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Investigation of cavitation bubble collapse near rigid boundary by lattice Boltzmann method*

Ming-lei SHAN (单鸣雷), Chang-ping ZHU (朱昌平), Xi ZHOU (周曦), Cheng YIN (殷澄), Qing-bang HAN (韩庆邦)
College of Internet of Things Engineering and Jiangsu Key Laboratory of Power Transmission and Distribution Equipment Technology, Hohai University, Changzhou 213022, China, E-mail: shanming2003@126.com

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Abstract: The dynamics of the bubble collapse near a rigid boundary is a fundamental issue for the bubble collapse application and prevention. In this paper, the bubble collapse is modeled by adopting the lattice Boltzmann method (LBM) and is verified, and then the dynamic characteristics of the collapsing bubble with the second collapse is investigated. The widely used Shan-Chen model in the LBM multiphase community is modified by coupling with the Carnahan-Starling equation of state (C-S EOS) and the exact difference method (EDM) for the forcing term treatment. The simulation results of the bubble profile evolution by the LBM are in excellent agreements with the theoretical and experimental results. From the two-dimensional pressure field evolution, the dynamic characteristics of the different parts during the bubble collapse stage are studied. The role of the second collapse in the rigid boundary damage is discussed, and the impeding effect between two collapses is demonstrated.

Key words: cavitation mechanics, lattice Boltzmann method, bubble collapse, rigid boundary

Introduction

The bubble collapse near a rigid boundary may lead to a serious material damage owing to the resulted high velocities, pressures, temperature, but on the other hand, it could also be utilized in various important applications, such as for environmental protection, high-intensity ultrasonic therapy and material surface cleaning[1]. However, as too many phenomena are involved, a theoretical model is difficult to establish, and under particular boundary conditions, the analytical solution is usually impossible. Therefore, the numerical simulation becomes a powerful way to gain an understanding. The conventional numerical simulation methods for the non-spherical cavitation bubble mainly include the finite volume method (FVM), the finite element method (FEM) and the boundary element method (BEM)[2]. In the numerical simulations based on the classical partial differential equation, the methods to track or capture the interfaces are required (such as the volume of fluid (VOF) method or the level set method (LSM)[3]). In addition, the Poisson equation needs to be solved to satisfy the continuity equation, which drastically reduces the computational efficiency[4].

During the past decades the lattice Boltzmann method (LBM) has emerged as a powerful tool for simulating multiphase flow problems[4-7]. As a powerful tool for the numerical simulations and investigations of the multiphase flows, the LBM has many advantages, including clear physical pictures, easy implementation of boundary conditions, and fully parallel algorithms[4]. Particularly, it is not required to track or capture the interfaces in the LBM models due to their mesoscopic nature. The Shan-Chen model, which is widely used in the LBM multiphase community due to its simplicity, high computational efficiency and high flexibility, has been introduced into the field of the bubble cavitation recently. The first attempt to validate the application of the Shan-Chen model in the LBM for cavitation problems was made by

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Biography: Ming-lei SHAN (1977-), Male,
Ph. D. Candidate, Lecturer

Sukop and Or[8]. Chen et al.[9] simulated the cavitating bubble growth using a modified Shan-Chen model with a large density ratio in both quiescent and shear flows, and the results were compared with the Rayleigh-Plesset equation. The acoustic cavitation of the spherical bubble was simulated recently by Zhou et al.[10] using the original Shan-Chen pseudopotential model, and the result was compared with the Keller equation. Mishra et al.[11] introduced a model of cavitation based on the Shan-Chen multiphase model that allows for coupling between the hydrodynamics of a collapsing cavity and the supported solute chemical species. However, the pressure field evolution in the bubble collapse stage near a rigid boundary has not been extensively investigated yet, in particular, when multiple collapses exist. In addition, due to the inherent parallelism, the LBM promises to be a powerful tool for the studies of the multi-bubbles collapse and even the cavitation field.

