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Study on the spatial distribution of the liquid temperature near a cavitation bubble wall

Yang Shen [a], Kyuichi Yasui [b], Zhicheng Sun [a], Bin Mei [a], Meiyan You [a], Tong Zhu [a,*]

[a] School of Mechanical Engineering and Automation, Northeastern University, 3-11, Wenhua Road, Heping District, Shenyang 110004, China
[b] National Institute of Advanced Industrial Science and Technology (AIST), 2266-98 Anagahora, Shimoshidami, Moriyama-ku, Nagoya 463-8560, Japan

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ABSTRACT

A simple new model of the spatial distribution of the liquid temperature near a cavitation bubble wall (T_{li}) is employed to numerically calculate T_{li}. The result shows that T_{li} is almost same with the ambient liquid temperature (T_0) during the bubble oscillations except at strong collapse. At strong collapse, T_{li} can increase to about 1510 K, the same order of magnitude with that of the maximum temperature inside the bubble, which means that the chemical reactions occur not only in gas-phase inside the collapsing bubble but also in liquid-phase just outside the collapsing bubble. Four factors (ultrasonic vibration amplitude, ultrasonic frequency, the surface tension and the viscosity) are considered to study their effects for the thin liquid layer. The results show that for the thin layer, the thickness and the temperature increase as the ultrasonic vibration amplitude rise; conversely, the thickness and the temperature decrease with the increase of the ultrasonic frequency, the surface tension or the viscosity.

1. Introduction

A gas bubble undergoes wildly nonlinear oscillations: the creation, growth, contraction, collapse and rebound, when it is trapped in a fluid by a sufficiently intense acoustic field. This phenomenon under an ultrasonic field is known as acoustic cavitation [1]. High temperature of thousands of degrees and high pressure of hundreds or even thousands of atmosphere are generated inside the bubble for a short time at strong quasi-adiabatic collapse of the acoustic cavitation bubble. Under this extreme temperature condition, chemical reactions occur to generate highly reactive radicals within the collapsing bubble.

Recently, some researchers suggest that chemical reactions occur not only in gas-phase inside the bubble but in liquid-phase just outside the bubble. In 1985, Suslick found that the gas-phase reaction zone effective temperature is 5200 ± 650 K, and the liquid-phase – a thin liquid layer immediately surrounding the collapsing bubble – effective temperature is about 1900 K at strong collapse [2,3]. The latent heat of the intense vapor condensation, however, is completely neglected in their paper. It will be taken into account in this present study.

In 1996, Yasui [4–6] constructed a model of the spatial distribution of the liquid temperature satisfying some boundary conditions to calculate the temperature profile. However, one of boundary conditions was $T_l(r \to \infty) = T_0$ which was not accurate. In the present study, this condition is modified to $T_l(r \to R + \delta) = T_0$, R is the bubble radius and δ is the thickness of the thin liquid layer. What's more, in the present model, there are some differences from the model constructed by Yasui. The details will be described in II.

2. Model

A schematic diagram depicting the temperature profile both inside and outside the bubble is illustrated in Fig. 1. In this model, some assumptions are made as followed: (1) the bubble is spherically symmetric. (2) The effects of gravity and gas diffusion are negligible. (3) The pressure inside the bubble is spatially uniform. (4) The temperature inside the bubble (T) is spatially uniform except for the thin boundary layer ($n\lambda$), as shown in Fig. 1. (5) Some physical properties of liquid are constant, such as, the density ρ, the sound speed in the liquid c_0. (6) The amount of gas (air) inside a bubble is constant.

According to the assumption (4), the thickness of the thin boundary layer is $n\lambda$, where n is a constant and λ is the mean free path of a gas molecule. Schematic diagram depicting the temperature profile is shown in Fig. 1.

* Corresponding author.
E-mail address: tongzhu@mail.neu.edu.cn (T. Zhu).

