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Numerical analysis of the effects of radiation heat transfer and ionization energy loss on the cavitation Bubble's dynamics

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ABSTRACT

A numerical scheme for simulating the acoustic and hydrodynamic cavitation was developed. Bubble instantaneous radius was obtained using Gilmore equation which considered the compressibility of the liquid. A uniform temperature was assumed for the inside gas during the collapse. Radiation heat transfer inside the bubble and the heat conduction to the bubble was considered. The numerical code was validated with the experimental data and a good correspondence was observed. The dynamics of hydrofoil cavitation bubble were also investigated. It was concluded that the thermal radiation heat transfer rate strongly depended on the cavitation number, initial bubble radius and hydrofoil angle of attack.

1. Introduction

The bubble cavitation occurs when the nuclei in a fluid experience a pressure below the liquid vapor pressure. This small bubble grows to become cavitation bubble and if the cavitation bubble is swept into the regions of high pressure, it will collapse. At the collapse point, due to the high inertia of the liquid, the bubble eventually implodes with a high velocity and its interior reaches the temperatures and pressures which are large enough to produce a flash of light. Colloquially, this is often termed 'sonoluminescence'.

Single Bubble Sonoluminescence (SBSL) was first reported by Gaitan and Crum [1]. In their experimental investigation to produce SBSL, a single bubble was driven with an acoustic field which was intense enough to lead to the relatively large radius excursions. Yet, they were not so intense to lead to self-destructive instabilities. The procedure Gaitan followed was to levitate a bubble in an acoustic standing wave. As the acoustic-pressure amplitude slowly increased, a levitated gas bubble progressed through an evolution of states which led to SBSL.

Barber et al. [2,3] measured the width of the light pulse by studying the response of a single photomultiplier tube to the sonoluminescent flash. They demonstrated that both the light intensity and the bubble's oscillations amplitude depended on the forcing pressure amplitude, the concentration of the gas dissolved in the liquid and the temperature of the liquid.

For several years, experimental information accumulated about the properties of sonoluminescencing bubbles. Hiller et al. [4] measured the spectrum of sonoluminescencing air bubble in water and demonstrated that it increases toward the ultraviolet. They also found a sensitive dependence on the type of gas within the bubble; when the air dissolved in the liquid was replaced with pure nitrogen, the characteristically stable SBSL disappeared. However, by adding only 1% of argon (its approximate abundance in air), the sonoluminescence intensity returned to that of the air. Brenner et al. [5] suggested that the high temperatures generated by the bubble collapse dissociate the oxygen and the nitrogen and produce O and N radicals which react with the H and O radicals formed from the dissociation of water vapor. Rearrangement of the radicals leads to the formation of NO, OH and NH which eventually are dissolved in water to form HNO_2 and HNO_3 among other products. These reaction products pass into the surrounding liquid and are dissolved. This chemical process deprives the gas in the bubble of its reactive components. The only gases that can remain in the bubble are those which do not react with the liquid vapor at high temperatures, i.e. the rare gases.

Compared with the prevalence of acoustic systems, there are few studies on the cavitation luminescence generated by hydrodynamic flow. Van der Meulen [6] used a high speed flow tunnel with a NACA 16-022 hydrofoil set at various angles. He was un-

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able to detect any luminescence from undoped water; however, by adding xenon, the luminescence became detectable through the unaided eye. Leighton et al. [7] described a photon-counting study of the cavitation luminescence produced by the flow over a hydrofoil. The results showed that significant photon counts were recorded when the leading edge cavitation took place and the U-shaped vortices were shed from the main cavity. The photon count increased dramatically as the flow velocity increased or the cavitation index reduced.

Recently, Farhat et al. [8] studied the sonoluminescence of leading edge cavitation over a two-dimensional hydrofoil in a cavitation tunnel. They used an intensified charge coupled device video camera and a photomultiplier (PM) and analyzed the spatial properties of the emitted luminescence. The light emission was found to extend downstream from the region of cavity closure to the region where the traveling vortices collapsed.

Historically, the earliest analyses of the bubble growth and collapse of a vapor or gas bubble, or void, in a continuous liquid medium was that conducted by Besant [9] which was published in 1859. Using a different approach, the same result was also obtained by Lord Rayleigh [10]. The formalism was substantially refined and developed by Plesset [11], Prosperetti [12] and others over a span of several decades. In order to described the bubble dynamics, the Rayleigh–Plesset equation for the bubble wall motion and the polytropic relation for the gas behavior inside the bubble usually employed. In many practical bubble-collapse situations, it appears that local velocities reach an appreciable fraction of the velocity of sound in the liquid and the compressibility of the liquid cannot safely be neglected. Gilmore [13] was able to account for the compressibility of the liquid by using the Kirkwood and Bethe [14] approximation, which states that the waves are propagated with a velocity equal to the sum of the sound velocity and fluid velocity.

