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Influence of the nonequilibrium phase transition on the collapse of inertia nonspherical bubbles in a compressible liquid

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ABSTRACT

In this work, we investigate the shock wave–inertial vapor bubble interactions by taking the nonequilibrium phase transition at the interface, fluid compressibility, and axisymmetric bubble deformations including jet penetration into account. We use the level set method (Sussman et al., 1994) and the ghost fluid method (Fedkiw et al., 1999), which were improved so as to consider the nonequilibrium phase transition (Jinbo & Takahira, 2012). The numerical treatments for heat and mass fluxes through interfaces due to the phase transition are implemented, satisfying the conservation laws of mass, momentum, and energy at the interface and preventing the interface from becoming diffused. The influence of surface tension is also considered in the method. The improved method is applied to the shock–bubble interaction under the experimental conditions by Sankin et al. (2005). The pressure waveform of the incident shock wave is comprised of a leading compressive wave with a peak pressure of 39 MPa and a pulse duration of around 1 μs, followed by a trailing tensile wave of −8 MPa in peak pressure with a pulse duration of around 2 μs which is determined from the experiment. The liquid-jet formation and the generation of shock waves from the collapsing nonspherical bubble are simulated successfully by taking the nonequilibrium phase transition and surface tension into account. The validity of the simulation is shown by comparing the numerical results (e.g. the intensity of the shock wave generated by the bubble collapse and displacement of the bubble centroid) with those obtained from the experiments (Sankin et al., 2005; Klaseboer et al., 2007). We investigate the effects of the phase of bubble oscillations when the incident shock wave impinges on the spherically-shrinking bubble, on the shock wave radiated from the bubble collapse. It is also shown that when the nonequilibrium phase transition at the interface of nonspherically collapsing bubbles is considered, the minimum bubble radius and the maximum space-averaged pressure value inside the bubble reached during its collapse decreases and increases, respectively, compared with those in the case without the phase transition.

1. Introduction

A purely vaporous bubble may produce higher energy concentration and resulting stronger pressure waves in the liquid than those from the collapsing bubble filled with noncondensable gas [1]. Moreover, the jet velocity following the nonspherical bubble collapse induced by shock wave impingement reaches several km/s [2]. According to their researches, quite high pressure and temperature fields and quite fast liquid flow would be locally generated in cavitation flows where many vapor bubbles are generated with evaporation and some of them collapse; the shock waves generated from the collapsing bubbles interact with the surrounding vapor bubbles. Thus, the shock wave–inertial vapor bubble interaction is an important issue to clarify cavitation phenomena, which is attracting attention in various fields, such as industrial and medical applications. As is well known, cavitation causes material damages such as the erosion on ship propellers or pump structures [3]. In order to avoid such damage, it is necessary to evaluate the maximum jet velocity and local high pressure, relating to the pitting of materials. On the other hand, useful applications with cavitation are developed for decontamination and purification of water. It is also important to investigate the high temperature locally generated from an almost adiabatically compressed bubble and shear stresses generated by high speed water jets in order to optimize the efficiency of cleaning using cavitation. In addition, the collapse of cloud cavitation is effectively used in

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Nomenclature

C_p	constant in the stiffened gas equation of state, J kg^{-1} K^{-1}
E	internal energy per unit mass, J kg^{-1}
H	Heaviside function
L	latent heat per unit mass, J kg^{-1}
$\dot{m}$	mass flux, kg m^{-2} s^{-1}
$\boldsymbol{n}$	unit normal directed toward vapor from liquid
p	pressure, Pa
P_c	nominal pressure amplitude resulting from a bubble collapse introduced in Refs. [5,6], Pa
P_{c8}, P_{c10}	nominal pressure amplitudes measured at 1.1 mm downstream in the present computation when $R_0/R_{\max}$ = 0.8 and 1.0, Pa
p_s	the maximum pressure of the incident shock wave, Pa
p_0	saturation pressure at 296 K, Pa
$\boldsymbol{q}$	heat flux vector, J m^{-2} s^{-1}
r, z	radial and axial components in cylindrical coordinates
r_s	radial component in spherical coordinates
Δr, Δz, Δr_s	grid spacing
R_{eq}	equivalent bubble radius, m
$R_{\max}$	the maximum bubble radius, m
R_0, R'_0	initial bubble radius in the present axial symmetric computation, and modified initial bubble radius followed by the definition in Refs. [5,6], m
s	entropy, J K^{-1}
T	temperature, K
t	time, s
$\boldsymbol{t}$	unit tangential vector
t_0	characteristic time defined as $R_{\max}(\rho_s/\Delta p)^{1/2}$ where $\Delta p = p_s - p_0$, s
Δt	time step, s
ΔT	temperature jump at the interface due to phase transition, K
$\boldsymbol{u}$	velocity vector, m s^{-1}
$\boldsymbol{u}_R$	relative velocity vector defined in Eq. (8), m s^{-1}
V	bubble volume, m^3

