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Single Component Multiphase Lattice Boltzmann Method for Taylor/Bretherton Bubble Train Flow Simulations

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Abstract. In this study long bubble rising in a narrow channel was investigated using multiphase lattice Boltzmann method. The problem is known as a Bretherton or Taylor bubble flow [2] and is used here to verify the performance of the scheme proposed by [13]. The scheme is modified by incorporation of multiple relaxation time (MRT) collision scheme according to the original suggestion of the author. The purpose is to improve the stability of the method. The numerical simulation results show a good agreement with analytic solution provided by [2]. Moreover the convergence study demonstrates that the method achieves more than the first order of convergence. The paper investigates also the influence of simulation parameters on the interface resolution and shape.

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Key words: Bretherton problem, microchannel simulation, multiphase flow, lattice Boltzmann method, flow between plates.

Introduction

The lattice Boltzmann method (LBM) is a well established numerical approach, widely used for numerical simulations of single phase fluid flows. It is particularly popular in areas, where extremely complex geometry (e.g., for porous media flows) prevents from application of more traditional methods based on finite element or finite volume discretisations. LBM is also used successfully for multiphase flows, even though many unresolved issues appear in this case (the presence of spurious velocity field, lack of in/out flow boundary conditions, etc. [6,8,18,23]). In the current study, we investigate a modification of the multiphase lattice Boltzmann scheme reported by [13]. This scheme is used to simulate a long vapour bubble rising in a narrow channel filled with liquid.

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This flow configuration is also known as either Bretherton or Taylor bubble flow [2]. It can be considered as a well established test problem for modelling of multiphase flows. In this case partial analytical solutions as well as several experimental and numerical studies can be found in the literature [9, 14, 30]. For the case of small Capillary numbers Ca the ODE based solution was given by Bretherton [2]. The analytical correlations for wider range of Ca were given and extensively verified by [9]. For this flow the multiphase lattice Boltzmann method based on the Cahn-Hillard equation (two viscosities, one density, two immiscible liquids system) was used by [14] and good agreement with analytical correlations by [9] was demonstrated. Similar study was performed by [30] using the Shan-Chen [28] (liquid-vapour system) type model. Nevertheless, this study lacked a more detailed verification of the influence of the grid resolution and the model parameters on the results. Such quantitative study is essential for verification of the model intended to be used for flows without a-priori known solutions. Therefore, in the present paper, we aim at the quantitative verification of the chosen free-energy based scheme with modifications suggested by its original author [13].

The proposed scheme forms an extension of the multiphase lattice Boltzmann method and uses the concept of interaction-potential, which is the base of many multiphase lattice Boltzmann methods, including the widely used model by [28]. In this case the potential is computed directly from the non-ideal equation of state. The present study combines the successful approach of [13] with Multiple Relaxation Time (MRT) approach proposed in [5]. Other approaches aimed on improving stability, for example implicit iterations [26], are also possible and may be subject of further study. In the original paper [13], only simple flow cases were verified (flat and circular interfaces were verified by the Laplace law), as the work was focused more on parametric study of the model.

The original paper lacks also the inflow/outflow boundary conditions. As long as the phase interface is far from the boundary, the standard pressure/velocity boundary conditions can be used. Severe errors are introduced if the interface is touching such boundaries. To overcome this problem, periodic boundary conditions are used in the present paper. The flow is driven by gravity forces, so that the considered test case is similar to the one used in [14].

It should be noted that the majority of the diffuse interface methods generate spurious velocity field near the interface. This can be interpreted as a lack of balance between different terms of the interfacial forces computed on discrete stencils [3]. Many authors proposed different schemes for alleviation of this problem. This is studied in detail in [17]. The model proposed by [17] is based on rewriting the interfacial forces in terms of the chemical potential. This procedure allows to obtain a stable equilibrium with a zero velocity. Following this procedure together with implementation of proper compact stencil [17] the obtained scheme is free from the spurious velocity field. Although it is an interesting development, the scheme suffers from the lack of mass conservation [19], having also some unstable high-frequency (density or momentum) modes and is unable to cope with the standard boundary conditions.

Additionally all the schemes based on the chemical potential are strongly dissipative