Computers and Fluids 136 (2016) 228–246

Contents lists available at ScienceDirect

Computers and Fluids

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

Improving lattice Boltzmann simulation of moving particles in a viscous flow using local grid refinement

Songying Chen [a,*], Cheng Peng [b], Yihua Teng [c], Lian-Ping Wang [b,d], Kun Zhang [a]

[a] School of Mechanical Engineering, Key Laboratory of High Efficiency and Clean Mechanical Manufacture, Shandong University, Jinan 250062, P.R. China
[b] Department of Mechanical Engineering, 126 Spencer Laboratory, University of Delaware, Newark, Delaware 19716-3140, USA
[c] Department of Energy and Resource Engineering, Peking University, Beijing, P.R. China
[d] National Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan, P.R. China

ARTICLE INFO

Article history:
Received 4 December 2015
Revised 1 June 2016
Accepted 7 June 2016
Available online 9 June 2016

Keywords:
Lattice Boltzmann method
Local grid refinement
Moving particles
Force fluctuation
Viscous flow

ABSTRACT

Accurate simulations of moving particles in a viscous flow require an adequate grid resolution near the surface of a moving particle. Within the framework of the lattice Boltzmann approach, inadequate grid resolution could also lead to numerical instability and large fluctuations of the computed hydrodynamic force and torque. Here we explore the use of local grid refinement around a moving particle to improve the simulation results using the multiple-relaxation-time (MRT) lattice Boltzmann method (LBM). We first re-examine the necessary relationships, within MRT LBM, between the relaxation parameters and the distribution functions on the coarse and fine grids, in order to meet the physical requirements of the fluid hydrodynamics.We also propose additional relationships based on the Chapman–Enskog multi-scaling analysis. Several aspects of the implementation details are discussed, including the treatment of interface buffer nodes, the method to transfer information between the coarse domain and fine domain, and the computation of macroscopic variables including stress components. Our approach is then applied in two numerical tests to demonstrate that the local grid refinement can significantly improve the physical results with a high computational efficiency. We compare simulation results from three grid configurations: a uniformly coarse grid, a uniformly coarse grid with local refinement, and a uniformly fine grid. For the lid-driven cavity flow, the local refinement essentially yields a local flow field that is comparable to the use of uniformly fine grid, but with much less computational cost. In the Couette flow with a moving cylinder, the local refinement suppresses the level of force fluctuations. In these tests, the stress profiles are carefully examined to help illustrate the benefits of local grid refinement. We also confirm that the coarse-fine grid relationships between the non-equilibrium moments of energy square and energy fluxes do not affect the simulation results.

1. Introduction

As a highly efficient and capable mesoscopic computational method, the lattice Boltzmann method (LBM) [1–4] has been widely employed to solve a variety of fluid dynamics problems. The standard LBM describes the fluid as made up by imaginative elements which can stream along a uniform lattice grid and collide with one another only at lattice nodes. The method solves a quasi-linear collision-streaming equation for a set of distribution functions associated with discrete microscopic velocities. The macroscopic hydrodynamic variables such as pressure and velocity are obtained by taking the moments of the distribution functions.

One of the popular LBM schemes is based on the single relaxation time approach (*i.e.*, Bhatnagar-Gross-Krook collision operator [5]), which is known as the LBGK model. Another popular scheme is based on the multiple-relaxation-time (MRT) collision model [6,7]. The MRT collision is performed in the moment space with different moments relaxing at different rates. By decomposing the particle relaxation process into several independent relaxation processes, the MRT model has been shown to not only improve the computational stability but also the accuracy [6–8].

In order to obtain accurate macroscopic quantities, such as force and torque acting on a solid particle or the boundary, small grid spacing is needed near the solid particle or a boundary. Away from the boundary or fluid-solid interfaces, the flow may be more smoother so a coarser grid is adequate to resolve the flow. The

* Corresponding author. Fax: +86053188988791.
E-mail addresses: chensy66@sdu.edu.cn (S. Chen), cpengxpp@udel.edu (C. Peng), tengyihua99@gmail.com (Y. Teng), lwang@udel.edu (L.-P. Wang), 254509511@qq.com (K. Zhang).

http://dx.doi.org/10.1016/j.compfluid.2016.06.009

most efficient approach in terms of both memory and overall accuracy is thus to use a coarse grid for most of the bulk flow region, combined with a local grid refinement near a fluid-solid interface or wall boundary.

