Computers and Mathematics with Applications 61 (2011) 3577–3584

Contents lists available at ScienceDirect

Computers and Mathematics with Applications

journal homepage: www.elsevier.com/locate/camwa

Lattice Boltzmann simulation of cavitating bubble growth with large density ratio

Xiao-Peng Chen [a,*], Cheng-Wen Zhong [b], Xu-Long Yuan [c]

[a] School of Mechanics, Civil Engineering and Architecture, Northwestern Polytechnical University, Xi'an, Shaanxi, 710072, PR China
[b] School of Aeronautics, Northwestern Polytechnical University, Xi'an, Shaanxi, 710072, PR China
[c] School of Marine Technology, Northwestern Polytechnical University, Xi'an, Shaanxi, 710072, PR China

ARTICLE INFO

Article history:
Received 27 October 2009
Received in revised form 9 July 2010
Accepted 13 July 2010

Keywords:
Cavitation
Phase transition
Bubble dynamics
Lattice Boltzmann method
Equation of state
High density ratio

ABSTRACT

Natural cavitation is defined as the formation of vapor bubbles in a flow due to the pressure falling below the liquid's vapor pressure. The inception of the cavitation bubble is influenced by a lot of aspects, such as impurities, turbulence, liquid thermal properties, etc. In this paper, the exact difference method (EDM) and the Carnahan–Starling real-gas equation of state (EOS) are coupled in the Shan–Chen multiphase lattice Boltzmann model, which is validated as being suitable for simulating high liquid/vapor density ratio multiphase flows. The 2D cavitation "bubble" growth is simulated under a quiescent and shear flow in the inception stage. Besides yielding the large density ratio, the real-gas EOS also leads to apparently different compressibilities for liquid and vapor. The results agree with Rayleigh–Plesset predictions much better than those of a previous publication [X. Chen, Simulation of 2D cavitation bubble growth under shear flow by lattice Boltzmann model, Communications in Computational Physics 7 (2010) 212–223]. In the meantime, a comparison is conducted for single-bubble behavior under different shear rates, with reduced temperature $T/T_{critical} = 0.6891$ and relaxation time $\tau = 1.0$. The simulation results show that the cavitation bubble deformation is consistent with the bubble dynamics, $D \propto \mathrm{Ca}$, where D and Ca are the bubble deformation and the capillary number respectively. The shear rate hardly influences the bubble growth rate.
© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

Natural cavitation is defined as the phenomenon of the formation of vapor bubbles in a flow due to the pressure falling below the liquid's vapor pressure, which can cause degradation of fluid machinery performance [1,2] *and* drag reduction for high speed underwater vehicles [3]. In the past few decades, numerous efforts have contributed to the study of cavitation bubble inception [4,5], which can be treated as the initial condition for the bubble evolution. However, study shows that the cavitation inception is very complex. It is influenced by the number and qualities of the nuclei in the liquids, the flow structure, thermodynamic parameters, etc. Different inception forms were found, including the bubble band, bubble ring, traveling bubble, traveling patch, fixed patch, and developed attached cavitation [4].

In addition to the experimental and scaling analysis, numerical simulation is conducted widely as a powerful tool for cavitation study. Vortmann et al. [6] applied the volume of fluid method coupled with thermodynamic models to predict typical effects of cavitations. By the finite volume method, Chau et al. [7] studied the hydrodynamic characteristics of foils. Particular emphasis was placed by Kunz et al. [8] on solving two-phase Reynolds averaged Navier–Stokes equations

* Corresponding author.
E-mail addresses: xchen76@nwpu.edu.cn (X.-P. Chen), zhongcw@nwpu.edu.cn (C.-W. Zhong), yuanxulong@nwpu.edu.cn (X.-L. Yuan).

0898-1221/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.camwa.2010.07.018

(RANS), including the prediction strategy, flux evaluation, limiting strategies etc. Senocak and Shyy [9] applied a pressure–velocity–density coupling scheme to handle the large density ratio cavitating flow. In these classical partial differential equation based numerical simulations, two major obstacles must be overcome. The first one is establishing the numerical scheme. Because phase properties, such as density and viscosity, vary steeply across the interface, the numerical schemes should be designed carefully to prevent nonphysical oscillations. Limiting strategies, filtering techniques and/or sophisticated interface updating algorithms should be applied. Secondly, the phase transition model should be postulated correctly according to the thermodynamic fundamentals.

