International Journal of Heat and Mass Transfer 121 (2018) 1099–1117

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

A thermal immersed boundary–lattice Boltzmann method for moving-boundary flows with Dirichlet and Neumann conditions

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ARTICLE INFO

Article history:
Received 15 September 2017
Received in revised form 8 January 2018
Accepted 8 January 2018

Keywords:
Immersed boundary method
Lattice Boltzmann method
Moving-boundary flow
Heat transfer
Dirichlet condition
Neumann condition

ABSTRACT

We construct a simple immersed boundary–lattice Boltzmann method for moving-boundary flows with heat transfer. On the basis of the immersed boundary–lattice Boltzmann method for calculating the fluid velocity and the pressure fields presented in the previous work by Suzuki and Inamuro (2011), the present method incorporates a lattice Boltzmann method for the temperature field combined with immersed boundary methods for satisfying thermal boundary conditions, i.e., the Dirichlet (iso-thermal) and Neumann (iso-heat-flux) conditions. We validate the present method through many benchmark problems including stationary and moving boundaries with iso-thermal and iso-heat-flux conditions, and we find that the present results have good agreement with other numerical results. Also, we investigate the internal heat effect through simulations of moving-boundary flows with heat transfer by using the present method. In addition, we apply the method to an interesting example of a moving-boundary flow with heat transfer, i.e., a two-dimensional thermal flow in a heated channel with moving cold particles, which is a simplified model of ice slurry flow.

1. Introduction

One of the important issues in computational fluid dynamics is to simulate moving-boundary flows efficiently and accurately. The simplest way is to approximate the boundary by staircase-like steps in a fixed Cartesian grid. In applying the approximation to moving-boundary flows, however, it is required to construct new staircase-like steps in each time step, and the procedure is complicated and time-consuming in spite of its low accuracy. Other ways are body-fitted or unstructured-grid methods in which the grid conforms to the boundary. These methods can express arbitrary boundaries accurately and have traditionally been used for moving-boundary flows. However, due to re-meshing procedures, the algorithms of the methods are generally complicated, and also the computation costs are expensive. Recently, the immersed boundary method (IBM), which was proposed by Peskin [1,2] in 1970s in order to simulate blood flows in the heart, has been reconsidered as an efficient method for simulating moving-boundary flows on a fixed Cartesian grid. In the IBM, it is assumed that a fluid is filled in the inside of a boundary as well as in the outside of the boundary, and then appropriate body force is applied near the boundary in order to enforce the no-slip condition on the boundary. The IBM is a simple approach to moving-boundary flows, although certain techniques are necessary to determine the body force applied near the boundary. Various approaches and applications using the IBM were reviewed by Mittal and Iaccarino [3].

The idea of the IBM has been applied to moving-boundary flows with heat transfer. In the IBMs for heat transfer (referred to as *thermal* IBMs), an appropriate heat source/sink term is applied near the boundary in order to enforce the thermal boundary conditions, which are classified into two types, i.e., the Dirichlet (iso-thermal) condition and the Neumann (iso-heat-flux) condition. Several thermal IBMs for the two types of boundary conditions have been proposed. Kim and Choi [4] proposed a thermal IBM for both Dirichlet and Neumann conditions by introducing a heat source/sink term on the body surface or inside the body based on the finite volume approach on a staggered grid together with a fractional step method, and applied the thermal IBM to convection phenomena around stationary circular cylinders. Pacheco et al. [5] also proposed a thermal IBM for both Dirichlet and Neumann conditions based on the finite volume approach on a non-staggered grid, and validated it extensively through many heat-transfer

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.01.033
0017-9310/

problems with two-dimensional stationary boundaries which do not coincide with the grid. Pan [6] proposed a thermal IBM for the Dirichlet condition using volume-of-body function on multigrid Cartesian meshes, and validated it through force-convection and natural-convection problems around a stationary circular cylinder. Zhang et al. [7] presented a thermal IBM for both Dirichlet and Neumann conditions with a simple algorithm based on a direct-forcing approach, and applied it to heat-transfer problems with flows over not only a stationary cylinder but also an oscillating cylinder. Feng and Michaelides [8] developed a simple numerical method to solve the thermal interaction between particles and fluid in particulate flows. This method utilizes a thermal IBM for the Dirichlet condition. They validated it extensively through many heat-transfer problems with both stationary and moving boundaries, and applied it to the sedimentation of 56 heated circular particles. Wang et al. [9] proposed a thermal IBM (referred to as the multi-direct heat source scheme) in which the heat source/sink term is iteratively determined to enforce the Dirichlet condition on the boundary more accurately, and validated it through simulations of natural convection between concentric cylinders and of flow past a stationary circular cylinder. In addition, it was applied to flow past a staggered tube bank with heat transfer. Ren et al. [10] presented an efficient thermal IBM (referred to as the heat flux correction scheme) for the Neumann condition, in which the heat source/sink term is determined by the difference between the desired heat flux and the one calculated from the temporary temperature field without regard to the boundary. Numerical experiments for heat-transfer problems with stationary cylinders were conducted to validate the capability and efficiency of this method.

