International Journal of Heat and Mass Transfer 89 (2015) 856–865

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Simulating heat transfer from moving rigid bodies using high-order ghost-cell based immersed-boundary method

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ARTICLE INFO

Article history:
Received 8 December 2014
Received in revised form 10 April 2015
Accepted 25 May 2015

Keywords:
Immersed Boundary Method
Heat transfer
Moving particle
Buoyancy
Multiphase flow

ABSTRACT

In this paper we develop a new high-order ghost-cell based Immersed Boundary Method (IBM) for flow and thermal simulation of multiphase flow system with moving bodies, based on our previous edition with only stationary boundary treatment. The newly developed approach is validated by comparing with earlier reported simulation and experimental results of both the pressure drag coefficient of a prescribed harmonic in-line oscillating sphere and the trajectory, velocity history of a free falling sphere under gravity and the rising of a spherical catalyst particle in an enclosure, using relatively coarse mesh resolution. Excellent agreement is obtained, demonstrating the accuracy and efficiency of our newly developed method. Finally, we employ the new method to investigate the cooling process of a freely settling spherical particle under gravity, aiming at revealing the impact of natural convection on particle cooling. It turns out that the heat transfer and hydrodynamics interaction is the most obvious when the Richardson number is the largest in our simulations. When the Reynolds number equals, the Nusselt number is always higher for the no buoyancy case than the case with buoyancy force.

1. Introduction

In multiphase flow system, heat transfer between fluid and dispersed phase is very common. Under these circumstances, dispersed phase usually drift in the fluid while exchanging thermal energy with it. When it happens, the dispersed phase may break away from surrounding fluid; intrude into a new place and exchange heat with fresh fluid there.

Considering particle movement is more realistic than investigating statically arranged particle(s). However, since it is more complex, difficulties arise. Haeri et al. [1] and Deen et al. [2] summarized direct numerical simulation (DNS) techniques for particulate flows with fully resolved particles, such as overset grid method, Arbitrary Lagrangian–Eulerian (ALE) method, Immersed Boundary Method (IBM), Distributed Lagrange Multiplier/Fictitious Domain (DLM/FD) method [3] and Lattice Boltzmann method.

Among all these currently available methods, IBM has recently been demonstrated to be a highly versatile and quite attractive one. It discretizes the equations of motion for the fluid phase on a fixed Cartesian grid and treats immerse boundary (IB) in a non-body-conformal manner, which is free from time-consuming grid generation/re-generation (when IB moves), hence very efficient in simulating flows around moving/deforming bodies with complex geometrical shapes.

During its history of development, IBM is mainly used for handing fluid-particle hydrodynamic interaction. It is only in the last decade that IBM was introduced into heat transfer simulation.

Feng and Michaelides [4] implemented a well documented direct-forcing IBM scheme to obtain numerical results with a group of 56 interacting circular particles that cool while settling. Deen et al. [5] utilized an IBM method to perform DNS of fluid flow and heat transfer in dense suspensions, fully resolved simulation results of both stationary random array of particles and liquid fluidized bed were presented. Liao and Lin [6] adopted a so-called solid-body-forcing strategy to compute flows and heat transfer with moving objects. Most recently, Feng and Musong [7] applied IBM to study heat transfer of 225 spheres in a narrow channel fluidized bed.

However, specific remedy has to be made to a primitive IBM before successfully implementing numerical simulation with moving boundary problems. The primary undesirable property of IBM turns out to be unphysical, temporal oscillation of the pressure fields [8], when it is employed to deal with moving bodies. And these pressure oscillations are observed virtually for all type of IBMs.

Liao et al. [9] obtained significantly lower amplitude oscillations via a combination strategy of a "solid-body-forcing" applied at solid nodes and interpolation at fluid nodes. By first identifying

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.05.098
0017-9310/

the primary cause of these oscillations to be the violation of the geometric conservation law near the immersed boundary, Seo and Mittal [10] adopt a cut-cell based approach to strictly enforce geometric conservation, successfully reducing pressure oscillations for moving boundary by roughly an order of magnitude.

