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Study of cavitation inception using multiphase lattice Boltzmann method with incorporating equations of state

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ABSTRACT: In the present study, a multiphase lattice Boltzmann method is implemented for simulation of the cavitation bubbles dynamics and characteristics of cavitating flows. The effect of employing various equations of state is investigated on the computing of interaction forces and the phase separation between the liquid and its vapor in the cavitating flows. Herein, the cubic equations of state of Shan-Chen and Carnahan-Starling and the non-cubic equation of state of Peng-Robinson are applied and the exact difference method is imposed to improve the numerical stability. The efficiency of the present method is examined by comparison of the results obtained for the homogeneous and heterogeneous cavitation with those reported in the literature. Then, the implemented multiphase lattice Boltzmann method is used for studying the inception and growth of the cavitation bubbles in the throat of a venturi. The effect of hydrophobicity and hydrophobicity of the nozzle wall on the cavitation dynamics is investigated and a detailed discussion is made for the results from the physical point of view. Evaluation of the present results shows that the multiphase lattice Boltzmann method with incorporating an appropriate equation of state has an excellent capability for prediction of the bubble dynamics and cavitating flow characteristics in applied geometries.

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1. Introduction

The cavitation phenomenon occurs due to a decrease in local pressure to a degree less than the saturated vapor pressure of a liquid under almost isotherm conditions, which results in the rapid formation of vapor bubbles in the liquid stream [1, 2]. With this definition, cavitation can occur in industrial applications related to aerospace engineering and mechanics, including hydraulic turbines, nozzles, impellers, turbopumps, spray generators, etc. For this reason, it is important to study the occurrence of this phenomenon in different experimental and numerical methods. Among the numerical methods, the Lattice Boltzmann Method (LMB) is known as a mesoscopic scheme and a powerful tool for studying multiphase flows. This method is a good alternative to conventional numerical methods based on the numerical solution of Navier-Stokes equations in simulating complex multiphase flows, microfluidics, and porous media.

In this paper, the numerical algorithm developed using the multiphase lattice Boltzmann method using the Shan-Chen model and applying different Equations of State (EOS) to simulate the growth and collapse of cavitation bubbles, as well as the dynamic study of cavitation phenomenon in a convergent-divergent nozzle. To maintain the stability of the numerical algorithm for capturing the interactions between the two phases of the liquid and its vapor, the exact difference method is used in the collision operator of the lattice Boltzmann method. The effects of hydrophilicity and hydrophobicity of the nozzle walls on the structure of cavitation flow have been studied and the results of these simulations have been studied from a physical and numerical point of view. Various methods and techniques for simulating multiphase flows have been proposed by the lattice Boltzmann method. These methods include the color gradient model [3], the pseudo-potential model [4], the free energy model [5], and the kinetic theory model [6]. Among these methods, the pseudo-potential method proposed by Shan and Chen [4] is very popular due to its simplicity in programming and facilitating the application of equations of state for physical simulation of fluids flows.

2. Governing Equations

The LBM equation can be defined in the discretized form as follows:

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

where f_α is the distribution function, $\boldsymbol{e}_\alpha$ is the particle velocity, τ is the relaxation time. The equilibrium distribution function f_α^{eq} is given by

$$f_\alpha^{eq}=\rho\omega_\alpha(1+3\frac{\boldsymbol{e}_\alpha \boldsymbol{u}}{c^2}+\frac{9}{2}\frac{(\boldsymbol{e}_\alpha \boldsymbol{u})^2}{c^4}-\frac{3}{2}\frac{|\boldsymbol{u}|^2}{c^2}) \tag{2}$$

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and the density ρ , and velocity $\boldsymbol{u}$ can be obtained by

$$\rho = \sum_{\alpha} f_{\alpha} \tag{3}$$

$$\boldsymbol{u} = \sum_{\alpha} f_{\alpha} \boldsymbol{e}_{\alpha} \tag{4}$$

To model the phase separation and interaction, the Shan-Chen model with the Shan-Chen (SC), Carnahan-Starling (CS) and Peng-Robinson (PR) equations of state are used [7,8].

3. Results and Discussions

The homogeneous cavitation phenomenon involves phase separation due to extreme local tensile stresses that occur only in pure liquids. To ensure the accuracy and precision of the developed algorithm in capturing the dynamics of phase separation during cavitation flows, the results of homogeneous cavitation in the present study have been compared with the results presented in [7]. Density values in these points show good compliance with the mentioned reference results.

The growth and collapse of the heterogeneous cavitation bubble using the multiphase lattice Boltzmann method are investigated by applying the CS equation. The results of the present solution are compared with the analytical solution of the Rayleigh-Plesset equation to ensure the accuracy and precision of the numerical solution (Fig. 1). A comparison of the results obtained from numerical and analytical solutions in this study shows the accuracy and good performance of the multiphase lattice Boltzmann method for simulating the dynamics of growth and destruction of bubbles in heterogeneous cavitation.

