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A Simplified Lattice Boltzmann Method for Turbulent Flow Simulation

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Abstract. To simulate the incompressible turbulent flows, two models, known as the simplified and highly stable lattice Boltzmann method (SHSLBM) and large eddy simulation (LES) model, are employed in this paper. The SHSLBM was developed for simulating incompressible viscous flows and showed great performance in numerical stability at high Reynolds numbers, which means that this model is capable of dealing with turbulent flows by adding the turbulence model. Therefore, the LES model is combined with SHSLBM. Inspired by the less amount of grids required for SHSLBM, a local grid refinement method is used at relatively high Reynolds numbers to improve computational efficiency. Several benchmark cases are simulated and the obtained numerical results are compared with the available results in literature, which show excellent agreement together with greater computational performance than other algorithms.

AMS subject classifications: 76M28, 76P99

Key words: SHSLBM, LES model, refined mesh, lid-driven cavity flow, cavity flow.

1 Introduction

Lattice Boltzmann method (LBM) [1–4] is a mesoscopic model that focuses on the density of fluid molecules and obtains the macroscopic flow information by studying the evo-

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lution of distribution functions. This method is between microcosmic view and macroscopic view, which has the advantage of fewer assumptions and not caring about the details of the molecular motion. In the past 40 years, this method has been developed rapidly in the field of fluid mechanics and so many outstanding scholars have made great contributions, including improving the collision models [5–10], adding turbulence or thermodynamic models [11, 12], completing the boundary condition [13] and so on. However, apart from the merits mentioned above, the LBM also suffers from a number of drawbacks. Firstly, the standard LBM can only work on the uniform mesh. The second one is that the standard LBM requires more virtual memories compared with the Navier-Stokes (N-S) solvers, which are used to store the distribution functions. Such storage requirement may lead to a heavy burden for large-scale problems. In addition, the boundary conditions for the macroscopic variables need to be transformed into the conditions for the distribution functions. Therefore, it is inconvenient to implement the physical boundary conditions, especially for the problems with complex boundary conditions.

Different from the conventional LBM, the simplified lattice Boltzmann method (SLBM), proposed by Chen et al. [14], no longer needs to capture the evolution of the distribution function. This method is developed from reconstructing the solutions of macroscopic governing equations, which are recovered from the lattice Boltzmann equation by using the Chapman-Enskog expansion analysis, and resolving the equations in the predictor-corrector scheme. The whole algorithm focuses on the equilibrium distribution functions, which is calculated based on the macroscopic variables. Even the non-equilibrium distribution function can simply be evaluated from the difference of two equilibrium distribution functions. Therefore, compared with the conventional LBM, the SLBM requires fewer virtual memories. In addition, it is more convenient to implement physical boundary conditions, which greatly overcomes the drawbacks of standard LBM. Additionally, in order to improve time-marching accuracy in SLBM while maintaining its merits, the unconditionally stable lattice Boltzmann method (USLBM) was presented by Chen et al. [15]. Later, Chen et al. [16] compared the USLBM with the conventional LBM by Neumann stability analysis, and it was indicated that the USLBM is much more stable than the conventional LBM at high Reynolds numbers. Thus, the USLBM was renamed as the simplified and highly stable LBM (SHSLBM).

On the other hand, although the LBM can be directly employed to simulate turbulent flows [17–19], the efficient turbulence simulations for LBM are still the incorporation of turbulence models in Reynolds-averaged Navier-Stokes (RANS) and large eddy simulation (LES) [20–23]. One of the most widely used LES turbulence model is the standard Smagorinsky model [24], which has been successfully combined with LBM for simulating different turbulent flows [25–27]. In order to extend the SHSLBM to handle the turbulent flows in this work, the LES turbulence model is also employed. Same as the previous work, the standard Smagorinsky model is selected due to its simplicity and capability of capturing the essential flow physics. Additionally, the local grid refinement technique [28] is also applied in the SHSLBM to improve the computational efficiency.