

Multiphase flows — overview

Flows with more than one phase arise in many engineering applications. Liquid fuel injection, atomization, and spray dynamics are important factors in the design of efficient gas turbine combustors as well as diesel engines. As another example, prediction and understanding of the dynamics of cavitation in liquid flows is important to the prevention of impeller wear. Simulation of turbulent multiphase flows is particularly challenging because interfaces between phases give rise to additional physics and new length scales. The multiphase group consisted of eight projects, organized into three subtopics: (i) simulation of turbulent gas/liquid interfaces, (ii) fragmentation and atomization models and (iii) simulation of turbulent disperse-phase flows.

Several different numerical techniques have been proposed in the past to track the position of a gas/liquid interface as it evolves in time. These include interface tracking schemes that follow explicitly the motion of the phase interface using marker particles or even mesh points, and interface capturing methods that describe the motion of the phase interface implicitly. Level set methods are implicit methods that have the advantage of being simple and offering an easy and accurate way to calculate geometric properties of the phase interface. They have a major disadvantage, however, in that they cannot be constructed to discretely conserve liquid volume in the incompressible limit. This disadvantage is addressed by two different projects. The starting point for the project by Ovsyannikov *et al.* is a standard distance function level set method, where the level set scalar is equal to the signed minimum distance to the phase interface. As it evolves, the level set scalar does not remain a distance function and thus requires reinitialization to maintain its property. As numerous studies have shown, volume errors in the incompressible limit are caused predominantly by the successive application of the reinitialization operator. Ovsyannikov *et al.* propose a modification to the level set transport equation that significantly reduces the need to reinitialize the level set scalar and thereby improves the accuracy of the overall level set method. However, the modification is straightforward to add to existing level set solvers and thus should find widespread adoption. The approach by Jibben & Herrmann is based on the conservative level set formulation by Olsson & Kreiss and recasts the level set advection equation into a conservative form in the incompressible limit. The resulting conservative level set scalar equation is then solved using a Runge-Kutta Discontinuous Galerkin method resulting in a highly accurate level set method that is significantly better at conserving liquid volume and interface shape than traditional distance function level set methods.

At high Weber numbers, the simultaneous resolution of many length and timescales, from microscopic rupture scales to macroscopic turbulence scales of the interface stretching, renders direct numerical simulation (DNS) of interface dynamics computationally intractable. Simple filtering of small length and time scales applied to the direct approach violates conservation of mass, motivating the need for statistically correct models of the interface micro-dynamics, based upon the physics of the overall breakup mechanism. To meet this challenge, the second group of multiphase summer program projects addressed the stochastic simulation of interfaces for cases when the liquid disintegration process is much faster than the resolved scales of large-eddy simulations (LES). Starting from a presumed mechanism of breakup, a stochastic scenario is derived based on fragmentation under a scaling symmetry model, where a parent particle length scale splits into daugh-

ter particle length scales with a partition probability independent of the particle length scale. When fragmentation is a continuous process, a linear integro-differential equation governs the temporal evolution of the particle-length distribution. For constant fragmentation rates, this fragmentation equation may be applied to LES in one of two ways. The first method assumes a high rate of fragmentation, and generates the stochastic process by applying a long-time analytical solution to the length-distribution function. Such an approach was developed in the project by Gorokhovski *et al.*, and assessed for two applications: primary air-blast atomization and bubble production in a cavitation process. In the second method, a specific form is assumed for the fragmentation kernel and then the fragmentation equation is integrated numerically. This approach was developed and assessed in the project by Rimbert *et al.* in the case of the secondary atomization of drops in the bag-breakup regime. To our knowledge, this is the first example in the literature of direct integration of the kinetic fragmentation equation.

The third group of multiphase flow researchers investigated DNS and LES of disperse two-phase flows for small to moderate Stokes numbers and for dilute to moderately dense polydisperse sprays where the droplets are represented by point particles. Whereas the first three contributions focus on Eulerian models and rely on detailed comparisons with Lagrangian approaches, the fourth is devoted to a Lagrangian LES approach. Fréret *et al.* evaluate the Eulerian multifluid model and related numerical methods for the DNS of a turbulent 3-D free jet with hot co-flow and spray injection with and without evaporation. By using detailed dynamic comparisons, they demonstrate that an Euler-Euler approach can reach the same level of accuracy as an Euler-Lagrange method with comparable computational cost but without the statistical noise inherent to Lagrangian approaches. Vié *et al.* evaluate algebraic-closure-based (ACBMM) and kinetic-based (KBMM) moment methods for DNS of inertial particles using an Euler-Euler approach, which is well suited for massively parallel simulations of reactive two-phase flows. Using simulations of a shear layer superimposed on homogeneous isotropic turbulence over a wide range of Stokes numbers, they show that the Gaussian KBMM and 2Φ -EASM ACBMM methods provide very good results for a large range of Stokes numbers, bridging the gap between two types of approaches in the literature and holding promise for complex flow configurations. In the same framework, but for moderately dense sprays, Doisneau *et al.* focus on Eulerian modeling of coalescence and droplet trajectory crossing (DTC) using a flow configuration with two crossing droplet jets at finite Knudsen number in a uniform gaseous flow. In the context of Eulerian methods, the main challenge is to capture DTC and the correct coalescence rate without resorting to high-order velocity moment methods. Using discrete droplet simulations as a reference, they demonstrate that the Eulerian model predicts the proper polydispersity and flow dynamics, which is an important step towards simulation of alumina particles in rocket boosters. He *et al.* develop a subgrid LES model for the fluid velocity seen by particles in dilute particle-laden turbulent flows. The principal challenge was to capture preferential concentration generated by the unresolved turbulence scales using information contained in the resolved scales. By comparing Lagrangian simulations coupled to fluid LES, they demonstrate the ability of the subgrid LES model to capture most of the preferential concentration observed with fluid DNS over a range of Stokes numbers.

Rodney Fox
Mikhael Gorokhovski
Marcus Herrmann
Marc Massot