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DNS and LES of Particle-Laden Turbulent Flows: Status and Perspectives

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Turbulent gas flows containing dilute suspensions of solid particles or droplets are encountered in a vast array of engineering and environmental systems. Examples include coal combustors, chemical reactors, semiconductor processing devices, pneumatic transport and processing systems, and atmospheric dispersion of pollutants. The flows within these systems are complex due to the presence of a wide range of turbulent scales in the continuum, in addition to the dispersed particulate phase.

In many systems, reaction and deposition rates, mixing, and transport within particle-laden flows are controlled by the detailed dynamics of particle-turbulence and particle-particle interactions. In the general case, these flows are too complex to simulate directly, even with the most powerful supercomputers. Instead, engineers must rely on models to predict flow characteristics and system performance.

For the foreseeable future, prediction for practical applications will be based on the use of statistical models that require much empirical input. The presence of a dispersed phase of particles or droplets introduces several new parameters, the relevant timescales, for example, include the particle response time, the inter-particle collision time, and for wall-bounded flows the timescale characterizing particle-wall collisions. Phenomenological models often incorporate a given effect based on an a priori assumption of its importance. The values of timescales representing the dispersed phase compared to the appropriate fluid flow timescales, for example, has generally been thought to indicate the relative importance of a given effect, though it is increasingly clear that in multi-phase flows it is not possible to develop simple rules that accurately dictate the dominance of particular phenomena

It is difficult to advance the fundamental knowledge base crucial for guiding the development of models solely from experiments because of the difficulty in measuring quantities in the reference frame most naturally suited for analysis: the Lagrangian reference frame attached to a particle. This in turn motivates the application of sophisticated numerical simulations that will allow detailed investigation of many of the processes governing turbulent two-phase flows. Given the wide range of particle-laden flows, the current focus is on dilute systems of particles with material densities much larger than those characterizing the carrier flow. This represents a regime where significant progress can be made, and from which new understanding can be extrapolated to denser flows and possibly to other systems.

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 properties of the dispersed phase. These numerical approaches – Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES) – together with Discrete Particle Simulation (DPS) have been relative widely applied in fundamental studies aimed at understanding particle transport by turbulence, particle-particle collisions, and turbulence modulation by momentum exchange with heavy particles.

DNS/LES/DPS approaches will be reviewed; important to such simulation techniques are the numerical approaches used to resolve the underlying carrier-phase flow field. Constraints and limitations of DNS and LES for predicting turbulent fluid flows will be highlighted, especially as these limitations influence the parameter range of two-phase flows that may be realistically considered.

In DNS/LES/DPS approaches a point-particle treatment is often adopted, which in turn implies the introduction of models that must describe the local particle dynamics. In gas-solid flows these approaches typically reduce to imposition of a quasi-steady drag force and possibly the inclusion of a body force such as gravity. The numerical procedures for accurately computing properties of the particulate phase will be given attention.

Examples of DNS/LES/DPS methods for predicting particle-laden flows will also be highlighted. Applications of the methods to canonical flows such as particle-laden isotropic turbulence and fully-developed turbulent channel flow will be summarized, with the particular emphasis on particle transport by turbulent structures, inter-particle collisions, and the modulation of carrier-phase turbulence by momentum exchange with particles. DNS/LES/DPS techniques are well-suited to shed new light on the basic aspects governing these phenomena and recent work will be reviewed, including new directions in which DNS/LES/DPS will be essential.