Within the LBGK model, local grid refinement has been considered for some time to simulate incompressible viscous flows with complex geometries. Filippova and Hanel [9] was among the first to consider patching certain regions with a fine grid in a domain mostly covered by a coarse grid, values of the distribution functions on the coarse grid which are coming from the fine patches are calculated on the nodes common to both grids. Filippova and Hanel [10] presented an accelerated implementation of grid refinement by using different particle speeds on the coarse and fine grids. A smaller time step size was used on the fine grid while the spatial or temporal accuracy was kept. Steady-state and time-dependent problems were studied and the CPU time per time step was reduced by about 50% relative to the results computed by the standard LBM. Yu et al. [11] proposed a multi-block technique with the LBGK model. Different mesh sizes are used for different blocks that do not overlap. Macro-variables such as mass, momentum, and stress components are assumed to be continuous across the block-block interface, and this condition determines the relaxation parameters in the fine domain. The cubic spline scheme was used for spatial interpolation and the three-point Lagrangian formula was used for temporal interpolation on all nodes at the fine block boundary after the distribution functions are transferred from the coarse domain to the fine domain. Yu and Girimaji [12] extended their approach to 3D using the LBGK model. Two 3D test cases, an isotropic decaying turbulence and a lid-driven cavity flow, were presented to show the improved computational efficiency. Farhat and Lee [13] was the first to suggest a migrating multi-block scheme to combine with the Gunstensen model for immiscible mixtures in 2D geometries. A fine grid block covered the entire fluid interface and was allowed to migrate by tracking the center of mass of the body. The upstream and downstream coarse blocks are separated by the fine block. After the fine domain shifted, extrapolation was used to compute the variables at all the newly created fine and coarse nodes as well as the old diminishing coarse nodes. Two benchmark simulations, namely, single phase flow around an asymmetrically placed cylinder in a channel and the motion of a neutrally buoyant drop in a parabolic flow, were simulated to validate their model.

A more general and efficient approach is adaptive grid refinement, where the computational grid is modified dynamically, with as many refinement levels as needed and each level can be of arbitrary shape. Typically, a physical criterion is applied to determine whether a local grid cell should be refined further or can be coarsened. An early example of adaptive grid refinement applied within LBGK is the study of Crouse et al. [14] in which they used a local divergence sensor to dynamically adjust the local grid spacing. Eitel-Amor et al. [15] introduced a cell-centered lattice structure to reconstruct the pre-collision distribution functions via spatial interpolation in LBGK model. They showed that, with hierarchically refined meshes, each cell can be refined or coarsened regardless of the refinement level of neighbor cells. Lagrava [16] introduced a decimation technique to guarantee the stability of the numerical scheme especially at high flow Reynolds number when the information is transferred from the coarse nodes to the fine nodes. Dietzel and Sommerfeld [17] calculated flow resistance over agglomerates with different morphology through LBGK local grid refinement. They slightly overlapped the coarse and fine regions and designed a method to communicate the distribution functions between the two grids at the interface. Premnath et al. [18] presented a staggered mesh arrangement in large-eddy simulation of a complex turbulent separated flow, using the MRT D3Q19 model. Subgrid scale model was employed in conjunction with the MRT to augment the relaxation time scales of hydrodynamic modes, in order to represent the effect of subgrid scale fluid motion.

One of the first attempts to implement local grid refinement within MRT was performed by Peng et al. [19] using the D2Q9 model, where they related the distribution functions and relaxation parameters in the two domains based on the continuity of macro-variables at the coarse-fine interface. The method to communicate distributions functions between the two domains was derived. They used lid-driven cavity flow, steady and unsteady flows past a circular cylinder, and flow over an airfoil to validate their approach. As will be shown later in this paper, their implementation was not fully consistent since they did not explicitly consider the relationship of energy relaxation parameters between the fine and coarse domains. Geller et al. [20,21] considered local grid refinement within MRT and they noted that only the two stress moments in the D2Q9 model between the two grid levels need to be properly rescaled, while other relaxation times can be made flexible. They considered pre-collision rescaling in 2D. The same group later extended local grid refinement to 3D LBM-MRT models under the same strategy in order to simulate multi-phase flow with deformable interfaces [22], or to perform large-eddy simulations of a turbulent flow around a sphere in a channel [23] or a turbulent jet flow [24]. The rescaling in these papers was also performed before collision. Grid refinements using MRT have also been considered in another recent study [25], without a careful consideration of the full flexibility in MRT to relate the distribution functions on fine and coarse grids.A shifting discontinuous-grid-block lattice Boltzmann method for moving boundary simulations using MRT model was recently reported by Arora et al. [26], where the fine domain moves with the moving body. Three simulation cases, namely, a cylinder in a shear flow, a single wing employing 'clap and fling' motion, and rigid plunging flat plate, are presented to show the accuracy of their model.

The above literature survey indicates that there are two general ways of communicating the distribution functions at the fine-coarse domain interface, namely, post-collision rescaling and pre-collision rescaling [9,19]. The connection of the rescaling process to the Chapman-Enskog expansion for the MRT model has not been fully explored. Our first objective is to re-examine the details of coupling the distribution functions and model parameters between the fine and course grids within the MRT framework. Our second objective is to test local grid refinement in moving particle simulation. In Section 2, a brief background description of the D2Q9 MRT model is provided. Details of local grid refinement implementation are discussed in Section 3, together with the development of relationships between the course and fine grid. Our implementation follows in spirit the previous studies of Tölke et al. [20,22]. Necessary interpolation details at the coarse-fine interface are presented in Section 4. In section 5, we then validate our methodology using 2D lid-driven cavity flow, and a Couette flow with a fixed or a moving cylinder. In the case of the moving cylinder, the refined region also moves with the cylinder. Test results demonstrate that local grid refinement indeed improves the accuracy in the moving particle simulation. We also compare CPU time and memory consumption when different grid arrangements (e.g., hybrid coarse / fine grid versus uniformly fine) are used. Key conclusions are summarized in Section 6.

2. The multiple-relaxation-time lattice Boltzmann method

In this section, we briefly introduce the multiple-relaxation-time (MRT) lattice Boltzmann method (LBM) in order to prepare for the discussions on the local grid refinement. The detailed description of MRT LBM can be found in [6,7].