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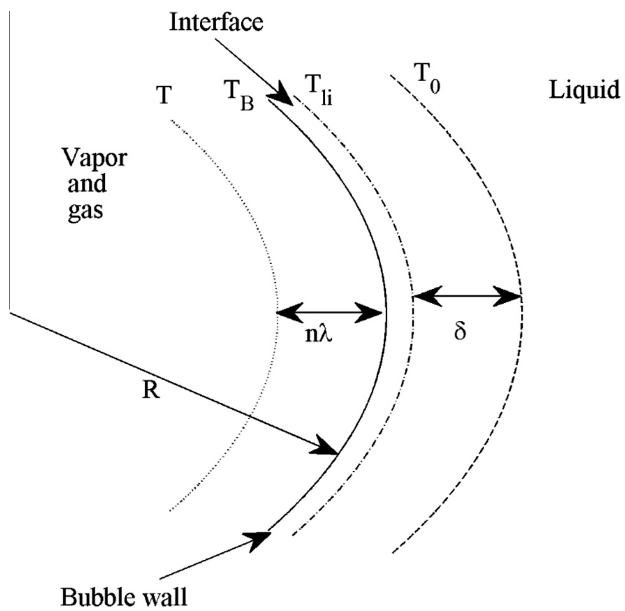

Fig. 1. Schematic diagram depicting the temperature profile.

The temperature distribution (T_m) inside the bubble can be assumed to be

$$\begin{aligned} &T_m = T, && 0 \leqslant r \leqslant R - n\lambda \\ &T_m = T_B - \tfrac{\partial T_m}{\partial r}\big|_{r=R}(r-R), && R - n\lambda \leqslant r \leqslant R, \end{aligned} \tag{1}$$

where T_B is the gas temperature at bubble wall. With regard to the constant n, there are a lot of researches. Finch assumed that n is about three. Knudsen said n is 0.95 and Langmuir said n is 1.2 [7]. Yasui said that n should be between 3 and 7.

As a well-known result of the kinetic theory of gas, temperature jump (ΔT) exists at the bubble wall [4–6]:

$$T_B = T_{li} + \Delta T \tag{2}$$

where T_{li} is the liquid temperature at the bubble wall, the temperature jump (ΔT):

$$\Delta T = -\frac{s}{2k}\sqrt{\frac{\pi m'}{kT_B}}\frac{2 - a'\alpha_e}{\alpha_e}\kappa\frac{T_B - T}{n} \tag{3}$$

where k is the Boltzmann constant, m' is the mean mass of a molecule, a' is a constant, κ is the thermal conductivity of the gas, s is the cross section of a molecule in the bubble.

Under the above assumptions, Eq. (4) is employed to depict the bubble radius (R), in which effects of evaporation and condensation of water vapor and that of thermal conduction and that of the compressibility of the liquid are taken into account [5]:

$$\begin{aligned} &\left(1 - \tfrac{\dot R}{c_0} + \tfrac{\dot m}{c_0\rho}\right)R\left(\ddot R - \tfrac{\dot m \dot R}{\rho}\right) + \tfrac{3}{2}\dot R^2\left(1 - \tfrac{\dot R}{3c_0} + \tfrac{\dot m}{3c_0\rho}\right) \\ &= \tfrac{1}{\rho}\left(1 + \tfrac{\dot R}{c_0}\right)\left[p_B - p_S\left(t + \tfrac{R}{c_0}\right) - p_0\right] \\ &\quad + \tfrac{\dot m}{\rho}\left(\dot R + \tfrac{\dot m}{2\rho} + \tfrac{\dot m \dot R}{2c_0\rho}\right) + \tfrac{R}{c_0\rho}\left(1 - \tfrac{\dot R}{c_0}\right)\tfrac{dp_B}{dt}, \end{aligned} \tag{4}$$

where $\cdot$ is the time derivative, $\dot m$ is the net rate of evaporation and condensation per unit area and unit time, p_0 is the liquid pressure at infinite, $p_s(t)$ is the actuating pressure. The difference from the equation in Refs. [4,5] is the additional factor $\left(1 - \dot R/c_0\right)$ on the time derivative of pressure at the bubble wall, which is very important for cutting down the collapse strength when the bubble radial acceleration is close to the sound speed in the liquid c_0 [8].