In an earlier paper, Xia et al. [11] introduced a ghost-cell based high-order Immersed Boundary Method to investigate forced convection and heat transfer around a cluster of sphere particles. In the present paper, our previous proposed high-order ghost-cell based boundary reconstruction technique is further improved and extended, by retaining the high-order algorithm of our previous work as well as absorbing the ideology of regionally conservative cut-cell based method to alleviate the intrinsic pressure oscillation from Seo and Mittal [10], such that it is capable of handling moving particles stably and efficiently.

The organization of this paper is as follows: first the methodology of the immersed boundary technique along with numerical solution methods to be employed is given in Section 2. Section 3 is devoted to the verification of the method for three dimensional (3D) test cases: a prescribed harmonic in-line oscillating sphere, a free falling sphere under gravity and the rising of a spherical catalyst particle in an enclosure. Then in Section 4 the cooling of a free-settling hot spherical particle with and without buoyancy is simulated, using the newly developed high-order Immersed Boundary Method. And finally conclusions are presented in Section 5.

2. Numerical strategy

For constant properties viscous incompressible Newtonian fluid, the transport phenomena are governed by the conservation equation for mass, momentum and thermal energy, in dimensionless form, given by:

$$\nabla \cdot \mathrm{u}^* = 0 \tag{1}$$

$$\frac{\partial \mathrm{u}^*}{\partial t} + \mathrm{u}^* \cdot \nabla \mathrm{u}^* = -\nabla P^* + \frac{1}{\mathrm{Re}}\nabla^2 \mathrm{u}^* + \frac{Gr}{\mathrm{Re}^2} T^* \vec{e}_g \tag{2}$$

$$\frac{\partial T^*}{\partial t} + \mathrm{u}^* \cdot \nabla T^* = \frac{1}{Pe}\nabla^2 T^* \tag{3}$$

where $\mathrm{u}^* = (u, v, w)$ is the dimensionless velocity vector, P^* is the dimensionless pressure. The dimensionless temperature is defined as $T^* = (T - T_0)/(T_S - T_0)$, T_0 is the constant far-field temperature, T_s is the isothermal particle temperature and T is the dimensional fluid temperature. The three dimensionless characteristic numbers in the governing equations are Reynolds number $Re = (\rho_0 \cdot U \cdot D)/\mu$, Peclet number $Pe = Re \cdot \mathrm{Pr}$ (with Prandtl number $\mathrm{Pr} = (c_P \cdot \mu)/k$) and Grashof number $Gr = g\beta(T_s - T_0)\rho_0^2 D^3/\mu^2$. Here take the uniform inflow velocity U as characteristic velocity, particle diameter D as characteristic length scale. ρ_0, μ, β, c_P and k are fluid density, dynamic viscosity, thermal expansion coefficient, heat capacity and coefficient of thermal conductivity; g is the gravitational acceleration, $\vec{e}_g$ is the unit vector in the direction of the gravitational acceleration.

The pressure-Poisson equation derived by applying the divergence operator to the momentum equations replaces the continuity Eq. (1) that is satisfied indirectly through the solution of the pressure equation. Eqs. (2) and (3) are integrated in time using a four-stage fourth-order Runge–Kutta method with the third-order Adams–Bashforth method for convection terms and Crank-Nicolson method for diffusion terms. More details about the solution methodologies are available in [11].

For suspended solid particles, their translational and rotational motion is governed by the Newtonian equations of motion, respectively, given by:

$$m_p \frac{d\vec{u}_p}{dt} = m_p \vec{g} + \vec{F}_{f\to s} \tag{4}$$

$$I_p \frac{d\vec{\omega}_p}{dt} = \vec{T}_{f\to s} \tag{5}$$

where m_p and I_p are the mass and the moment of inertia of the particle, respectively.

