# Fluid-phase velocity fluctuations in fixed particle beds and freely evolving

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**Research Program: Complex Fluid Systems** 

### Introduction

Gas-solid flows are commonly encountered in industrial applications such as fluidized bed combustion, fluid catalytic cracking, coal gasification processes, and biomass energy generation [1]. In industrial applications of gas-solid flows, particles are inertial with diameter  $d_n$ 

usually larger than the length scale of dissipative fluid motions  $\eta$ . The interaction of carrier flow structures with solid particles gives rise to challenges in the device-scale analysis of gas-solid flows. For instance, the interaction of large particles with carrier flow generates pseudo-turbulent fluid-phase velocity fluctuations due to the relative mean velocity between the two phases. These fluid-phase velocity fluctuations are responsible for the transport of particles to walls in vertical risers [2], resulting in the core-annular structure observed in circulating fluidized beds.

The scale-up of the process equipment from laboratory scale to the industrial scale is very difficult. device-scale calculations using CFD simulations of multiphase flows are a promising route to the inexpensive design and scaling of industrial devices [3]. CFD of multiphase flows involves solving averaged equations for mass, momentum and energy with coupling terms that correspond to interphase interactions. The closure of these equations requires modeling of unclosed terms. Such accurate models can be developed using particle-resolved direct numerical simulation (PR-DNS).

#### Particle-resolved direct numerical simulation

PR-DNS is a first-principles physics-based numerical approach in which the Navier-Stokes equations are solved in the fluid-phase by imposing exact boundary conditions

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Figure 1. Evolution of  $k^{(f)}$ . Symbol (O) shows the steady value of fluid pseudo-turbulence. Symbols  $(\nabla)$  correspond to flow initialized with isotropic turbulence  $\operatorname{Re}_{\lambda} = 12$ . Symbols ( $\Delta$ ) represent decay of

excess level of  $k^{(f)}$ .

on each particle surface. The most popular PR-DNS approaches employ fixed, uniform Cartesian grids. The specific implementation of PR-DNS used in this work is the Particle-resolved Uncontaminated-fluid Reconcilable Immersed Boundary Method (PUReIBM). The approach has PUReIBM been validated in a comprehensive suite of test cases and has been shown to be accurate and numerically convergent [4]. In this work we employ PUReIBM to solve for flow past arbitrary arrangements of spherical solid particles in order to

- quantify the level of turbulent and pseudoturbulent fluid velocity fluctuations in fixed particle assemblies
- quantify the level of fluid-phase velocity fluctuations in freely evolving suspensions

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# Fluid-phase velocity fluctuations in steady flow past fixed particle assemblies

The presence of particles in a carrier flow generates pseudo-turbulent fluid velocity fluctuations, even in laminar flows. In the current study, we simulate initially turbulent flow in fixed particle assemblies to quantify the relative magnitude of gas-phase velocity fluctuations arising from turbulent and pseudo-turbulent sources. The results shown in Figure 1 reveals that the velocity fluctuations arising from the particles in fluid-phase are much higher than the turbulent velocity fluctuations, and the principal contribution to the fluid-phase velocity fluctuations is the pseudo-turbulent part.

# Fluid-phase velocity fluctuations in freely evolving suspensions

Although fixed beds are good approximations to particleladen flows with high Stokes number particles, in reality the configuration of particles changes in time due to hydrodynamic and collisional forces. We extend our simulations to freely evolving suspension of elastic particles to examine the influence of flow parameters on fluid-phase velocity fluctuations. We realize that the level of  $k^{(f)}$  is in agreement with fixed bed results with less than 10% error (see Figure 2). This finding verifies the validity of the similarity assumption between fixed beds and freely evolving suspensions of high Stokes number particles.

In freely evolving suspensions, if particle collisions are inelastic then the energy of the system is dissipated by the collisional dissipation among particles on one hand, and the viscous dissipation of



Figure 2. Evolution of  $k^{(f)}$  in freely evolving suspensions with elastic particles.



Figure 3. Evolution of  $k^{(f)}$  in freely evolving suspensions with inelastic particles ( $\rho^{(p)} / \rho^{(f)} = 1000$ ). the flow, on the other hand. To investigate the effect of coefficient of restitution on fluid-phase velocity fluctuations, we performed simulations with different coefficient of restitution (COR) ranging from 0.7 to 1.0. Our DNS data shown in Figure 3 indicates that COR does not influence  $k^{(f)}$ significantly since the flow in these suspensions belongs to a regime that is dominated by viscous dissipation as opposed to collisionally dissipative regimes [5].

## References

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