NUMERICAL MODELS AND METHODS FOR COMPRESSIBLE INTERFACIAL FLOWS WITH SHOCKS

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Abstract:
There has been increasing interest in capabilities to simulate compressible interfacial gas/liquid flows with shocks. To address shortcomings of previous methods, we develop a conservative and consistent Phase-Field formulation that maintains uniform, thin interfaces. This model is implemented into a high-order Discontinuous Galerkin framework with adaptive mesh refinement. This approach enables us to accurately simulate problems such as bubble collapse and high-speed droplet impact.

Keywords: Shocks, Material Interfaces, Phase Fields, Discontinuous Galerkin

Introduction:

There has been an increasing interest in developing capabilities for numerical simulations of compressible interfacial flows, including gases, liquids, and solids, with shocks. Examples include cavitation erosion in propulsor systems, steam explosions, cavity collapse in shock-assisted combustion, hydrometeor impact in high-speed flight, therapeutic ultrasound techniques, high-energy-density experiments, and blast-induced traumatic brain injury. In such flows, shock waves interact with material interfaces between substances of very different densities (e.g., over 1000:1 density ratios), sometimes producing fine-scale flow structures. Progress in understanding and predicting such interfacial flows was enabled by the development of compressible two-phase flows of the Baer-Nunziato type [1]. In this Eulerian, interface-capturing approach, the Euler or compressible Navier-Stokes equations are solved in all phases, along with a compatibility equation (e.g., for volume fraction), and appropriate interfacial exchange terms describing computational cells. Following a strategy similar to shock capturing, material interfaces are regularized over a few grid points in a manner to preserves interface jump conditions. Early investigations focused on addressing spurious pressure errors due to the discontinuous equation of state, conservation errors, and temperature errors. These methods allowed researchers to investigate problems such as the dynamics of non-spherical bubble collapse and shock-droplet interactions. However, serious shortcomings hindered the widespread applicability of such methods. For instance, material interfaces continuously diffuse in a non-uniform manner over the course of the simulations, leading to ambiguous mixture regions and unintended dynamics. Other shortcomings include out-of-bounds solutions, e.g., imaginary sound speeds, volume fractions less than zero or greater than unity, and the production of voids and fictious phases.

Numerical model and methods:

To address the shortcomings described above, we extend the Phase-Field methodology to compressible interfacial flows [2, 3]. Without loss of generality, we start with the five-equations compressible multiphase model and add Phase-Field fluxes, which are computed from an Allen-Cahn formulation. By following an appropriate time-step constraint and using an appropriate bound-preserving limiter and Riemann solver, we achieve a conservative and consistent Phase-Field formulation capable of maintaining a constant and uniform interface thickness. This approach naturally satisfies *consistency of reduction* (i.e., any N-phase system should be able to recover the corresponding M-phase system when $N - M$ phases are absent) such that no overfilling, voids, or fictitious phases are produced. The reconstruction guarantees physically admissible states (pressure/internal energy, mass, volume fraction, etc.), satisfies the second law of thermodynamics, and prevents spurious errors at itnerfaces. Mass, momentum, and energy are conserved and the Phase Field does not change the volume of each phase. The approach readily extends to N phases. This model is implemented into the AMReX adaptive mesh refinement framework [5] extended to high-order accuracy via the Discontinuous Galerkin method [4].

Results and discusison:

The computational framework described above has been verified and validated using a suite of test problems. In Figure 1, we show sample three-dimensional simulations from flow physics problems we are currently investigating (bubble collapse near a wall and droplet impact onto a solid surface).

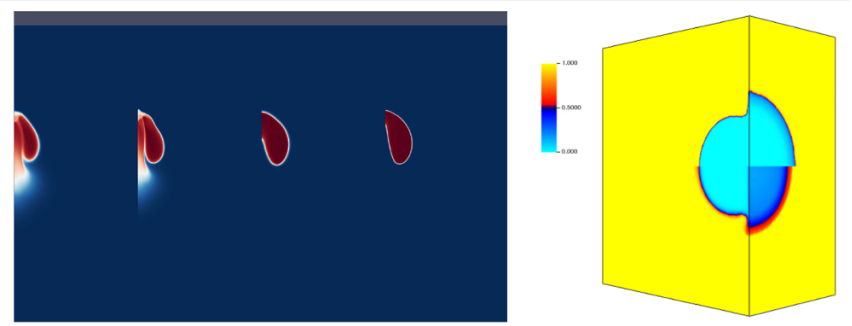

Figure 1: Left: Volume fraction contours of bubble collapse in water near a rigid wall (grey) driven by a 1400:1 pressure ratio for low resolution and no Phase Field, high resolution and no Phase Field, low resolution and Phase Field, and high resolution and Phase Field (left to right); right: Volume fraction contours of a Mach 4 water droplet impact onto a rigid surface (top: with Phase Field; bottom: no Phase Field.

Conclusion:

We present a conservative and consistent Phase-Field formulation that maintains uniform, thin interfaces implemented into a high-order Discontinuous Galerkin framework with adaptive mesh refinement. This approach enables us to accurately simulate problems such as bubble collapse and high-speed droplet impact.

Acknowledgments:

This work was supported in part by the Lawrence Livermore National Laboratory under subcontract B642551, the Office of Naval Research through grant number N00014-22-1-2828 under Dr. Timothy Bentley, and DOE grant DE-SC0023341 (under Dr. Kramer Akli).

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