On the other hand, the lattice Boltzmann method (LBM) has been developed into an alternative and promising numerical scheme for simulating viscous fluid flows in the Cartesian grid without solving the Poisson equation for pressure fields [11]. Since both of the LBM and the IBM are based on the Cartesian grid, the LBM combined with the IBM (so-called IB-LBM) is well-suited to simulations of moving-boundary flows. Recently, several IB-LBMs which incorporate a thermal IBM (referred to as thermal IB-LBMs) have been proposed for solving heat-transfer problems with flows around complex geometries and/or moving boundaries. Jeong et al. [12] proposed a thermal IB-LBM using an equilibrium internal energy density approach to simulate natural convections in a cavity with stationary circular and square cylinders. Kang and Hassan [13] combined the direct-forcing thermal IBM formulas with two types of LBMs, i.e., a hybrid model and a simplified double-population method, and validated them through two-dimensional convective heat-transfer problems with not only stationary but also moving boundaries. Zhang et al. [14] combined a thermal IB-LBM with the discrete element method to simulate particulate flows with heat transfer. Eshghinejadfard and Thévenin [15] extended a thermal IB-LBM to three-dimensional particulate flows with heat transfer. Wu et al. [16] proposed a thermal IB-LBM in which the heat source/sink term at the next time step is taken as unknowns and iteratively corrected, and not only validated it through some two-dimensional heat-transfer problems but also applied it to a three-dimensional sedimentation of a single particle. While the above thermal IB-LBMs are for only the Dirichlet conditions, Hu et al. [17] proposed a thermal IB-LBM for Dirichlet, Neumann, and Robin (weighted combination of iso-thermal and iso-heat-flux) conditions, and tested it by some natural and forced convective problems including moving-boundary flows. Wang et al. [18] proposed a thermal IB-LBM for thermal flows with the Neumann conditions on the basis of the lattice Boltzmann flux solver, and applied it to several benchmarks of natural, forced, and mixed convection problems around a stationary circular cylinder.

As shown in the above-mentioned researches on the development of the thermal IB-LBM and its applications, there is growing concern about the thermal IB-LBM to solve heat-transfer problems with flows around complex geometries and/or moving boundaries efficiently. However, more work is needed to prove its effectiveness in simulations of moving-boundary flows with heat transfer. Especially, there is little to validate the thermal IB-LBM for iso-heat-flux moving-boundary flows and to apply it to such problems.

The purposes of this study are to construct a simple thermal IB-LBM for solving heat-transfer problems with flows around moving boundaries efficiently, to validate it through many benchmark problems including stationary- and moving-boundary flows with the Dirichlet and Neumann conditions, and to apply it to an interesting example of a moving-boundary problem with heat transfer. In the present study, on the basis of the IB-LBM proposed by Suzuki and Inamuro [19] for calculating the fluid velocity and pressure fields, we construct a new thermal IB-LBM by combining a simple thermal LBM proposed by Inamuro et al. [20] and Yoshino and Inamuro [21] with two types of thermal IBMs, i.e., the multi-direct heat source scheme [9] and the heat flux correction scheme [10] for calculating the temperature field with the Dirichlet and Neumann conditions, respectively. It should be noted that the above two thermal IBMs have not been implemented in the framework of the LBM. The IB-LBM proposed by Suzuki and Inamuro [19] is a combination of the LBM and the multi-direct forcing scheme [22], which can enforce the no-slip condition accurately by determining the body force iteratively from the difference between the desired velocity and the flow velocity without regard to the boundary. The method has been extensively validated through many benchmark problems of moving-boundary flows in their work [19]. In addition, the method has been used for investigating the internal mass effect for the force and torque acting on the boundary, and it was revealed that the internal mass effect is very important in moving-boundary flows at high Reynolds numbers [19]. However, no one has investigated the importance of the internal mass effect for the rate of total heat transferred from the boundary to the surrounding fluid (referred to as the *internal heat effect*) in moving-boundary flows with heat transfer. In the present study, we investigate the internal heat effect in a similar way to the work by Suzuki and Inamuro [19] concerning the internal mass effect for the force and torque acting on the boundary.

The paper is organized as follows. In Section 2, we explain the formulation of the problem in the framework of the IBM. In Section 3, we describe the present numerical method. In Section 4, we validate the present numerical method through thermal flows around a circular cylinder with the Dirichlet and Neumann conditions, Taylor–Couette flows with heat transfer, the sedimentation of a cold circular cylinder in a long channel, natural convection in an annulus, and the heat convection with flow over an oscillating circular cylinder with the iso-heat-flux condition. In addition, we investigate the internal heat effect through simulations of a heated circular cylinder which oscillates translationally in a closed small box at a low temperature. In Section 5, we apply the present method to an interesting example of a moving-boundary flow with heat transfer, i.e., a two-dimensional thermal flow in a heated channel with moving cold particles, which is a simplified model of ice slurry flow [23]. We finally conclude in Section 6.

2. Formulation of the problem

We consider the system where a rigid body moves in an incompressible viscous fluid with heat transfer.

2.1. Thermal fluid flow with a moving body represented by the IBM

Let Ω_{all} be the entire domain of the system, $\Omega(t)$ be the closed domain inside the rigid body, and $\partial\Omega(t)$ be the surface of the body