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Application of a ghost fluid approach for a thermal lattice Boltzmann method

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ABSTRACT

In this paper, a ghost fluid (GF) method is utilized to propose a numerical approach to enhance the capability of thermal lattice Boltzmann method (TLBM) in dealing with complex geometries. A ghost fluid approach is imposed on a double-population thermal lattice Boltzmann method. A Cartesian grid handles the flow and the boundaries are imposed by a ghost fluid approach. The essence of this method is to decompose the unknown distribution functions into equilibrium and non-equilibrium parts at each ghost points. The major quantities are extrapolated from the image points to the corresponding ghost points to form the equilibrium parts. The non- equilibrium parts are then determined by using the bounce-back scheme. The method is relatively easy to apply, and second order accurate. There is no need to modify the original governing equations, and both Dirichlet and Neumann boundary conditions can be handled. The method is applied to Couette flow between two concentric circular cylinders, natural convection in a square cavity, natural convection in an annulus, and a forced convection in a lid-driven semi-circular cavity. The results obtained are generally in good agreement with that predicted by other theoretical and numerical efforts.

1. Introduction

The lattice Boltzmann method (LBM) [1–3] has been used in recent years as a viable alternative to conventional computational fluid dynamics (CFD). Unlike standard numerical methods, which are based on the discretization of macroscopic governing equations, the LBM is based on mesoscopic kinetic equations, which represent characteristics of flow due to the evolution of a single particle velocity distribution. The LBM is easy to implement, numerically stable, computationally efficient, highly accurate and straight forward for parallelization.

So far, many methods have been proposed to impose hydrodynamic boundary conditions for the LBM. The bounce-back approach [4], half-way bounce-back approach [5], hydrodynamic method [6], non-equilibrium bounce-back method [7], and the extrapolation scheme [8] are among the popular choices.

On the other hand, several thermal lattice Boltzmann methods have been proposed to satisfactorily simulate heat transfer problems. In general, current lattice Boltzmann methods for thermal flows can be classified into three categories: the multispeed model [9–11], the passive scalar model [12,13] and the double population model. The multispeed models suffer from intense numerical instability, and can be used for a narrow temperature range. In the multispeed approach, only the density distribution function is used, but the internal energy equation is derived using separate discrete velocities. In the passive-scalar model, an independent internal energy distribution function has been utilized to obtain the

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temperature field. This model has a better numerical stability compared with the multi-speed model but the viscous dissipation and compression work done by the pressure are neglected. The double population model introduced by He et al. [14], which is similar to the passive-scalar model, contains an independent internal energy distribution function which results a better numerical stability. In addition, the viscous dissipation term and the compression work done by pressure have been taken into account in this model. However, due to the contribution of a complicated gradient operator term in the thermal lattice Boltzmann equation (TLBE) the implementation of this technique is not easy. Consequently, several simplified models have been proposed in which the effects of pressure work and/or viscous dissipation in the energy equation have been neglected [15–17]. So far, several approaches have been proposed to implement thermal boundary conditions for the TLBE [18–20].

However, due to some limitations in the standard LBM (e.g. the requirement of using uniform orthogonal lattices and a constant time step), it is not so easy to implement boundary conditions for complex geometries. To alleviate such difficulties, several attempts have been made [21]. As the first study in this respect, Fillipova and Hänel [22] proposed an approach based on the bounce-back rule for imposing a no-slip curved boundary condition. Later, this method was improved by Mei et al. [23]. A non-equilibrium distribution extrapolation approach was presented by Guo et al. [24]. Chang et al. [25] introduced a boundary condition for the LBM to simulate flows within complex geometries. Verschaeve [26] developed a curved no-slip boundary condition for the LBM based on a reformation of the populations from the velocity, density and the strain rate.

