Chapter 4
Interfacial Interactions: Drag

Wei Ge
Chinese Academy of Sciences, China

Ning Yang
Chinese Academy of Sciences, China

Wei Wang
Chinese Academy of Sciences, China

Jinghai Li
Chinese Academy of Sciences, China

ABSTRACT

The drag interaction between gas and solids not only acts as a driving force for solids in gas-solids flows but also plays as a major role in the dissipation of the energy due to drag losses. This leads to enormous complexities as these drag terms are highly non-linear and multiscale in nature because of the variations in solids spatio-temporal distribution. This chapter provides an overview of this important aspect of the hydrodynamic interactions between the gas and solids and the role of spatio-temporal heterogeneities on the quantification of this drag force. In particular, a model is presented which introduces a mesoscale description into two-fluid models for gas-solids flows. This description is formulated in terms of the stability of gas-solids suspension. The stability condition is, in turn, posed as a minimization problem where the competing factors are the energy consumption required to suspend and transport the solids and their gravitational potential energy. However, the lack of scale-separation leads to many uncertainties in quantifying mesoscale structures. The authors have incorporated this model into computational fluid dynamics (CFD) simulations which have shown improvements over traditional drag models. Fully resolved simulations, such as those mentioned in this chapter and the subject of a later chapter on Immersed Boundary Methods, can be used to obtain additional information about these mesoscale structures. This can be used to formulate better constitutive equations for continuum models.

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INTRODUCTION

To a large extent, hydrodynamic interactions between the gas and solid phases are responsible for the complexity of gas-solids flows since otherwise the two phases would move independently. Drag force is almost always the dominant component of these interactions and its quantification is critical for the predictability of simulations on gas-solids flows. Although dozens of correlations have been proposed for this force, considerable uncertainties and discrepancies remain. Significant multi-scale heterogeneity and its dynamic behavior present a major difficulty for accurate estimation of drag force, most drag force models are based on the assumption of homogenous two-phase flows and seems to be not accurate enough for typical heterogeneous gas-solids flows in engineering.

In fact, it is all very often to find that quantification of meso-scale structures is a challenge in many different areas. For the drag force in gas-solids systems, we have relatively accurate correlation of a single particle in unbounded flow field and we can measure its average value for a large amount of particles through pressure drop or solids concentration. However, correlations for the drag force in a computational cell in continuum models can give predictions that are different in orders. For heat and mass transfer in gas-solids flows, when correlating the transfer rate to average parameters such as the particle Reynolds number based on the mean slip velocity, the difference can even reach more orders and we may expect even larger discrepancies when chemical reactions are involved, due to the meso-scale heterogeneity prevailing in such systems.

This challenge is tackled from different angles in this chapter. A two-phase two-fluid model is used to develop a drag force model that has considered the meso-scale (MS) structure in the simulation of gas-solids flows. A criterion for the stability of the gas-solids suspension is introduced to close this model that involves more variables than homogeneous models. This stability condition is based on an analysis of the compromise between the minimization of energy consumption for suspending and transporting solids in unit space and minimization of its gravitational potential. Along with the drag force, parameters for the meso-scale structure are also provided by this model, which can be used to improve the characterization of mass and heat transfer properties in heterogeneous systems. This model has been incorporated into computational fluid dynamics (CFD) simulations and has contributed substantially to its predictability.

However, partly due to the lack of scale separation in gas-solids systems, many uncertainties remind in quantifying meso-scale structures. To understand these structures from a more fundamental level, direct numerical simulations (DNS) of gas-solids suspension, down to scales far below particle size, has been performed using macro-scale particle methods. Such simulations needs no drag correlations as model input, and in fact, it can provide the interaction details between the two phases, the flow field around each particle, the pressure and tangential forces on particle surfaces, from which the drag force properties on larger scales can be analyzed and, in long term, new correlations can be proposed. The authors' preliminary studies have shown pronounced anisotropy of the magnitude of the drag force in a heterogeneous gas-solids systems.

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