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Lattice Boltzmann Method for Simulating the Temperature Jump and Velocity Slip in Microchannels

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Abstract. The velocity slip and temperature jump in micro-Couette flow are investigated with the lattice Boltzmann method (LBM). A new slip boundary condition with the non-equilibrium extrapolation scheme is used in a thermal lattice Boltzmann model (TLBM) where double distribution functions are used to simulate the velocity and the temperature fields in order to capture the velocity slip and the temperature jump of the wall boundary. The simulated velocity and temperature profiles are in good agreement with the analytic results, which shows the suitability of the present model and the new boundary treatment for describing thermal microflows with viscous heat dissipation.

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Key words: Lattice Boltzmann, velocity slip, temperature jump.

1 Introduction

With the rapid development in Micro-electro-mechanical systems (MEMS), flow and heat transfer in micro devices have become an area that receives a significant attention over the last decade [1–3]. The mechanism of the microscopic flow and heat transfer is quite different from that of macroscopic counterparts because the characteristic length of the flow H is of comparable order of magnitude to the mean free path λ, and the inter-molecular interactions are manifested. The microscopic flows are usually characterized by a dimensionless parameter – the Knudsen number $Kn=\lambda/H$. Theoretically, when $Kn>0.01$,

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traditional hydrodynamic descriptions such as the Navier-Stokes equations (NSE) and the Fourier heat conduction equation are invalid and the solvers of the full Boltzmann equation [4, 5], the particle-based methods such as molecular dynamics [6], and the direct simulation Monte Carlo (DSMC) [7] are often used for numerical studies. However, the computational effort of this traditional methods suffers from the expensive computational cost and high statistical noise in simulating low-speed flows. Fortunately, the velocity slip and temperature jump in the microflow still could be captured in the slip-flow regime by NSE with proper slip boundary conditions.

Recently, the LBM has been considered as an efficient numerical tool for simulating fluid flows and transport phenomena based on kinetic equations and statistical physics. Because of its distinctive advantages over conventional numerical methods, the LBM has become an attractive method for micro-fluidic flows. Some numerical methods based on the gas kinetic theory have been proposed to study the gas flows at finite Knudsen numbers [8-15]. Nie et al. [8] used the halfway bounce-back rule for the slip velocity at the solid surface, but it was considered as a no-slip boundary condition by Succi [9] who introduced the specular bounce-back rule. In the same year, both the specular bounce-back rule and the extrapolation scheme were employed to generate the slip effect by Lim et al. [10]. It was concluded that the LBM is an efficient approach for simulation of microflow. Sofonea and Sekerka [13] studied the effect of various boundary conditions for two dimensional first-order upwind finite difference LBM in the microchannel. It is noticed that all the above works discuss mainly the isothermal microflows, while Sofonea and Sekerka [14] and Shu et al. [15] focused on the implementation of diffusion reflection boundary conditions for the TLBM. Two series relaxation time expressions are compared with the analytical velocity and temperature profile in [14]. However, an extra factor (1.15 is chosen in part VI in Ref. [14]) has to be added to obtain a better capture of the slip velocity. Shu et al. [15] analyze the kinetic boundary condition and get similar boundary conditions as that of Karniadakis and Beskok [3]. However, they ignore the viscous dissipation in their analysis. Moreover, for more complex geometry, the above boundary conditions may not be trivial. In Tian et al. [16], they use the classical Maxwell first-order slip boundary conditions. However, they have to deal with the viscous dissipation term in the simulation with complex space discretization. Therefore, one of the key points in the micro-fluidic system is about the appropriate slip boundary conditions in the LBM.

The purpose of present study is to propose a new slip boundary condition using the non-equilibrium extrapolation scheme proposed by Guo et al. [17] for LBM. For convenience, our discussion will refer to a recently introduced TLBM in two dimensions [18], which will be briefly reviewed in Section 2. The new slip boundary conditions and the relaxation time, as well as the definition of the mean free path and the Knudsen number, will be addressed in Section 3. Implementation of the non-equilibrium extrapolation scheme for the TLBM is described in Section 4. To test our new slip boundary conditions, two physical problems will be considered. The first one is the problem of heat transport between two parallel walls with the same constant temperatures in the micro-Couette flow. The second one is the micro-Couette flow between two parallel walls with different