$P_B(t)$ is the liquid pressure on the external side of the bubble wall which is related to the pressure inside the bubble ($p_g(t)$) [9]:

$$p_B(t) = p_g(t) - \frac{2\sigma}{R} - \frac{4\mu}{R}\left(\dot R - \frac{\dot m}{\rho}\right) - \dot m^2\left(\frac{1}{\rho} - \frac{1}{\rho_g}\right) \tag{5}$$

where σ is the surface tension, μ is the liquid viscosity, and ρ_g is the density inside the bubble.

The rate of evaporation and condensation $\dot m$ is expressed as followed [9]:

$$\dot m = \frac{\alpha_M}{\sqrt{2\pi R_v}}\left(\frac{p_v^*}{\sqrt{T_{li}}} - \frac{\Gamma p_v}{\sqrt{T_B}}\right) \tag{6}$$

where α_M is the accommodation coefficient for evaporation or condensation, p_v is the actual vapor pressure, p_v^* is the saturated vapor pressure. R_v is the gas constant of the vapor. The correction factor Γ is expressed as followed:

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

where

$$\Omega = \frac{\dot m}{p_v}\left(\frac{R_v T}{2}\right)^{1/2}.$$

The pressure inside the bubble ($p_g(t)$) can be obtained from the van der Waals equation:

$$p_g(t) = \frac{R_g T}{v - b} - \frac{a}{v(v+b)} \tag{7}$$

where R_g is the gas constant, v is the molar volume, a and b are the van der Waals constants.

The gas temperature inside the bubble (T) can be expressed as followed:

$$T = \frac{N_A^2 EV + \left(n_{H_2O} + n_{air}\right)^2 a}{\left(n_{air}C_{v,air} + n_{H_2O}C_{v,H_2O}\right)N_A V} \tag{8}$$

where N_A is the Avogadro number, V is the bubble volume, E is the internal energy of the bubble, n is the amount of molecule, C_v is the heat capacity at constant volume, the suffix *air* and H_2O represent the air and water vapor respectively.

The change of the thermal energy of a bubble (ΔE) in time (Δt) is expressed by

$$\Delta E(t) = -p_g(t)\Delta V(t) + \frac{N_A}{M_{H_2O}}4\pi R^2 \dot m e_{H_2O}\Delta t + 4\pi R^2\kappa\frac{\partial T_m}{\partial r}\bigg|_{r=R}\Delta t \tag{9}$$

The amount of the water vapor molecule n_{H_2O} can be expressed:

$$n_{H_2O}(t + \Delta t) = n_{H_2O}(t) + \frac{N_A}{M_{H_2O}}4\pi R^2 \dot m \Delta t \tag{10}$$

where M_{H_2O} is the molar mass of the water vapor, e_{H_2O} is the energy carried by an evaporating or condensing vapor molecule, which is expressed by

$$e_{H_2O} = \frac{C_{v,H_2O}}{N_A}T_B. \tag{11}$$

The description of the variation of liquid temperature at the bubble wall is as followed. Eq. (12) can be obtained from continuity of energy flux at the bubble wall:

$$\kappa_l\frac{\partial T_l}{\partial r}\bigg|_{r=R} = \kappa\frac{\partial T_m}{\partial r}\bigg|_{r=R} + \dot m L + \frac{\dot m}{M_{H_2O}}C_{V,H_2O}\Delta T \tag{12}$$

where κ_l is the thermal conductivity of the liquid, $T_l(r)$ is the liquid temperature at radius r from the center of the bubble outside the bubble.