

Multiphase and Particle-Laden Flows group: overview

In the past two decades, multiphase flows have emerged as an important topic of research within the Center for Turbulence Research (CTR). In this Summer Program, similar to the past six editions, projects in the field of multiphase flows were agglomerated as a separate group. The Multiphase and Particle-Laden Flow group was in fact the largest among all groups, consisting of 8 projects, 15 participants, and 14 hosts. The work in this group spanned a wide range of topics, including four projects on particle-laden flows, two projects on interfacial flows, one project on transcritical flows, and one project on direct kinetic modeling of plasmas. In spite of the size of the group and diversity of the projects, we make note of a remarkably cordial, interactive, productive, and collaborative environment, which is reflected in the quality of the work carried out, summarized in the following.

Apte developed a novel approach that corrects for the self-disturbance created by particles in a two-way coupled approach. The method uses an overset grid to solve a system of advection-diffusion-reaction (ADR) equations to compute the disturbance field. One of the main advantages of the proposed method compared to other methods in the literature is that it is easily applicable to a wide range of flows, including wall-bounded flows, and can be used with different interpolation kernels and arbitrary grids. Using this ADR method in simulations of particle-laden decaying isotropic turbulence, Apte *et al.* performed a systematic study on the effect of the choice of interpolation kernels (grid-based Roma and Gaussian) and kernel widths. They showed that the kernel widths used for Euler-to-Lagrange and Lagrange-to-Euler interpolations should scale with the particle size and be independent of the grid resolution to maintain the same region of influence of the particle on the flow, irrespective of the grid resolution. This was found to yield optimal accuracy. They also found that use of a wider kernel in proportion to the particle size, for Euler-to-Lagrange interpolation, will sample the flow from a region less affected by the particle disturbance, leading to better predictions of the particle velocity even without using any correction model for self-disturbance. This has significant implications in point-particle simulations of particle-laden flows.

As part of a large team effort led by Professor Schneider, Matsuda *et al.* developed a wavelet transformation-based multiresolution tessellation technique to analyze scale-dependent statistics of particle velocity divergence in turbulent flows. They verified the newly developed method by comparing it against the energy spectrum obtained from a Fourier-based approach using two test cases: (i) synthetic randomly distributed particles and (ii) inertial particles in isotropic turbulence from direct numerical simulations (DNSs). This fast and efficient tool, which doesn't require the projection of particle cloud data onto Eulerian grids, can be used to understand the multiscale dynamics of particle clustering in turbulent flows. Another work from this team was on the development of data-driven machine learning models for predicting preferential concentration of particles in isotropic turbulence (Oujia *et al.*). They trained autoencoder, U-Net, and generative adversarial networks (GANs) to predict the particle density fields using the flow field as the input, and vice versa, and validated the models using DNS data. They found that the GANs are accurate in predicting the statistical quantities of interest for particle distributions, which has implications for subgrid modeling of particle-laden turbulence.

Finally, West *et al.* performed four way-coupled simulations of particle-laden turbulent channel flow for various mass loadings, and computed the divergence and curl of the particle velocity using Delaunay tessellation. They performed statistical analyses of these quantities at various locations away from the wall and found that the divergence and curl are strongest in the buffer layer, owing to the stronger fluctuations of fluid velocity. They also found that increasing mass loading results in damping of these quantities in the viscous sublayer.

Vartdal and Jain performed particle-resolved simulations to generate a database of the flow around monodispersed particles at various Mach and Reynolds numbers, particularly in the presence of volume fraction gradients. Using the database, closure models for volume-averaged multiphase flows were improved. They found that the drag law that was previously derived from homogeneous conditions gave accurate predictions in the presence of volume fraction gradients. Additionally, they proposed a modification to the previously developed algebraic model for pseudo-turbulent stresses by correctly accounting for the effect of volume fraction gradients using the information of the wake of the particles upstream. This work can be applied to modeling various particle-laden flows of engineering interest.

Santos *et al.* studied the effect of subgrid-scale (SGS) turbulence on the flight behavior, transport, and settling distribution of size-changing firebrand particles in atmospheric turbulent boundary layers. An approximate deconvolution-based SGS model was used to account for the effect of SGS turbulence on particles, and a dynamic burning model was incorporated to account for the variation in size and mass of the smoldering flying firebrand particles. They found that the SGS turbulence makes particles travel larger distances along the streamwise direction and shorter distances along the spanwise direction, and results in reduction of overall dispersion of particles. This study has implications for the accurate prediction and modeling of wildland fires, since the transport of firebrand particles by wind is the primary mechanism responsible for the spread of these fires.

Scapin *et al.* developed a numerical method for simulating low-Mach compressible two-phase flows involving phase change and wetting effects. The method uses a four-equation diffuse interface model, augmented by regularization terms for maintaining the interface thickness, relaxation terms for phase change, and Lagrange multipliers for imposing contact angles while preserving mass conservation. Multiple test cases, including tests involving boiling for varying levels of surface wettability, demonstrated the method's robustness and accuracy for practical simulations.

Goodrich *et al.* extended the dual-scale subgrid closure for large-eddy simulation (LES) of two-phase flows to handle phase change. By capturing the transport of the interface due to resolved and modeled subgrid velocities on a high-resolution overset mesh, filtered interface quantities are computed directly. This work studied the effect of subgrid velocities due to phase change and their interaction with surface tension forces. Comparing against DNS of an interface undergoing phase change in HIT, the authors demonstrated their LES model's accuracy in the infinite Weber number regime. Moreover, these simulations were analyzed to reveal the restorative role of surface tension forces on interface curvature statistics during phase change.

In a trailblazing effort, Bernades *et al.* (*a,b*) explored the possibility of turbulence in microfluidic devices, allowing for enhanced mixing and transfer rates that can be especially beneficial in energy applications. They introduced a novel kinetic-energy-preserving and pressure-equilibrium-preserving numerical scheme [Bernades *et al.* (*a*)] that enabled the computational observation of microconfined turbulence in high-pressure transcritical

conditions [Bernades *et al.* (b)]. The numerical model developed in this work can be useful to the community in the broad context of modeling compressible flows with real-gas effects (e.g., transcritical and supercritical conditions). Most notably though, the DNS results in this project revealed that the statistics of microconfined turbulence in supercritical fluids deviates from standard turbulent flows (e.g., modified law of the wall), and that heat transfer rates are amplified by a factor of 20 compared to an equivalent subcritical configuration.

With the overarching goal of achieving a fundamental understanding of plasma turbulence, Chan *et al.* developed a direct kinetic solver to study current-driven plasma instabilities in one- and two-dimensional settings. Spectral analysis was used to reveal the interplay of longitudinal and transverse instabilities in the transition to plasma turbulence, in addition to the similarities and disparities of plasma turbulence compared to hydrodynamic turbulence. We expect the simulation tool and analysis approach developed in this project to aid in addressing many fundamental questions in the field of plasma turbulence.

We thank all the participants and CTR hosts that contributed to the Multiphase and Particle-Laden Flow group for many engaging and productive discussions during the 2022 CTR Summer Program. Hopefully, these interactions can lead to fruitful collaborations and advancements in the field in the future.

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