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A Modeling Study on Particle Dispersion in Wall-Bounded Turbulent Flows

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Abstract. Three physical mechanisms which may affect dispersion of particle's motion in wall-bounded turbulent flows, including the effects of turbulence, wall roughness in particle-wall collisions, and inter-particle collisions, are numerically investigated in this study. Parametric studies with different wall roughness extents and with different mass loading ratios of particles are performed in fully developed channel flows with the Eulerian-Lagrangian approach. A low-Reynolds-number $k-\epsilon$ turbulence model is applied for the solution of the carrier-flow field, while the deterministic Lagrangian method together with binary-collision hard-sphere model is applied for the solution of particle motion. It is shown that the mechanism of inter-particle collisions should be taken into account in the modeling except for the flows laden with sufficiently low mass loading ratios of particles. Influences of wall roughness on particle dispersion due to particle-wall collisions are found to be considerable in the bounded particle-laden flow. Since the investigated particles are associated with large Stokes numbers, i.e., larger than $\mathcal{O}(1)$, in the test problem, the effects of turbulence on particle dispersion are much less considerable, as expected, in comparison with another two physical mechanisms investigated in the study.

AMS subject classifications: 65M10, 78A48

Key words: Particle-laden flow, turbulent dispersion, inter-particle collision, particle-wall collision.

1 Introduction

Understanding the physical mechanisms which affect particle motion in turbulent flow is a prerequisite for accurate predictions of turbulent quantities of particles. For instances, it is well agreed that the effect of turbulence on particle, i.e., turbulent dispersion, has

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to be considered under the condition of Stokes numbers (St) less than $\mathcal{O}(1)$, where the Stokes number is defined as the ratio of the particle relaxation time (τ_p) to the turbulence characteristic time (τ_f). Sommerfeld [1] showed significance of inter-particle collisions in the cases with $\tau_p/\tau_c > \mathcal{O}(1)$, where τ_c denotes the mean free time of particle collisions. Moreover, the experimental study of Benson and Eaton [2] revealed remarkable effects of particle-wall collisions on particle dispersion in the bounded turbulent flows laden with the particles of relatively large St values (i.e., $St > \mathcal{O}(1)$). Particle-wall collision particularly occurred in rough walls have been shown [3, 4] to play a significant role in predictions of particle dispersion in a number of wall-bounded turbulent flows because the particles that collide with a rough wall have a tendency to be suspended into the flow.

In this study, the effects of turbulence, inter-particle collisions, and particle-wall collisions on particle dispersion are numerically investigated by using the Eulerian-Lagrangian approach in fully developed, turbulent flows laden with the particles of various mass loading ratios. Traditional approach based on the Reynolds-averaged Navier-Stokes (RANS) equations together with a low Reynolds number $k-\epsilon$ turbulence model is applied for the solution of the carrier-fluid flow field [5], while the stochastic separated flow model [6] is applied for the solution of the dispersed-phase (i.e., particles) flow field.

2 Test problem

The experimental work on fully developed, turbulent downward channel flow laden with particles at various mass loading ratios conducted by Kulick et al. [7] is chosen as the test problem. Although the investigated problem is a fully developed flow, a three-dimensional flow model is used to account for the 3-dimensional nature of the inter-particle collisions for the translating and rotating particles. The hydraulic diameter of this channel is equal to the half heights (i.e., $D_h = H/2 = 0.02$m). The mean stream-wise velocity of the carrier fluid (air) at the inlet is equal to 10.5m/s, which corresponds to the Reynolds number, based on the hydraulic diameter, of 13,800. The length of this channel ($L_{\rm exp} = 5.2$m) is sufficiently long ($L_{\rm exp}/D_h = 260$) to assure both carrier-fluid and particles reaching their fully developed conditions in the downstream of channel. Here, the fully developed condition for particles denotes a phenomenon that the particle motion has reached its own terminal velocity. The ratio of the width of this channel ($W_{\rm exp} = 0.457$m) to D_h is 23. The span-wise wall effects can be, thus, negligible in the span-wisely central regions. In order to save the computational expenditure, a computational domain in form of Cartesian coordinate is set as 1m(L) $\times$ 0.04m(H) $\times$ 0.01m(W) as schematically shown in Fig. 1 in this study.

3 Physical modeling

The low-Reynolds-number version of the $k-\epsilon$ turbulence model is capable of simulating the fully developed channel flows, including the near-wall regions, which possess some-