In the next section, the numerical algorithm developed using the lattice Boltzmann method and different equations of state is used to simulate the occurrence of the cavitation phenomenon in a convergent-divergent nozzle (Fig. 2). The effects of wettability of the walls on the structure of cavitation flow have been studied and the results of these simulations have been investigated from the physical and numerical point of view. The values recorded for the moment of the first phase separation and the occurrence of cavitation over time are reported. It is observed that as the dimensionless number of cavitation increases, the time

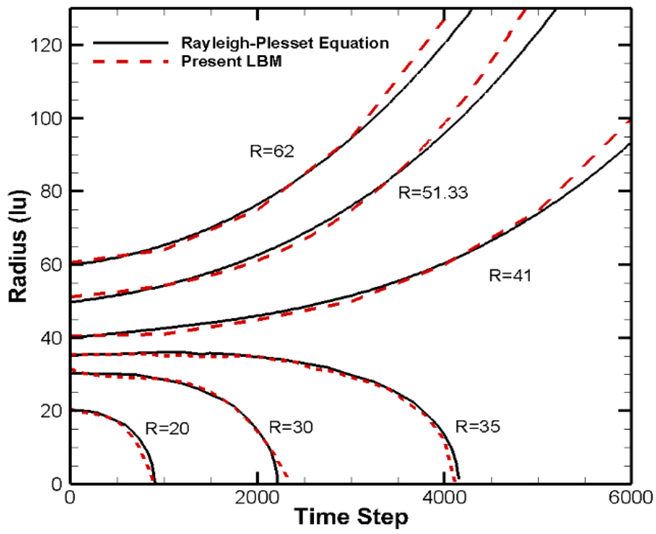

Fig. 1. Comparison of the results obtained by C-S EOS and revised Rayleigh-Plesset equation for the gradual change in the size of non-homogeneous cavitation bubbles at $\Delta P =$ -0.0595 and R_c = 37.2

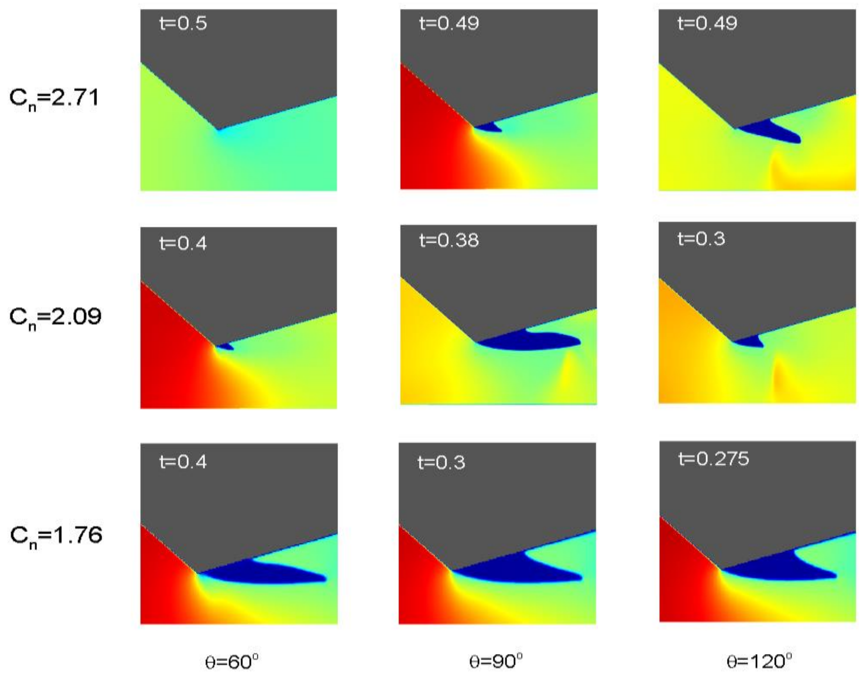

Fig. 2. Comparison of cavitation zone formed in convergent-divergent nozzle throat, obtained from present numerical solution with SC equation of state in cavitation numbers and different contact angles

required to separate the vapor phase from the liquid phase increases, and the process of cavitation bubble growth slows down. On the other hand, as the cavitation number decreases, the velocity of the flow passing through the nozzle throat increases and the local pressure drop in this area is faster. It is also observed that the onset of cavitation phenomenon and the growth of cavitation bubbles are affected by the effects of hydrophilicity and hydrophobicity of the nozzle surface, and an increase in the surface tends to absorb liquid phase (60º) even in low cavitation numbers leads to growth reduction. On the other hand, the passage of liquid flow over hydrophobic surfaces (180 º) provides the maximum growth conditions for cavitation bubbles.

4. Conclusions

In the present paper, the numerical study of the dynamics of cavitation phenomenon, growth, and collapse of cavitation bubbles and cavitation flow characteristics in a convergent-divergent nozzle were performed using multi-phase lattice Boltzmann method and by applying different equations of state. From the numerical point of view, the present results show that the PR and CS state equations have better accuracy and stability than the SC equation for studying the growth process of cavitation bubbles. Due to the instabilities created in the SC model and the pressure waves returned to the solution field, the simulation capability of the bubble growth process by this model is not available and is only suitable for capturing the moment of phase separation. From the physical point of view, the results of this study show that the hydrophilicity and hydrophobicity properties of surfaces affect the time of cavitation and phase separation according to the flow rate and contact angle of the surface. In a convergent-divergent nozzle with hydrophobic surfaces, there is a possibility of phase separation and cavitation growth even at high cavitation numbers. Studies in this paper show the accuracy and efficiency of the multiphase-phase lattice Boltzmann method used to simulate cavitation currents and the interaction between the two phases.

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