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A ghost-cell based high-order immersed boundary method for inter-phase heat transfer simulation

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ABSTRACT

A ghost-cell based high-order immersed boundary method (IBM) is introduced to simulate heat transfer problems and compared with multi-heat source method which is widely recognized of second-order accuracy. It turns out that about 2/3 computational grid points can be saved by employing the higher-order method. In addition, the ghost-cell based method inherently treats the Dirichlet and Neumann type boundary conditions consistently. Benefiting from this convenience, the influence of different thermal boundary conditions on local Nusselt number over a stationary sphere particle is investigated. An increase in local Nusselt number all over the particle surface is detected for iso-heat-flux condition. At all Reynolds numbers under consideration, the surface-averaged Nusselt number of iso-heat-flux particle is about 16% higher than the isothermal particle, independent of the Reynolds number. At last, simulations of gas-to-particle cluster convective heat transfer are carried out to assess the capability of the method for dense particulate systems. Flow pattern shows the cluster behaves like an isolate particle with the same equivalent diameter, while statistics reveal that heat exchange between gas and particles has been blocked by the cluster.

1. Introduction

Heat transfer phenomenon takes place in many multiphase-flow involved natural and engineering processes, such as transport and sedimentation of pollutants like soot; evaporation and combustion of drops; and fluidization of solid fuels in reacting bed systems. The understanding of the characteristics of heat transfer process between gas and solid phases is of great importance in engineering.

Over the past decades, a lot of efforts have been devoted into the study of heat transfer in gas–solid flows. Many of them experimentally established empirical heat transfer coefficients which were proposed for design reference. But these empirical correlations only give an average description of the thermal system, no heat flux distribution or detail of thermal dynamics is provided. In order to get insight into the phenomenon of heat transfer, and furthermore to reveal the mechanism of heat transfer, particle resolved direct numerical simulation (PR-DNS) is an attractive methodology. In heat transfer problems, temperature distribution, flow pattern and their influence with each other are of fundamental importance, which can be extracted from elaborate and substantial data information provided by PR-DNS.

Dandy and Dwyer [1] used boundary-fitted coordinates direct numerical simulated a fixed, heated spherical particle in shear flow and obtained results on particle lift, drag, and heat transfer. Jia and Gogos [2] numerically studied steady-state natural convection over a sphere in a modified spherical coordinate. Bagchi et al. [3] studied the flow and heat transfer past a sphere in a uniform flow with direct numerical solution using an accurate and effective Fourier–Chebysev pseudospectral method for Reynolds numbers up to 500. They reported steady and axisymmetric flow when the Reynolds number is less than 210, steady and nonaxisymmetric flow without vortex shedding when the Reynolds number is between 210 and 270, and unsteady three-dimensional flow with vortex shedding when the Reynolds number is above 270.

When dealing with multi-particles systems, spherical coordinates encounter enormous difficulties. A series of methodology frameworks to handle problem with more than one particle and moving particles have been proposed. Haeri and Shrimpton [4] reviewed available methods based on the Navier–Stokes equations for simulation of particulate flows which fully resolve the particles. Immersed boundary method (IBM) is one of the methods which are designed to simulate movements of boundary with complex geometries.

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Since first proposed by Peskin [5], IBM continues to evolve and improve. The key issue to implement immersed boundary method is how to impose specific boundary condition on the immersed boundary (IB) which represents the interface between solid and fluid phase. Up to now, there are mainly two kinds of frames to reach this goal: one employs 'continuous forcing' (also called 'direct-forcing' scheme) wherein a forcing term is added to the continuous Navier–Stokes equations before they are discretized; the other employs discrete forcing where the forcing is either explicitly or implicitly (usually by the utilization of 'ghost-cell') applied to the discretized Navier–Stokes equations.

Goldstein et al. [6] proposed a feedback forcing scheme with two free parameters. Fadlun et al. [7] introduced a direct formulation of the force term to calculate the interaction force between immersed boundary and fluid. Uhlmann [8] applied the direct forcing with immersed boundary to study the particulate flows in multiphase system. Zhang and Zheng [9] proposed a scheme in which the direct forcing was consistently applied to the internal layer to avoid numerically thickening the boundary curve. Wang et al. [10] applied 'multi-direct forcing' scheme to iteratively reinforce the satisfaction of the no-slip boundary condition on the immersed surface. Breugem [11] proposed a correction for the excess in the effective particle diameter by a slight retraction of the IB points from the surface towards the interior of the particles with a fraction of the computational Eulerian grid spacing. Kempe and Frohlich [12] proved velocity error on the IB remained after the explicit forcing procedure in the original direct forcing scheme. On this basis, an expression of a potentially more accurate implicit forcing was given, but additional forcing loops were performed in actual simulation for cost reasons. Ren et al. [13] suggested estimating the boundary forces implicitly by the solution of an equation system.