The evolutions of the bubble profile and the jet velocity were investigated by experiments with respect to the dynamics of the bubble collapse near rigid boundary[12-14]. As an intuitive clue to investigate the mechanism of the collapsing bubble, the pressure field evolution and the damage of the rigid boundary are more complex and diverse when multiple collapses exist. However, the direct measurement by the experimental method is difficult because all the intrusive measurements will disturb the original pressure field, and the non-intrusive methods cannot be applied unless the fluctuation of the pressure is large enough. In order to visualize the impulsive high pressure regions around the collapsing bubbles, Philipp[12] used the shadow graph method in a high-speed photograph. But the details of the pressure field cannot be obtained except by the emitted shock waves. In Ref.[15], the velocity field and the pressure distribution around the bubble in the dielectric fluid were studied numerically. By solving the Navier-Stokes equation, Liu[16] simulated the pressure distribution numerically outside a nonlinear resonance bubble in one dimension. However, the 2-D pressure distribution and the evolution of a collapsing bubble throughout the whole collapsing stage were not obtained. Since the pressure distribution can be directly obtained by solving the equation of state (EOS), the LBM is very effective to simulate the 2-D or 3-D pressure field and the evolution of a collapsing bubble near a rigid boundary.

In the present work, an approach of bubble collapse simulation is developed based on a modified Shan-Chen model to investigate the bubble collapse near a rigid boundary, especially to investigate the 2-D pressure filed evolution around a collapsing bubble associated with twice collapses. The modified Shan-Chen model is coupled with the Carnahan-Starling equation of state (C-S EOS) and the exact difference method (EDM) in the interaction forcing term treatment, to obtain a large density ratio liquid-vapor system while reducing the spurious currents and minimizing the thermodynamics inconsistency. In this work, the simulations by the LBM is verified through a comparison between the simulation results of the bubble profile evolution and the experimental results. Subsequently, the 2-D pressure field evolution around the collapsing bubble associated with twice collapses is investigated, and the role of the second collapse in the rigid boundary damage is discussed.

1. Numerical model

The LBM is a mesoscopic numerical simulation method based on statistical physics and can well simulate the Navier-Stokes equations at the macroscopic scale[4-6]. In the LBM, the motion of fluid is described by a set of particle distribution functions. The standard LBM with a force term based on Bhatnagar-Gross-Krook (BGK) collision term, called the LBGK, can be expressed as follows

$$f_\alpha(\boldsymbol{x}+c\boldsymbol{e}_\alpha\Delta t, t+\Delta t)-f_\alpha(x,t)=$$

$$-\frac{1}{\tau}[f_\alpha(\boldsymbol{x},t)-f_\alpha^{eq}(\boldsymbol{x},t)]+F_\alpha(\boldsymbol{x},t) \tag{1}$$

where f_α is the density distribution function at the lattice site $\boldsymbol{x}$ and the time t along each velocity direction α, f_α^{eq} denotes the equilibrium distribution function, $c=\Delta x/\Delta t$ is the lattice speed with Δx and Δt as the lattice spacing and the time step, respectively. The dimensionless relaxation time, τ, is related with the viscosity by $\tau=\nu/(\Delta t c_s^2+0.5)$ with $c_s=\sqrt{RT}$ as the lattice sound speed. The left-hand side of Eq.(1) stands for the streaming process whereas the right-hand side represents the collision process, which leads to the local equilibrium on a time scale τ.

The discrete velocity $\boldsymbol{e}_\alpha$ depends on the particular velocity model. For the D2Q9 (2-D nine velocity) model, $\boldsymbol{e}_\alpha$ is given by

$$\boldsymbol{e}_\alpha=0,\quad \alpha=0 \tag{2a}$$

$$\boldsymbol{e}_\alpha=\left(\cos\left[(\alpha-1)\frac{\pi}{2}\right],\sin\left[(\alpha-1)\frac{\pi}{2}\right]\right),\quad \alpha=1,2,3,4 \tag{2b}$$

$$\boldsymbol{e}_\alpha=\sqrt{2}\left(\cos\left[(\alpha-5)\frac{\pi}{2}+\frac{\pi}{4}\right],\sin\left[(\alpha-5)\frac{\pi}{2}+\frac{\pi}{4}\right]\right),$$

$$\alpha=5,6,7,8 \tag{2c}$$