Greek symbols

α_P	accommodation coefficient
γ	constant in the stiffened gas equation of state
ε	constant in the stiffened gas equation of state, J kg^{-1}
φ	level set function
κ	curvature, m^{-1}
Π	constant in the stiffened gas equation of state, Pa
ρ	density, kg m^{-3}
ρ_s	water density when the pressure is p_s, kg m^{-3}
σ	surface tension, N m^{-1}

Subscripts

v	vapor
l	liquid
i	interface

Superscripts

ext	extrapolated values from real fluids
ghost	values of ghost fluids
real	values of real fluids

the recent technique for fragmentation of kidney stones [4]. In the technique, the high-frequency pulse and the following low-frequency trailing pulse are used for creating cloud cavitation and for collapsing the cloud, respectively. Thus, the interaction between such a pressure wave and an inertial vapor bubble is also important for optimizing the efficiency of fragmentation.

Shock wave–inertial vapor bubble interaction experiments were conducted by Sankin et al. [5]. In their experiments, Nd:YAG laser was used to generate single vapor bubbles with reproducibility. The lithotripter shock wave hit on the bubble at the different phases of the bubble oscillation. Their experiment showed that the highest pressure waves were observed when the bubble was initially shrinking with 0.7 times larger radius than its maximum radius. Klaseboer et al. [6] also investigated the shock wave interaction with initially oscillating bubbles experimentally and numerically. They proposed a fast and stable numerical simulation method to simulate the shock wave–bubble interaction by using the boundary element method. However, it was not sufficient for their method to deal with shock wave–vapor bubble interactions because fluids were assumed to be incompressible and phase transition was not considered in their method.

In the present work, we numerically analyze the shock wave–inertial vapor bubble interactions by considering the nonequilibrium phase transition through interfaces, fluid compressibility, axisymmetric bubble deformations including jet penetration, and surface tension coupled with the nonspherical bubble collapse. In our previous work [7,8], we improved the level set method [9] and the ghost fluid method (GFM) [10] to capture boundary locations and to satisfy boundary conditions at vapor–liquid interfaces including the effects of nonequilibrium phase transition. In the present paper, we extend the method to deal with surface tension at the interface. The improved method is applied to shock–bubble interaction under the experimental conditions by Sankin et al. [5], and the numerical results are compared with the experimental ones [5,6]. The effects of the nonequilibrium phase transition and the phase of bubble oscillations, the moment of a shock impacting on the spherically-shrinking bubble, on bubble collapse are discussed.

2. Numerical method

In our previous works, we developed the method that can treat vapor–liquid interfaces with nonequilibrium phase transition, resolving the complicated interface structure and preventing the structure from being diffused [7,8]. The level set method [9] and the ghost fluid method (GFM) [10] were improved to deal with the discontinuity, with less numerical diffusion, across the interface due to the phase transition. The idea of adaptive zonal grids was implemented in the GFM to capture the fine interface structure of collapsing bubbles efficiently. In the present work, we extend the method to deal with the effects of surface tension including the variation of the bubble surface accompanied by phase transition.

2.1. Governing equations

The spherical or axisymmetric Euler equations are solved by considering the thermal diffusion. The diffusion obeys Fourier's law. The following stiffened gas equations of state [7,11] are used:

$$p = (\gamma - 1)\rho(E - \epsilon) - \gamma\Pi \tag{1}$$

$$E = \frac{C_p}{\gamma}T + \frac{\Pi}{\rho} + \epsilon \tag{2}$$

where ρ is the density, p the pressure, E the internal energy per unit mass, and T the temperature. γ, Π, ε, and C_p are the parameters used