In recent decades, lattice Boltzmann methods (LBM) have emerged as attractive CFD methods, based on the mesoscale particle dynamics [10–12]. Some sophisticated flow phenomena, such as interfacial flow and reactive flow, are simulated successfully by the particle method, where the particle motion is simply divided into "collision" and "stream" loops. Shan and Chen [13] postulated a long range interaction, by which the liquid phase transition and interfacial tension were simulated perfectly. Swift et al. [14] coupled the Cahn–Hilliard free energy formula with the LBM. Phase separation and two-phase flow modeling were validated as being feasible. The key issue of the two models is reproducing the non-ideal gas EOS. So far, multiphase LBM have been applied in many fields [15,16], and large density ratio models attract great attention. For instance, Yuan and Schaefer [17] compared different EOSs applied in the Chen–Shan model. Excellent performance of Carnahan–Starling EOSs is proved in multiphase flow simulations with the density ratio over 10^3. Kupershtokh et al. [18] recently improved the maximum ratio to be 10^7 by coupling a proper EOS with the Zhang–Chen approach [19]. The model is also applied in dielectric liquid discharge simulations [20].

On the other hand, there are a few LBM simulations with a phase transition. Zhang and Chen [19] simulated the thermodynamic multiphase flow with the liquid–vapor density ratio of 3. In 2005, Sukop and Or [21] validated the capability of the LBM to simulate the cavitation problems using the Shan–Chen model. 2D bubble evolution (growth or collapse) was reported. Chen [22] simulated the cavitating bubble growth with the LBM in both quiescent and shear flows, where the results are compared with the Rayleigh–Plesset equation. However, in the latter work, the density ratio of the two phases was limited.

In this paper, the Carnahan–Starling real-gas EOS is applied to obtain a high density ratio liquid–vapor system. *The goal of this paper is to demonstrate the feasibility of using the LBM in qualitative cavitation simulations, which can be regarded as a starting point for future work.*

With this model, we also intend to study the 2D cavitation bubble growth under shear flow during its inception stage, which is often lacking in traditional numerical simulations. The scientific definition of the inception is adopted in our work, which means initial rapid growth of vapor-filled and gas-filled bubbles as a consequence of hydrodynamic forces [4]. In the situation of shear flow, the results are compared with the quiescent case in order to analyze the shear flow influences.

The rest of the paper is organized as follows. In Section 2, the Shan–Chen multiphase LBM method coupled with the Carnahan–Starling equation of state is introduced briefly. The exact difference method (EDM) is applied in the forcing term treatment. The flow domain setup is described in this section as well. In Section 3, the parameter setting and bubble growth under quiescent and shear flow are analyzed, and are compared with Rayleigh–Plesset and bubble dynamic models respectively. Conclusions are drawn in Section 4.

2. Mathematical models and the computational domain

2.1. Lattice Boltzmann model

A crucial idea of the lattice Boltzmann model is that both the location and velocity of the particles are discretized (see Fig. 1). The typical LB equation is presented as

$$f_i(\mathbf{x}+\mathbf{e}_i\Delta t, t+\Delta t) - f_i(\mathbf{x}, t) = -\frac{1}{\tau}\cdot(f_i(\mathbf{x}, t) - f_i^{eq}(\mathbf{x}, t)) + \Delta f_i, \tag{1}$$

where f_i $(i = 0, 1, \ldots, b)$ denotes the particle velocity distribution function along the ith direction, f_i^{eq} the corresponding local equilibrium distribution satisfying the Maxwell distribution. $\mathbf{x}$, $\mathbf{e}_i$ are the lattice site coordinates and the particle velocities towards the nearest neighbor sites respectively. b is the number of the neighbors. The lattice Boltzmann equation implies two kinds of particle operations, streaming and collision. On the left hand side of Eq. (1), particles jump from the local site, $\mathbf{x}$, to its nearest neighbor sites, $\mathbf{x}+\mathbf{e}_i\Delta t$, in each time step, $\Delta t \equiv 1$. On the right hand side, the collision leads to loss or gain of the particles with velocity of $\mathbf{e}_i$. After collision, the velocity distribution will relax to an equilibrium distribution, f_i^{eq}. τ is the collision relaxation time. Δf_i is the body force term which will be discussed in the Section 2.2.

In this study, the D2Q9 model is applied, which is depicted in Fig. 1. The equilibrium velocity distribution reads

$$f_i^{eq}(x, t) = w_i\rho(x)\left[1 + 3\frac{\mathbf{e}_i\cdot u}{c^2} + \frac{9}{2}\frac{(\mathbf{e}_i\cdot u)^2}{c^4} - \frac{3}{2}\frac{u^2}{c^2}\right], \tag{2}$$

where the weights w_i are 4/9 for the rest particles $(i = 0)$, 1/9 for $i = 1, 2, 3, 4$, and 1/36 for $i = 5, 6, 7, 8$ (as in Fig. 1). $\mathbf{u}$, $\mathbf{c}$ are the macrovelocity and the lattice speed respectively. The corresponding macrovariables are defined as

$$\rho = \sum_{i=0}^{8} f_i \tag{3}$$

Download English Version:

https://daneshyari.com/en/article/472786

Download Persian Version:

https://daneshyari.com/article/472786

Daneshyari.com