The polytropic approximation fails to account for the thermal damping effect due to the finite heat transfer through the bubble wall during the bubble evolution and collapses. In fact, the polytropic relation conjunction with the Rayleigh–Plesset equation provides a considerable overestimation about the peak pressure and an underestimation of the peak temperature for a gas bubble. Prosperetti [15] studied the polytropic model to calculate the proper polytropic index used for describing the thermal behavior inside the bubble. Matsumoto [16] performed detailed computations of a single gas/vapor bubble including the thermal diffusion in both the gas and liquid phases. He showed that heat transfer had a great influence on the bubble motion. Moshaii et al. [17] showed that the thermal conduction played an important role in radiation from a single cavitation bubble.

All previous studies about the acoustic and hydrodynamic cavitation have demonstrated that the temperature and pressure inside the bubble are high enough to produce a flash of light. Past numerical investigations on the spherical bubble have also shown that thermal conduction has an important effect on the bubble dynamic. Due to the light emission of cavitation bubbles, the thermal radiation and ionization of atoms could have some influences on the bubble behavior. In the present Letter, the roles of radiation heat transfer and ionization energy loss on the acoustic and hydrodynamic spherical cavitation bubble dynamic are discussed. The contents of the bubble are assumed to be non-condensable argon gas. An analogous equation for the energy balance is obtained from the first law of thermodynamics to compute the temperature. The temperature inside the bubble is assumed to be spatially uniform, even at the collapse of the bubble, expect for a thin boundary layer near the bubble wall. The pressure inside a bubble is assumed to be spatially uniform. In this simulation, the radiation heat transfer inside the bubble and the heat conduction to the bubble is taken into account. The effects of various parameters like driving pressure amplitude and frequency, initial bubble radius, cavitation number and hydrofoil angle of attack on the amount of thermal radiation and ionization energy loss are also examined.

2. Hydrodynamics of bubble motion

The Gilmore equation describes the behavior of a spherical bubble within a static, compressible and inviscid liquid, subjected to a sinusoidal wave. Gravity or other asymmetrical perturbing effects are ignored, the equation describing the evolution of bubble radius (R) as a function of time (t) is [13]:

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

where C and H are, respectively, the speed of sound and the liquid enthalpy at the interface between the gas-filed bubble and the liquid. The dots in Eq. (1) refer to the first and second order time derivation. The enthalpy and the speed of sound in the liquid at the interface are [13]:

$$H=\frac{1}{\rho_\infty}\left(\frac{A}{A-1}\right)\left(\frac{1}{P_0+B}\right)^{-1}$$
$$\times\left[(P+B)^{\frac{A-1}{A}}-(P_\infty-B)^{\frac{A-1}{A}}\right] \tag{2}$$

$$C^2=\frac{A}{\rho_\infty}(P_0-B)^{\frac{1}{A}}(P+B)^{\frac{A-1}{A}} \tag{3}$$

The empirical constant coefficients A and B are considered 6.25 and 3546 bar respectively. $\rho_\infty = 1000\ \mathrm{kg/m^3}$ is liquid density and $P_0 = 1.01325$ bar is the ambient pressure. P_∞ is the pressure at infinity and P is the pressure at the interface in the liquid which are expressed as:

$$P=P_g-\frac{2S}{R}+4\mu\frac{\dot{R}}{R} \tag{4}$$

where $S = 0.0725$ N/m and $\mu = 0.001\ \mathrm{N\,s/m^2}$ are surface tension and dynamic viscosity of liquid, respectively. P_g is the gas pressure inside the bubble, modeled by a van der Waals-type process equation:

$$P_g=\frac{N(1+\alpha_e)k_bT}{(4\pi/3)(R^3-(R_0/8.86)^3)} \tag{5}$$

where N is the number of atoms per unit mass of gas, R_0 is the ambient bubble radius (stationary radius under the normal temperature and pressure), $k_b = 1.338\times10^{-23}$ J/K is the Boltzman constant and $\alpha_e = n_e/n$ is the degree of ionization that can be achieved using Saha equation [18]:

$$\frac{\alpha_{m+1}\alpha_e}{\alpha_m}=2\frac{u_{m+1}}{u_m}\frac{1}{n}\left(\frac{2\pi m_e k_b T}{h^2}\right)^{3/2}\exp\left(-\frac{I_{m+1}}{k_bT}\right) \tag{6}$$

m_e is the electron mass, n is the number density of atoms, $h = 6.62\times10^{-34}$ J s is Planck constant and I_m is the successive ionization potential of atoms. For argon, $I_1 = 15.8$ eV is the energy required for removing the first electron from a neutral atom and $I_2 = 27.63$ eV is the energy required for removing an electron from a singly ionized atom, etc. $\alpha_m = n_m/n$ is the concentration of m-ions and $\alpha_e = n_e/n$ is the degree of ionization of the gas. The concentrations α_m are connected with the condition of conserving