And the $f \to s$ terms represent the drag and torque exert upon the particle by the fluid. They are calculated from integrating viscous stress and pressure contribution components around the sphere surface:

$$\vec{F}_{f\to s} = \oint_S \vec{f}_{f\to s} dS = \oint_S (\mu \nabla u \cdot \vec{n} - p\vec{n}) dS \quad \text{and} \quad \vec{T}_{f\to s} = \oint_S (\vec{r} - \vec{r}_p) \times \vec{f}_{f\to s} dS \tag{6}$$

where $\vec{n}$ is the outward unit normal vector, $\vec{r}$ are position vectors to points at particle surface and $\vec{r}_p$ is the position vector to the center of sphere.

Similarly, the particle temperature is governed by:

$$m_p C_{p,s} \frac{dT_p}{dt} = \Phi_{f\to s} \quad \text{with} \quad \Phi_{f\to s} = -\oint_S (k \cdot \nabla T \cdot \vec{n}) dS \tag{7}$$

where $\Phi_{f\to s}$ is the heat transfer rate from fluid to solid phase.

In order to properly reflect the presence of immersed bodies, subtle boundary reconstruction technique is introduced into solution procedure. Mathematically, in the vicinity of the immersed boundary, a generic variable ϕ can be expressed as the Taylor series expansion based on a specifically chosen boundary point (body-intercept point $((x', y', z')|_{BI} = (0, 0, 0))$, with the form of:

$$\phi(x', y', z') \cong \phi_{BI} + \left.\frac{\partial \phi}{\partial x}\right|_{BI} x' + \left.\frac{\partial \phi}{\partial y}\right|_{BI} y' + \left.\frac{\partial \phi}{\partial z}\right|_{BI} z' + \frac{1}{2}\left.\frac{\partial^2 \phi}{\partial x^2}\right|_{BI} (x')^2 + \frac{1}{2}\left.\frac{\partial^2 \phi}{\partial y^2}\right|_{BI} (y')^2 + \cdots \tag{8}$$

where $x' = x - x_{BI}, y' = y - y_{BI}, z' = z - z_{BI}$.

To determine the value and derivatives at the body-intercept point, the above Eq. (8) is approximated by an Nth-order polynomial:

$$\phi(x', y', z') \approx \Phi(x', y', z') = \sum_{i=0}^{N}\sum_{j=0}^{N}\sum_{k=0}^{N} c_{ijk} (x')^i (y')^j (z')^k \qquad i + j + k \leqslant N \tag{9}$$

Hence, unknowns are the coefficients of the polynomial instead of derivatives. And these coefficients c_{ijk} can be determined by the least square fitting:

$$c = (WV)^+ W\phi = A\phi \tag{10}$$

where superscript '+' denotes the pseudo-inverse of a matrix. Vector c and ϕ contain coefficients c_{ijk} and data $\phi(x'_m, y'_m, z'_m)$ respectively, and W and V are the weight and Vandermonde matrices given by:

$$W = \begin{bmatrix} w_1 & & & \\ & w_2 & & \\ & & \ddots & \\ & & & w_m \end{bmatrix}, \quad V = \begin{bmatrix} 1 & x'_1 & y'_1 & z'_1 & x'^2_1 & y'^2_1 & z'^{2\prime}_1 & \cdots \\ & & & \vdots & & & & \\ 1 & x'_m & y'_m & z'_m & x'^2_m & y'^2_m & z'^2_m & \cdots \\ & & & \vdots & & & & \\ 1 & x'_M & y'_M & z'_M & x'^2_M & y'^2_M & z'^2_M & \cdots \end{bmatrix} \tag{11}$$

in which the subscript '1' denotes the ghost point, and the other $(M - 1)$ are fluid points in the vicinity of the body-intercept point, as described in Fig. 1(a).

Comparing Eqs. (8) and (9), with Eq. (10) in mind, we obtain a set of equalities as follows: