Particle-laden flows — overview

Many natural and technological fluid dynamical processes involve complex multiphase interactions in which the carrier fluid exchanges mass, momentum, and energy with a dispersed particle field. Examples of such flows in nature include rain formation in clouds, sand and dust storms, protoplanetary disks, volcanic eruptions, and geological sedimentation processes. Pharmaceutical sprays, liquid-fueled combustion, solid rocket motors, coal furnaces, and particle-based solar receivers are examples of engineering processes that involve particle-laden flows.

The equations governing interactions of particles with fluids in a particle-laden mixture have been known for many decades. However, their coupled dynamics often result in complex behavior such as preferential concentration and turbulence modulation. These are still ongoing topics of research. In most applications, additional complexity exists due to interactions with various phenomena, such as heat transfer, evaporation, deposition and ejection, and chemical reactions, leading to a wide range of multiphysics complex problems yet to be understood.

Recent advancements in computational capabilities, including the availability of massively parallel platforms and the development of robust numerical algorithms, provide exciting opportunities to investigate these problems. Although many practically relevant regimes of particle-laden flows are still too expensive to simulate from first principles, useful insights can be deduced from investigations of canonical settings or reduced systems.

Point-particle models offer significant reduction in computational cost, by multiple orders of magnitude, over particle-resolved models when simulating particle-laden flows. However, in many two-way coupled settings, in which momentum and energy exchanges are significant to both phases, point-particle models have limited success. The relative contribution of various sources of error (e.g. discretization, numerical implementation and model errors) is yet to be determined. One of the research activities in the Summer Program was dedicated to quantification of these errors and development of a database that can inform future point-particle model developments. To this end, Subramaniam *et al.* developed the first particle-resolved simulation that considered small enough particles to be in the regime of expected validity of point-particle models, and thus allowed for identification of other sources of error. Comparison of their results with corresponding point-particle implementations highlighted the regimes of large and small errors in the time evolution of a homogeneous particle-laden turbulent flow.

Motivated by recent interest in particle-based solar receivers, two of the research activities were focused on coupling of particle-laden flows with heat transfer. Frankel *et al.* investigated the impact of buoyant plumes, due to particle heating, on particle settling velocities, and found that for sufficiently intense heating the previously reported mechanism of preferential sweeping can be disrupted. They also investigated the process of kinetic-energy transfer from particles to the fluid phase, and showed a non-monotonic dependence of this effect on the heating intensity. In another investigation, Pouransari *et al.* studied the impact of particle heating on the energy spectrum and energy exchange processes in turbulent flows. They drew analogies between this novel pointwise heating mechanism and previously investigated turbulent-combustion phenomena in which heat transfer occurs within flames. In both regimes, the high-wavenumber content of turbulence is shown to be significantly impacted due to deposition of thermal energy.

Subgrid-scale modeling for large eddy simulations has been an integral theme of most research groups, and the particle-laden flows group has not been an exception to this rule. Gorokhovski and Zamansky developed new subgrid acceleration models for particles that compensate for agitation of particles due to unresolved flow scales in LES simulations. Inspired by scale dependence of turbulent motions, they developed separate models for dispersion of large and small particles.

Lastly, the activities in the group involved the use of first-principle models to inspire understanding of complex effects in practical flow regimes. Ghodke *et al.* used particle-resolved direct numerical simulations of sediment transport to study the onset condition for sediment pick up from a particle bed. They developed improved characterizations of sediment transport in sea beds by resolving interactions of sediments with oscillatory external flows in transitional and turbulent regimes.

In summary, the activities in the particle-laden flows group involved a broad range of approaches and target problems. These activities ranged from use of first-principle simulations in small domains, aimed at advancing reduced-order understanding, to use of reduced-order models, which enabled the understanding of complex interactions of particle-laden flows with other physical phenomena.

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