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Three-Dimensional Cavitation Bubble Simulations based on Lattice Boltzmann Model Coupled with Carnahan-Starling Equation of State

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Abstract. The Shan-Chen multiphase lattice Boltzmann model (LBM) coupled with Carnahan-Starling real-gas equation of state (C-S EOS) was proposed to simulate three-dimensional (3D) cavitation bubbles. Firstly, phase separation processes were predicted and the inter-phase large density ratio over 2×10^4 was captured successfully. The liquid-vapor density ratio at lower temperature is larger. Secondly, bubble surface tensions were computed and decreased with temperature increasing. Thirdly, the evolution of creation and condensation of cavitation bubbles were obtained. The effectiveness and reliability of present method were verified by energy barrier theory. The influences of temperature, pressure difference and critical bubble radius on cavitation bubbles were analyzed systematically. Only when the bubble radius is larger than the critical value will the cavitation occur, otherwise, cavitation bubbles will dissipate due to condensation. According to the analyses of radius change against time and the variation ratio of bubble radius, critical radius is larger under lower temperature and smaller pressure difference condition, thus bigger seed bubbles are needed to invoke cavitation. Under higher temperature and larger pressure difference, smaller seed bubbles can invoke cavitation and the expanding velocity of cavitation bubbles are faster. The cavitation bubble evolution including formation, developing and collapse was captured successfully under various pressure conditions.

AMS subject classifications: 65E05, 76B10, 76T10

Key words: Cavitation bubble, Carnahan-Starling equation of state, lattice Boltzmann model, Shan-Chen multiphase model, 3D numerical simulation.

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1 Introduction

Cavitation is defined as a rapid formation and collapse of vapor bubbles in a flow due to pressure falling below the liquid's vapor pressure [1]. The very fast and energy-focusing collapse of cavities [2] companied with cavitation always causes the adverse effects of noise, pressure pulsation, vibration and erosion in fluid machinery, propeller in the propulsion device, or the cascades of turbomachinery [3]. The dynamics of cavitation bubble is complex, including high non-linearity, mass transfer [4] and generating of shock waves [5]. Cavitation occurs either as "homogeneous" for the limit of the pure liquid tension, or as "heterogeneous" for nucleation caused by preexisting bubbles in a fluid [6]. The occurrence of cavitation depends on the vapor pressure and the size of the cavitation bubble nuclei in liquids. The relationship between the radius of nuclei and the cavitation was investigated by Or et al. [7].

In cavitation researches, the issues of gas-liquid two-phase flow have caught many attentions. The lattice Boltzmann method (LBM) has emerged as a powerful tool for simulating the behavior of complex multiphase fluid systems [8]. Based on the thermodynamic LBM with a full coupling of temperature, Zhang et al. [9] predicted the liquid-vapor boiling process, including liquid-vapor formation and coalescence. Yu et al. [10] carried out LBM simulations to obtain the bubble shape, bubble size, and formation mechanism in different mixer geometries of micro-channel sat different flow rates. A two-dimensional (2D) 9-velocity LBM using a single relaxation time (SRT) was developed for immiscible binary fluids with variable viscosities and density ratio [11]. Based on LBM, gas-liquid two-phase flows in a micro porous structure was numerically investigated for various capillary numbers at low Reynolds numbers [12]. Cristea et al. [13] studied the phase separation of a 2D van der Waals fluid subject to a gravitational force based on LBM combined a finite difference scheme. Diop et al. [14] employed 2D LBM to study multiple gas bubbles growing under buoyancy and electromagnetic forces in a quiescent incompressible fluid.

In recent years, many researchers have focused on Shan-Chen multiphase LBM (hereafter referred to as Shan-Chen model) [15, 16] to solve gas-liquid two-phase flow problems. Shan-Chen model was widely applied as a suitable tool for the immiscible two-phase flow in porous media [17]. Huang et al. [18] proposed a method to approximate the adhesion parameters in Shan-Chen model, which can provide the desired fluid-solid contact angle. Kimet al. [19] used D2Q9 Shan-Chen model to capture cavitation formation and its behavior. Qiu et al. [20] presented a multi-component and multiphase LBM combined with a passive-scalar approach and investigated natural convection in the case of a bubble with two different immiscible fluids in a 2D square cavity.

The non-local interactions between fluid particles at neighboring lattice sites were fulfilled by adding an additional forcing term to the velocity particle distributions in Shan-Chen model [15, 16]. Phase separation occurs by choosing an appropriate EOS (equation of state), which is controlled by the interaction potentials. A 2D cavitation "bubble" growth under shear flows was investigated using Shan-Chen model [21], and numerical