Compared to abundant flow simulations had been performed by the direct-forcing IBM scheme, there were only a few computational results on heat transfer problems using the same method being published. Zhang et al. [14] extended their direct forcing scheme to study heat-transfer problems of flow over a circular cylinder; both Dirichlet and Neumann-type boundary conditions were implemented. Wang et al. [15] proposed a 'multi-direct heat source' scheme together with the 'multi-direct force' scheme to study flow past a staggered tube bank with heat transfer. Feng and Michaelides [16] implemented the well documented direct-forcing scheme and a modified treatment of particles motion to obtained numerical results with a group of 56 interacting circular particles that cool while settling. Deen et al. [17] proposed an IBM method does not require using any effective diameter to simulate dense random particle systems. Most recently, Tavassoli et al. [18] simulated non-isothermal flows through random static arrays of spheres by iteratively implementation of IB heat source term, whose procedure was very similar to the scheme proposed by Wang et al. [15].

The schemes listed above prove to be second order accuracy at best. And due to the application of regular delta function in these schemes, there is no indication of further accuracy improvement.

The other class of IBM also traces back to Fadlun et al. [7], in which the value at the first grid point outside the body is obtained by linearly interpolating the value at the second grid point and the velocity at the body surface. While in the ghost-cell based IBM, the boundary conditions are implicitly incorporated through the ghost cells. The ghost-cell frame overcomes the disadvantage direct-forcing scheme of distributing the boundary over a band of several grid points which smears out discontinuities across the boundary and keeps the boundary sharp, so it is classified into the category of 'sharp-interface' method.

Tseng and Ferziger [19] discussed ways to linear and quadratic reconstruction boundary by utilizing ghost cells. They also discussed the treatment of Dirichlet type, Neumann type and mixed Dirichlet and Neumann type boundary conditions. Berthelsen and Faltinsen [20] proposed a local one-dimensional ghost cell based IBM approach which smoothly extends the solution across the boundary along the same direction as the discretization will be used for.

Mittal et al. [21] designed a multi-dimensional ghost-cell methodology capable of handling highly complex three-dimensional, stationary, moving and/or deforming bodies, by employing a pair of ghost-point and image-point for every unstructured triangular elements representing the complex immersed surfaces. Seo and Mittal [22] extended the ghost-cell based immersed boundary method to higher-orders by using an approximating polynomial method which originally proposed by Luo et al. [23], and showed computational results of time-domain acoustic fields. Zeng and Farhat [24] presented a systematic approach for constructing higher-order immersed boundary and ghost fluid methods for computational fluid dynamics (CFD) in general, whose implementation also relied on ghost cells.

Up to now, no simulation results on heat transfer based on ghost-cell immersed boundary method has been published. As a result of sharp representation of immersed boundary in the ghost-cell based method, it is expected that the ghost-cell based IBM can obtain surface information comparable with results from body-fitted grid simulation. But the ghost-cell based IBM is applicable to more general situation and more flexible to implement.

In order to study heat transfer in particulate flows, the code developed by Wang [15] with multi-direct heat source scheme had been extended to three dimensional domains in the first place. After a series of grid convergence tests, we got the conclusion that at least 48 grids per diameter of the sphere were needed. In fact, the work of Wang et al. [15] in two-dimensional domain was accomplished with 96 grids per diameter of circular particle. The total number of grid points scales as $(D_p/h)^3$ in three-dimensional simulation. As a consequence, for a large number of particles, the total number of grids is too high for actual implementation. That prompted the author to search for higher order implementation of immersed boundary method. Since given the precision of solution, the higher the order of the algorithm the less grid points are needed.

The higher-order immersed boundary method proposed by Seo and Mittal [22] enables arbitrary order of boundary formulations. As interpolation stencil increases with the order of the boundary formulations, there is a compromise between higher-order and cost of computing resources including central processing unit (CPU) and storage.

In present paper, the author firstly compared the temperature field resolution capability of multi-direct heat source based and third-order ghost cells based immersed boundary method. It turned out that in order to fully resolve the temperature distribution in the vicinity of the immersed boundary, 32 and 48 grids per particle diameter were needed respectively. The implementation of multi-direct heat source based immersed boundary method was a modified version of Wang et al. [15], and the third-order ghost cells based immersed boundary method came from reprogramming Seo and Mittal's scheme [22]. According to comparison results, the third-order ghost cells based immersed boundary method was chosen to simulate heat transfer from a cluster consists of 20 spherical particles.

The paper is organized as follows. Section 2 introduces distinct numerical treatments of the immersed boundary by the multi-heat source method and the third-order ghost cells based method. In Section 3, validation of the ghost cells based method on heat transfer simulation, along with comparison to the multi-heat source method are given in the first place. The rest of this section consists of two sets of results from simulations using the selected method: