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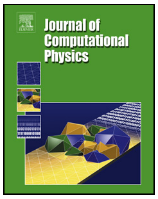

A mass-conserving axisymmetric multiphase lattice Boltzmann method and its application in simulation of bubble rising

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ABSTRACT

In many lattice Boltzmann studies about bubble rising, mass conservation is not satisfactory and the terminal bubble rising shape or velocity is not so consistent with experimental data as those obtained through other CFD techniques. In this paper, based on the multiphase model (He et al., 1999 [1]), a mass-conserving axisymmetric multiphase lattice Boltzmann model is developed. In the model, a mass correction step and an effective surface tension formula are introduced into the model. We demonstrate how the macroscopic axisymmetric Cahn–Hilliard equation and Navier–Stokes equation are recovered from the lattice Boltzmann equations through Chapman–Enskog expansion. The developed model is applied to simulate the bubble rising in viscous fluid. The mass correction step in our scheme significantly improves the bubble mass conservation. The surface tension calculation successfully predicts the terminal bubble shapes and reproduces the effect of initial bubble shape. The terminal bubble rising velocities are very consistent with experimental and numerical data in the literature. Qualitatively, the wakes behind the bubbles also agree well with experimental data. This model is useful for predicting the axisymmetric two-phase flows.

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1. Introduction

Lattice Boltzmann method (LBM) has been developed into a powerful tool to simulate multiphase flows [1–5]. The LBM has many advantages compared to the common computational fluid dynamics (CFD) method. First it is based on the molecular kinematic theory [6], it is able to recover macroscopic Navier–Stokes (NS) equation. Second, usually it involves an equation of state. Hence, it is not necessary to solve Poisson equation in the LBM, which may take much effort in the common CFD. Third it is an explicit scheme and easy to be parallelized.

There are several popular multiphase LBM models. The first one is the color-gradient model proposed by Gunstensen et al. [7], which is based on the Rothman–Keller (R–K) lattice gas model [8]. Usually, the color-gradient model is used to simulate binary fluid flows with identical densities [9].

The second type is the Shan–Chen (S–C) model [10]. The S–C single component multiphase model seems working well with high density ratios [11]. Recent study shows that the surface tension and the ratios of densities and viscosities also can be adjusted independently [12]. This finding may expand the application of the S–C model. However, our recent study [13] shows there is a defect in the forcing strategy on the S–C model. Through a correct forcing strategy, the S–C model

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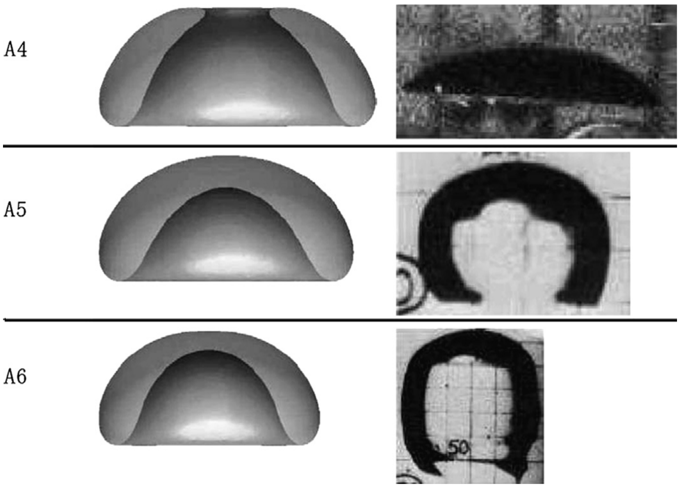

Fig. 1. Comparison of LBM result (Amaya-Bower and Lee [4], the left column) and experimental data [22] (the right column). The figure is copied from the Table 2 in Ref. [4]. The Eötvös number and Morton number of cases A4, A5, and A6 (upper, middle, and lower rows) are illustrated in Table 1.

can achieve the maximum density ratio about 300 for 2D simple cases about a liquid droplet immersed inside a vapor phase. Sankaranarayanan et al. [14] and Gupta and Kumar [15] used the S–C model to study the bubble rising. However, in both studies the parameters are limited to a very narrow range. Besides that, in the 2D study of Gupta and Kumar [15], the comparison between the LBM simulation and experimental data is poor in terms of bubble shape. Srivastava et al. [16] developed the Shan–Chen multiphase model for axisymmetric flows. However, no complex flow phenomena, e.g., bubble rising, were tested and the mass conservation issue is unknown.

The third type is the free energy (FE) LBM [17]. The original FE model [17] is known as not Galilean invariant for the viscous terms in the Navier–Stokes equation [6,17]. Inamuro et al. [18] achieved a high density ratio through improving Swift's free-energy model [17], but the model has to solve a Poisson equation, which decreased the simplicity of the LBM. Frank et al. using the LBM simulated the bubble rising [19]. However, only cases with very small Reynolds number were simulated and the corresponding terminal spherical and oblate ellipsoidal bubbles were observed [19]. Cheng et al. [20] using a free energy based model [21] studied 3D bubble–bubble interactions. However, because the model [21] they used is not able to include the density contrast effect, the result is only limited to density match cases.

Later He et al. [1] proposed an incompressible multiphase LBM, which is referred to as HCZ model. In the model, one set of distribution function is used to recover the incompressible condition and NS equations. The other set of distribution function is able to recover a macroscopic Cahn–Hilliard (CH) equation, which is usually used to track the interfaces between different phases. Recently, a series models [2,4,5] based on the model of He et al. [1] have been further developed to handle higher density-ratio multiphase flow, which is referred to as Lee–Lin models. These models seem to be able to simulate density ratio as high as 1000 [2,4]. For cases of a droplet splashing on a thin liquid film, the result looks good compared with some experiment data [2]. The parameter-study about bubble rising [4] is much wider than the other corresponding LBM studies.

However, in terms of terminal bubble shape, the result of Amaya-Bower and Lee [4] has large discrepancy with the experimental data. For example, Fig. 1 shows some comparison in Table 2 in Ref. [4]. For case A4, the shape of the bubble is spherical cap in the experiment [22]. However, the simulated result is a toroidal bubble, which is very different from the spherical cap bubble. They attributed the discrepancy to grid resolution [4]. But it is difficult to explain why the aspect ratio of the toroidal is very different from the experimental one. For the cases A5 and A6, basically the terminal bubble shapes are skirted with rounded lower edge. However, for cases with high *Re*, the rounded lower edge should become sharper (refer to Fig. 8). In a word, in terms of bubble shape, some simulation results with Lee–Lin model are not consistent with the experimental ones.

Although some other studies based on the HCZ model or Lee–Lin model to handle the axisymmetric two-phase flows are carried out [23–25], the validation cases are mainly focussed on very simple droplet flow problems, for example, droplet oscillation and droplet collision. In the following Section 3, we will show the poor comparison between the simulations using these models [24] and the experimental one. Beside, the issue of mass conservation is unknown [23–25]. Actually, in terms of mass conservation, the original HCZ model is not satisfactory [26]. Because these models (including the Lee–Lin model) are based on the HCZ model, the mass conservation property may be not so satisfactory for bubble rising [4].

Here based on the HCZ model and a technique to ensure mass conservation, an axisymmetric HCZ model is developed to simulate the bubble rising problem. The mass conservation is ensured through a mass correction step in the simulation. The revised surface tension calculation is shown more superior than the original surface tension calculation in the HCZ model. All typical bubble shapes in experiment [22] are observed and compared in detail. The effect of initial bubble shape in the literature is reproduced correctly using our model.

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