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LES–DPS of the effect of wall roughness on dispersed-phase transport in particle-laden turbulent channel flow

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Abstract

The influence of wall roughness on dispersed-phase properties of particle-laden turbulent channel flow is investigated using large eddy simulation (LES) for the fluid flow and discrete particle simulation (DPS) for the particulate phase. Gas–solid flows are considered for which the particle equation of motion includes the contribution from the drag force. The influence of wall roughness is treated stochastically in which the impact angle is comprised of the particle trajectory angle and a stochastic component due to wall roughness. Elastic particle–wall collisions are considered with surface roughness characterized in terms of the standard deviation of the distribution of wall roughness angles. Computations are performed for three Stokes numbers and standard deviations in the wall roughness angle of 0 (smooth wall), 2.5° and 5°. LES–DPS results show that for a given wall roughness angle and particle Stokes number the most pronounced effect is on the wall-normal component of the particle velocity, which can be substantially increased by roughness. While the streamwise particle velocity variance also increases, the spanwise particle fluctuating velocity exhibits relatively little sensitivity to surface roughness. In addition, LES/DPS results show that wall roughness increases turbulent transport of the wall-normal particle velocity variance, in turn providing a mechanism for elevation of the particle velocity fluctuations across the entire flow.

Keywords: Particle-laden turbulent flow; Wall roughness

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1. Introduction

Turbulent gas flows containing dilute suspensions of solid particles are complex and pose many technologically challenging and scientifically relevant questions. For the practical applications in which particle-laden turbulent flows are encountered, statistical models that require empirical input will continue to form the basis for engineering prediction. The fundamental knowledge base that is crucial for guiding the development of models for applications is not, however, sufficiently developed. This is in large part due to the difficulty in measuring quantities in the reference frame most naturally suited for analysis, i.e., the Lagrangian reference frame attached to a particle. This complicates experiments and motivates the application of numerical simulations that enable detailed investigation of many of the processes governing turbulent two-phase flows.

For dilute, gas–solid turbulent flows, numerical techniques that resolve some or all of the underlying eddy motions of the carrier-phase have an important role in advancing fundamental understanding of the various interactions important to accurately predicting dispersed-phase properties. These numerical approaches – direct numerical simulation (DNS) and large eddy simulation (LES) – together with discrete particle simulation (DPS) have been applied in several previous investigations aimed at understanding particle transport by turbulence, particle–particle collisions, and turbulence modulation by momentum exchange with heavy particles (e.g., see Laviéville et al., 1995; Wang and Squires, 1996; Boivin et al., 1998; Yamamoto et al., 2001).

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These and other works have been useful for exploring fundamental aspects of gas–solid turbulent flows through controlled, parametric studies. The capacity to precisely define and control the parameter space is useful since the presence of a dispersed phase of heavy particles introduces several additional parameters over those already relevant to characterizing single-phase turbulence. The relevant timescales include the particle response time, the inter-particle collision time, and for wall-bounded flows the timescale characterizing particle–wall collisions. Comparison against the appropriate fluid flow timescales has generally been thought to indicate the relative importance of a given effect, though it is increasingly clear in multiphase flows in general, and gas–solid turbulent flows in particular, that it is not possible to develop simple criteria that would accurately indicate the dominance of a particular effect.

Less investigated than the effects cited above using techniques such as DNS and LES, and the topic of the present effort, is the influence of wall roughness on particulate-phase transport. Experimental investigations have shown that wall roughness can strongly alter particle motion and in turn cause measurable changes to the overall flow properties. Sommerfeld and Huber (1999) showed that wall roughness altered the rebound behavior of particles in a horizontal channel flow which, on average, resulted in a re-dispersion of the particles as well as a lowering of the settling rate as compared to measurements in smooth-wall configurations. Kussin and Sommerfeld (2002) obtained measurements of gas–solid, horizontal channel flow using spherical beads with diameters ranging from 60 μm to 1 mm. A focus of that work was variation of wall roughness by changing the wall plates. Their measurements showed that wall roughness enhanced the particle fluctuating velocity due to the irregular bouncing of the particle with a rough wall and lead to a more uniform distribution of particles across the channel.

In general, measurements show that wall roughness introduces an effect analogous to that produced by particle–particle collisions: amplification of wall-normal (or, in a pipe, radial) particle velocity fluctuations that can substantially change the transport characteristics of the particles and cause large changes in other flow properties, e.g., the overall pressure drop of a gas–solid mixture. Sommerfeld and Huber (1999) used their experiments to measure parameters for a wall-collision model employed in Lagrangian approaches for gas-particle flows as described in Sommerfeld (1992) (see also Sommerfeld, 2003). As described below, a similar approach to incorporating the effect of wall roughness into the computations is employed in the present study. The reader is further referred to Tsuji et al. (1987), Sakiz and Simonin (1999), and Zhang and Zhou (2004) for additional discussion and background of related approaches to modeling particle–wall collisions.

As summarized in the next section, the computational approach is based on LES of fully-developed turbulent channel flow combined with discrete particle simulation (DPS) of the dispersed phase. The particle equation of motion and parameter space of the present investigations are presented and followed by statistical descriptors of particulate-phase motion used to assess roughness effects. A summary of the work and perspectives gained are then outlined.

2. Approach

2.1. LES of turbulent channel flow

The flow under consideration is a vertical, fully-developed turbulent channel flow (i.e., without gravitational settling on either of the channel walls). The numerical approach employs large eddy simulation (LES) of the carrier-phase flow and discrete particle simulation (DPS) for prediction of dispersed phase transport. The fluid flow is maintained at constant mass flux corresponding to a target Reynolds number $Re_\tau = 180$ based on the friction velocity u_τ and channel halfwidth δ. The dimensions of the channel are $4\pi\delta$ in the streamwise (x or x_1), $4\pi\delta/3$ in the spanwise (z or x_3), and 2δ in the wall-normal (y or x_2) directions. Periodic boundary conditions are applied to the dependent variables in the streamwise and spanwise dimensions and no-slip boundary conditions to the velocity at the channel walls. The subgrid-scale stress arising from the filtering of the Navier–Stokes equations is closed using the eddy viscosity model of Piomelli et al. (1989).

The equations governing the fluid flow are solved using a fractional step method (e.g., see Burton and Eaton, 2002) on a staggered mesh comprised of $64 \times 64 \times 64$ cells in the x, y, and z directions, respectively. The grid spacings in the streamwise and spanwise directions are uniform with corresponding spacings in viscous units of $\Delta x^+ = 35$ and $\Delta z^+ = 12$. Spatial derivatives are approximated using second-order accurate central differences. The Poisson equation formulated for the pressure variable that is used to obtain a divergence-free velocity field is solved using fast transforms in the streamwise and spanwise direction, resulting in a series of tri-diagonal matrices that are efficiently inverted in the direction normal to the solid walls. The wall-normal mesh is clustered near the solid surfaces and stretched away from the wall using a hyperbolic tangent function. The discretized system is advanced in time using an implicit/explicit time advance (Crank–Nicholson and second-order Adams–Bashforth).

2.2. Discrete particle simulation

The focus of the current work is on dilute gas–solid flows in the limit of one-way coupling (i.e., no modification of the carrier phase flow due to momentum exchange with the dispersed phase) and without inter-particle collisions. The particle density is much larger than that of the fluid phase, ($\rho_p \gg \rho_f$, where ρ_f is the fluid density and the ρ_p is the particle density). Owing to the large density ratio, the particle response time is large compared to the Kolmogorov timescale of the undisturbed flow.