Multiphase Flows group: overview

Multiphase flows continue to attract the attention of many researchers in the fluid mechanics community, as reflected in the existence of a Multiphase Flows group in the last several CTR Summer Programs. The Multiphase Flow group in the 2024 Summer Program included seven projects that focused on interfacial multiphase flows. Broadly, these projects addressed outstanding challenges in the field of multiphase flows related to the physics and modeling of turbulent interfacial flows, numerical methods for capturing interfaces, and the modeling of multiphysics effects. A remarkable new feature in 2024 was the prevalence of phase field (diffuse interface) models, as six out of the seven projects either directly contributed to the development of phase field models or used these models to perform their simulations. Overall, Multiphase Flow group participants in the Summer Program took advantage of a collaborative and interactive environment to make substantial contributions to the field.

Two of the projects focused on either directly studying the physics of multiphase turbulent flows or developing methods that will lead to accurate simulations of multiphase turbulent flows. Energy transfer mechanisms in incompressible two-phase turbulent flows have been well studied and understood over the last decade. However, the same mechanisms in the compressible regime are unexplored. Hatashita *et al.* performed isotropic two-phase turbulence simulations in a compressible regime to study the energy transfer mechanisms between phases and different scales. Specifically, they studied the kinetic energy transfer between resolved and subgrid scales and their interaction with pressure dilatation and surface energy. They found that dilatational velocity can directly modify surface energy through dilatational surface power, which explains the enhanced backscatter at the interface. The outcomes of this work will aid in subgrid model development for compressible two-phase turbulent flows.

For accurate simulations of interfacial turbulent flows at affordable cost, adaptive mesh refinement (AMR) has been used as an alternative to classical large-eddy simulation (LES) approaches to capture small-scale dynamics. But even with the use of AMR, resolvable small-scale dynamics can be misrepresented. Herrmann *et al.* assessed the use of a spectral enrichment AMR prolongation operator to accurately recover the resolvable scales in the flow. They used this spectrally enriched AMR approach in a hybrid LES-DNS method and evaluated the accuracy of their approach by studying the curvature statistics in isotropic turbulence. This hybrid LES-DNS approach has the potential to be used for larger engineering-scale simulations of multiphase turbulent flows.

Three other projects were dedicated to improving the state-of-the-art numerical methods for capturing interfaces. The Nordström team aimed to develop nonlinear energy stable schemes for multiphase flow problems. The team developed a computational solver using summation-by-parts operators in space for incompressible two-phase flows. Additionally, they extended the sharp-interface formulation to diffuse interface methods by deriving an energy-stable skew-symmetric form for multiphase initial boundary value problems in the presence of phase field (interface regularization) terms. Ten Eikelder and Khwanwale addressed the absence of Cahn-Hilliard Navier-Stokes phase field models that are conservative and bound-preserving for arbitrary density ratios. Building on the foundations of mixture theory and by using the Flory-Huggins free energy, they developed phase field models that achieve this feat and a numerical solver that discretely inherits the desired boundedness and conservation properties. Lastly, Huang *et al.* compared various phase field models for the simulation of compressible multiphase flows in a unified high-order and bound-preserving framework. This timely study reveals that the application of shock-capturing schemes for compressible flows can introduce nonisotropic numerical diffusion, which, combined with the phase field methods, can result in overwhelming artificial effects. In addition to providing solutions to circumvent or ameliorate these issues, this comparative study illustrated the different behavior of various phase field models when interfacial structures are poorly resolved.

Many practical multiphase flows involve complex multiphysics interactions such as phase change (melting, solidification, evaporation, etc.), N-phase flows ($N > 2$), multiple components, solid deformations, and heat/mass transfer. Two projects focused on deriving thermodynamically consistent models for such effects, as well as their robust integration, implementation, and validation. With the long-term goal of detailed simulations of melting and devolatilization of plastics, Long *et al.* derived and implemented consistent models for nonreactive and nondilute, N-phase, M-component systems involving heat transfer and phase change (melting/solidification). They presented several tests that demonstrate the robustness of their fully coupled multiphase multiphysics models and confirm the viability of diffuse interface methods for simulating the plastic recycling process. Carcana Barbosa *et al.* performed numerical simulations of inertial microbubble cavitation near a gel-water material interface with phase change. They used the reference map technique to simulate hyperelastic neo-Hookean materials and to simulate situations when the bubble was present in the gel and in water. They found that the bubble collapse generates higher strain rates when the bubble is present in the gel than in the water case. This finding agreed well with the experimental observations, validating their approach.

In summary, the Multiphase Flows group had projects in a wide spectrum of areas, focusing on (a) turbulent multiphase flows toward improved understanding of energy transfer mechanisms in compressible regimes and development of subgrid closures, (b) development of robust and nonlinearly stable schemes, and (c) development of thermodynamically consistent models and integration of multiphysics. These problems have a wide range of applications in propulsion, energy, sustainability, and biomedicine, among other areas. Through discussions, the Multiphase Flows group also identified the need for further integration of robust methods and multiphysics models for simulations at the engineering scale as well as for more experimental data for rigorous validation.

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