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A Lattice Boltzmann Modeling Fluid-Structure Interaction Problems and Its Applications in Natural Convections in a Square Cavity with Particles Suspended Inside

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Abstract. Fluid-structure interaction (FSI) occurs in many situations in nature and industries. Traditional descriptions of this problem in computational fluid dynamics (CFD) are mostly at macroscopic level. In this paper, an alternative mesoscopic description, based on lattice Boltzmann method (LBM), is presented for the FSI problems. The FSI are viewed as the collective behaviors of neighboring fictitious particles of the LBM deviating from their equilibrium state when solid boundaries presented in flow. To illustrate the rationality of the present idea, a forced convection over a stationary heated circular cylinder and a circular cylinder with in-line oscillation in fluids are simulated at first and the results are validated by comparing with existing numerical and experimental data in the literatures. For applications, natural convections in a square cavity with maximum three circle particles suspended inside are then carried out and the mechanisms of heat transfer enhancement are investigated. It is found that, adding particles destabilizes the flows in a square cavity and enhances heat transfer.

AMS subject classifications: 74F10, 76M28, 80A20, 80M99

Key words: Lattice Boltzmann method, fluid-structure interaction, natural convection, heat transfer.

1 Introduction

Fluid-structure interaction (FSI) are ubiquitous in nature and engineering applications, such as falling leaves in the air, fish swimming in the water, wind turbine power generation and cyclone separator in nuclear industries [1–3]. Traditionally, the descriptions of

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these problems in computational fluid dynamics (CFD) are mostly at macroscopic level and can be categorized into three methods: Hooke's Law first used by Peskin [4], Direct forcing method proposed by Fadlun et al. [5] and Boundary condition-enforced immersed boundary method (IBM) proposed by Shu et al. [6]. In classic kinetics, the FSI is actually the results of molecules colliding with the structural surface. Therefore, the microscopic or mesoscopic description of the FSI would be much helpful for understanding these problems.

As an alternative computational technique of CFD, the lattice Boltzmann method (LBM) has been undergoing a rapid progress in the past decades [7]. The LBM is originated from LGA (Lattice gas automata) and it views the macroscopic fluid flows the collective behaviors of the mesoscopic fictitious particles evolving with streaming and collision processes in flow field. As the standard LBM adopts a Euler grid, it is natural to combine the IBM to simulate the FSI problems. In 2006, Niu et al. proposed a momentum exchanged-based Immersed Boundary (IB) LBM (MEIB-LBM) [8] and gave a mesoscopic description of the FSI problems with a first attempt. In the MEIB-LBM, the FSI force concept is still used in this method but it is calculated by the collection of the momentum difference of the fictitious LBM particles on the fluid-structural interface. The MEIB-LBM has been successfully applied to model the particle suspension problems in the fluids [8].

In this paper, a purely mesoscopic description of the FSI problems, a distribution function correction-based IB-LBM (DFCIB-LBM), is further presented for the sake of keeping the mesoscopic feature of the LBM. The idea comes from the concept of disturbance, and is thinking that the FSI interface gives a small disturbance to its neighboring fluid. In the lattice Boltzmann theory, this small disturbance can be described by the non-equilibrium distribution function of the LBM particle on the FSI interface. The implementation procedure of the present method for the FSI is divided into three steps. Firstly, we interpolate the density distribution functions at the Eulerian mesh points to the FSI interface represented by a set of Lagrangian points. Secondly, the non-equilibrium bounce back rule [9] is performed for the interpolated distribution functions on the interface to mimic the non-slip velocity boundary condition Finally, the obtained non-equilibrium density distribution functions at the Lagrangian points are spread back to the adjacent Euler mesh points to correct the local density distribution functions.

The rationality of the proposed DFCIB-LBM for the FSI problems is proven by the Chapman-Enskog theoretical analysis [10]. To demonstrate its numerical validity, a forced convection over a stationary heated circular cylinder with heat flux condition and a circular cylinder with in-line oscillation in fluid are simulated. The obtained results are compared with the previous numerical and experimental works [6, 11–17]. Moreover, with the present LBM, a systematic study of a natural convection with moving heated circle particles inside a square cavity is carried out to further demonstrate its capability of modeling the FSI problems.

The rest of this paper is organized as follows. In Section 2, the DFCIB-LBM for the FSI problems including thermal effect is introduced with the Chapman-Enskog analysis in Appendix A. The numerical validations of the present method are given in Section 3. In