values of 940 kg/m\(^3\) and 1100 kg/m\(^3\), respectively. Moreover, these maxima are nearly constant in the range \( 3 < p_0 \leq 50 \) bar in the case of acetone and in the range \( 0.5 < p_0 \leq 50 \) bar in the case of benzol.

References

[1] Taleyarkhan R P, West C D, Cho J S, Lahey R T (Jr), Nigmatulin R I and Block R C 2002 Science 295 1868
[2] Nigmatulin R I, Lahey R T (Jr), Taleyarkhan R P, West C D and Block R C 2014 Physics-Uspekhi 57 (9) 947
[3] Shaw S J and Spelt P D M 2010 J. Fluid Mech. 646 363
[4] Nigmatulin R I, Akhatov I Sh, Topolnikov A S, Bolotnova R Kh, Vakhitova N K, Lahey R T (Jr) and Taleyarkhan R P 2005 Phys. Fluids 17 107106
[5] Nigmatulin R I, Aganin A A, Toporkov D Yu and Ilgamov M A 2014 Dokl. Phys. 59 431
[6] Nigmatulin R I 1990 Dynamics of Multiphase Media Vol. 1, 2. ( Hemisphere, New York)
[7] Nigmatulin R I and Bolotnova R Kh 2007 Dokl. Phys. 52 (8) 442
[8] Nigmatulin R I and Bolotnova R Kh 2011 High Temp. 49 (2) 303
[9] Nigmatulin R I and Bolotnova R Kh 2017 High Temp. 55 (2) 199