

## Chapter 8

# Direct Numerical Simulation of Gas–Solids Flow Based on the Immersed Boundary Method

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### ABSTRACT

*In this chapter, the Direct numerical simulation (DNS) of flow past particles is described. DNS is a first-principles approach for modeling interphase momentum transfer in gas-solids flows that does not require any further closure as the flow around the particles is fully resolved. In this chapter, immersed boundary method (IBM) is described where the governing Navier-Stokes equations are modeled with exact boundary conditions imposed at each particle surface using IBM and the resulting three dimensional time-dependent velocity and pressure fields are solved. Since this model has complete description of the gas-solids hydrodynamic behavior, one could extract all the Eulerian and Lagrangian statistics for validation and development of more accurate closures which could be used at coarse-grained simulations described in other chapters.*

### MOMENTUM TRANSFER IN GAS-SOLIDS FLOW

Accurate representation of the momentum transfer between particles and fluid is necessary for predictive simulation of gas-solids flow in industrial applications. Such device-level simulations are typically based on averaged equations of mass and momentum conservation corresponding to the fluid and particle

DOI: 10.4018/978-1-61520-651-3.ch008

phase(s) in gas-solids flow (Syamlal, Rogers, & O'Brien, 1993), and these constitute the multi-fluid theory. The momentum conservation equation in this theory contains a term representing the average interphase momentum transfer between particles and fluid. The dependence of this term on flow quantities such as the Reynolds number based on mean slip velocity, solid volume fraction, and particle size distribution must be modeled in order to solve the set of averaged equations, and is simply referred to as a drag law. If higher levels of statistical representation are adopted—such as the second moment of particle velocity, or the particle distribution function—then the corresponding terms (such as the interphase transfer of kinetic energy in the second velocity moment equations) appearing in those equations also need to be modeled.

Direct numerical simulation of flow past particles is a first-principles approach to developing accurate models for interphase momentum transfer in gas-solids flow at all levels of statistical closure. Since DNS solves the governing Navier-Stokes equations with exact boundary conditions imposed at each particle surface, it produces a model free solution with complete three dimensional time-dependent velocity and pressure fields. In principle, all Eulerian and Lagrangian flow statistics can be extracted from the DNS data making it a powerful tool for model validation and development (Pope, 2000; Rai, Gatski, & Erlebacher, 1995). While there are different numerical approaches available to perform DNS of gas-solids flow—such as the lattice Boltzmann method (LBM)—here we describe a DNS approach that is based on the immersed boundary method (IBM). The outline of this chapter is as follows. We first describe the context in which models for interphase momentum transfer arise. We begin with the transport equation for the one-particle distribution function that is the starting point for the kinetic theory of granular and multiphase flows. This is appropriate because all moment-based theories (averaged equations, second and higher moments) can be derived from this distribution function. Thus, by developing closure models at the level of the one-particle distribution function, we effectively model all moment equations. The appropriate physical problem that needs to be set up to approximate statistically homogeneous gas-solids suspension flow is then described. The expression for the mean interphase momentum transfer term in steady, homogeneous, gas-solids flow that arises from the averaged conservation equations in the two-fluid theory is then derived, and related to the equivalent term in the one-particle distribution function approach. Then the immersed boundary method and its implementation are described. Numerical error associated with forming statistical estimates of the interphase momentum transfer term is analyzed and decomposed into spatial, temporal and statistical contributions. This results in the identification of relevant numerical parameters (grid resolution, size of computational domain, number of particle configurations) corresponding to each of the error contributions. Numerical convergence of the IBM DNS code is established, and results from standard tests are presented that validate the simulation approach. Drag laws obtained from IBM simulations are discussed and compared with those obtained from other simulation methods. The IBM approach is compared with other simulation approaches, and relative advantages and disadvantages are discussed. Directions for further research in the formulation of models of gas-solids flow using DNS based on IBM are outlined. Finally, the contributions of this chapter are summarized along with concluding remarks regarding the use of IBM for direct numerical simulation of gas-solids flow.

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