On the other hand, the immersed boundary method (IBM) [27] has been utilized as another appropriate approach to handle fluid flows with complex geometries via the LBM [28–31]. In this approach, a local force is determined to enforce the effect of the wall on the fluid. In this aspect, Feng and Michaelides [28,29] successfully used the immersed boundary lattice Boltzmann method (IBLBM) to simulate particulate flows. Niu et al. [30] proposed a momentum-exchange-based IBLBM by using a multi-relaxation collision model where the forcing term was calculated through the implementation of the momentum exchange rule on boundary nodes. Wu and Shu [31] proposed an implicit velocity correction-based IBLBM which implicitly satisfies the no-slip boundary condition by considering an unknown velocity correction vector at each boundary points.

As another flexible approach, Tiwari and Vanka [32] used the ghost fluid method (GFM) to simulate the fluid flow with complex geometries. In this method, the density distribution function is decomposed into equilibrium and non- equilibrium parts and then the unknown values at the ghost points (e.g. velocity, density, and non- equilibrium parts) are determined by an extrapolation from the image points into the fluid field.

In general, the GFM has been introduced by Fedkiw et al. [33] to treat the multi-medium flows. The major appealing characteristics of the GFM are its easy implementation, its ease of extension to multi-dimensions and its preservation of a sharp interface without smearing. Recently, several studies have been made to develop a proper GFM to treat the fluid flow and/or heat transfer within complex geometries [34–36]. Mittal et al. [34] utilized the GFM to propose a versatile sharp interface method to handle complex three-dimensional bodies. Pan [35] developed a GFM to simulate heat transfer phenomenon for incompressible flow over bodies with complex geometries. Chaudhuri et al. [36] studied the complex shock-obstacle interactions using the GFM.

To the best of the author's knowledge, there are only a few proposed models in the open literature for handling both fluid flow and heat transfer phenomenon using the lattice Boltzmann model on complex geometries. The work of Huang et al. [37] may be considered as the first research in this respect. Their method is based on the idea of Guo et al. [24]. In this method, the distribution at a curved wall node has been decomposed into its equilibrium part and non- equilibrium part. The equilibrium part is determined using the values enforced by the boundary condition, and the non- equilibrium part is estimated by the first order extrapolation from the fluid nodes. Their results show a second order accuracy for the method. Jeong et al. [38] used feedback forcing scheme to impose the curve boundary condition for both energy and momentum fields, and simulated thermal flows around bluff bodies. However, this approach suffers from defects such as instability and arbitrariness in selecting the related parameters [14,39]. Furthermore, the implementation of this technique is further complicated using the complex double-population model [14]. Afterwards, Kang and Hassan [39] have utilized the coupling between the IBM and the TLBM to simulate thermal flows. They adopted the sharp interface scheme based on second-order bilinear and linear interpolations, and used two thermal LB models: a double-population model with a simplified thermal lattice Boltzmann equation and a hybrid model with an advection–diffusion equation for the temperature. Lin et al. [40] presented a boundary condition for the TLBM to simulate natural convection within complex shape solid objects.

In this paper, the ghost fluid method presented by Chaudhuri et al. [36] has been followed to develop a numerical approach termed as ghost fluid thermal lattice Boltzmann method (GFTLBM) to enhance the ability of TLBM in dealing with complex geometries. Our approach is generally based on interpolation-extrapolation methodology using ghost fluid method and without using the forcing concept (unlike direct forcing IBM). This method benefits from features such as generality, and second-order accuracy. The outline of the paper is as follows: In Section 2, the ghost fluid thermal lattice Boltzmann model is introduced. Section 2.1 describes the applied double population TLBM. In Section 2.2, the ghost fluid scheme to deal with complex geometries is addressed. Section 2.3 explains how to combine the ghost fluid method with the LBM and also discusses the presented hydrodynamic and thermal boundary conditions. To validate the method, various heat transfer problems have been simulated. These results are compared with those of analytical solutions and of other numerical approaches in Section 3. Finally, a brief conclusion is given in Section 4.