Effects of Pressure-Temperature Equilibrium on Richtmyer-Meshkov Instability

John W. Grove, Thomas Masser, CCS-2

The most common numerical method for treating multiple material component mixtures is to assume that the mixture consists of separated components that are in pressure-temperature (PT) equilibrium. For inviscid flows, the resulting partial differential equation model is the Euler equations expressing conservation of component mass, total momentum, and total energy. Such a model is relatively easy to implement in a standard compressible hydrodynamics code, but its appropriateness as a flow model is highly problem-dependent since it assumes that the time scales of interest are long relative to the thermal conduction rates of the material components. For high-speed flows with shocks, the component interactions are too fast for the materials to come into temperature equilibrium, and the use of such a model can lead to substantial errors in the computation.

We studied effects of PT equilibrium on flow hydrodynamics for Richtmyer-Meshkov (shock-driven) instability by comparing two hydrodynamic codes, the Advanced Simulation and Computing (ASC) code RAGE/SAGE, which uses PT equilibrium for mixed cells, and the University at Stony Brook's hydro-code FronTier, which maintains pure material cells separated by tracked material interfaces. FronTier also supports interfaces with shear, while RAGE/SAGE assumes a single velocity amongst mixture components.

We found that PT equilibrium causes several pernicious effects for a flow calculation. Figure 1 shows spurious initialization transients generated at temperature discontinuities. The flow is simple periodic translation of a slab of hot dense material at constant pressure. The exact solution is computed by FronTier, but even at early time nearly 10% oscillations in the density field are produced near interfaces when PT equilibrium is imposed. At late time these transients in fact dominate the flow. The graph compares three versions of RAGE/SAGE calculations, one with the default setting for the hydrodynamics, one with interface preserving artificial compression, and the other with volume of fluid interface reconstruction (VOF). The behavior of all three schemes is similar.

A second main effect is over-cooling of compressible regions. Figure 2 shows a late-time comparison for a cylindrical implosion of a tin layer into an air cavity. Two major differences are immediately apparent. The multiple shock refractions driving the instability have produced pockets of superheated air that are over an order of magnitude hotter when computed by explicit interfaces in FronTier as compared to the highly mixed PT equilibrium cells in RAGE. The vorticity field shows an even more marked difference, with XSAGE (a cousin of SAGE) yielding a much more diffuse vorticity field than the corresponding FronTier simulation.

For more information contact Thomas Masser at tmasser@lanl.gov.

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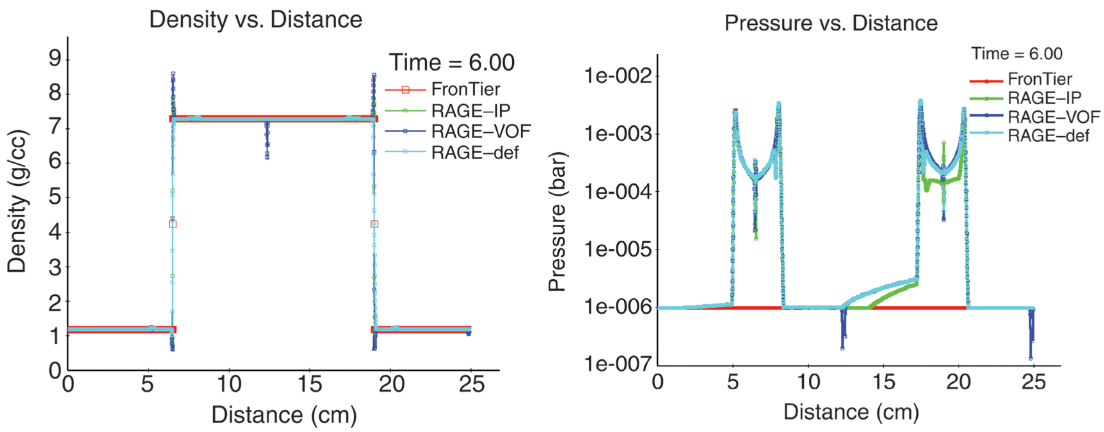

Fig. 1.
Pressure transients created by the imposition of temperature equilibrium at a density-temperature interface.

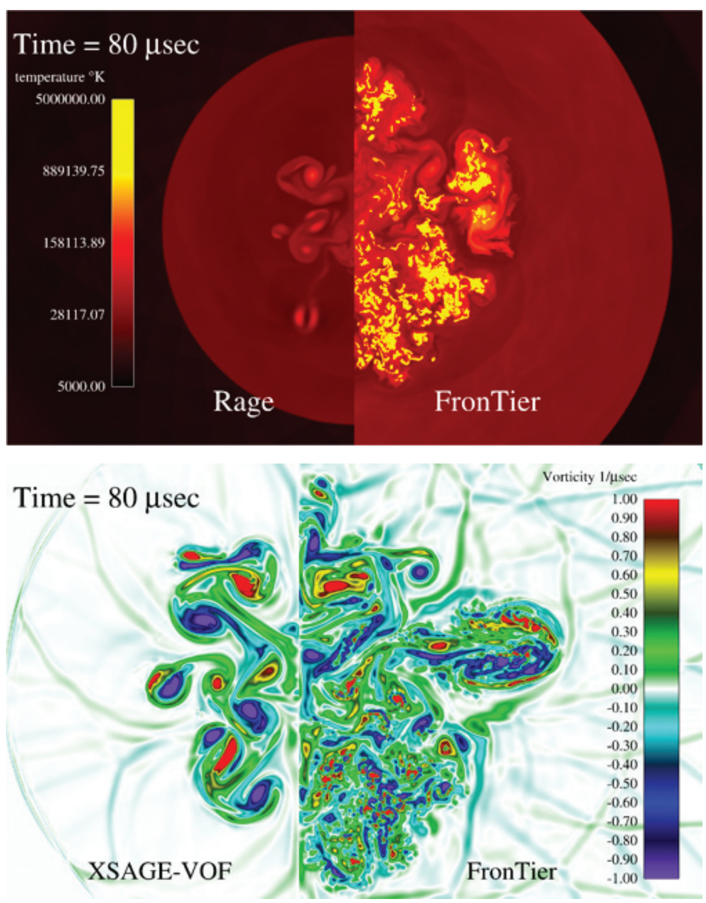

Fig. 2.
A late-time comparison of cylindrical Richtmyer-Meshkov instability. FronTier produces substantially hotter pockets of air with a more complex vorticity field than the RAGE/XSAGE calculation.