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Continuum and Particle Simulations of the Richtmyer-Meshkov Instabilities

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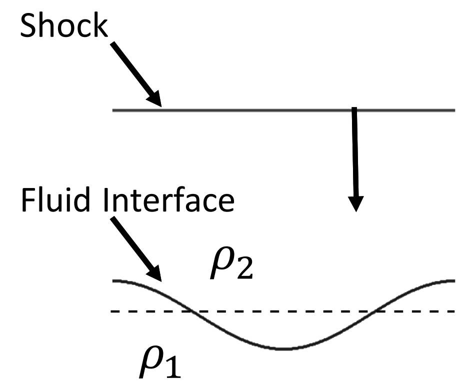
Introduction



Richtmyer-Meshkov Instability

- Shock-induced baroclinic vorticity generation that occurs at a fluid interface
- Extension of Rayleigh-Taylor Instability
  - Gravity driven
- Characterized by Atwood number: A

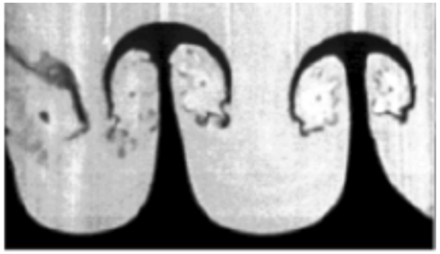
$$A = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}$$

Applications

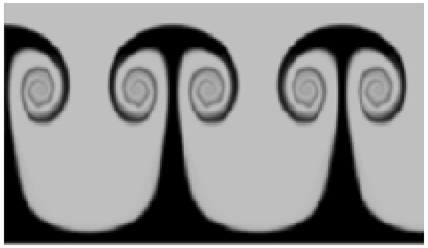
- Inertial confinement fusion
- Material mixing in supernovae
- Combustion systems

Motivation for applying DSMC

- Late-time development of the instability depends on the initial condition
  - Nishihara et al., Youngs
- Need a realistic initial condition to better reproduce experimental behavior



Experiment



Simulation

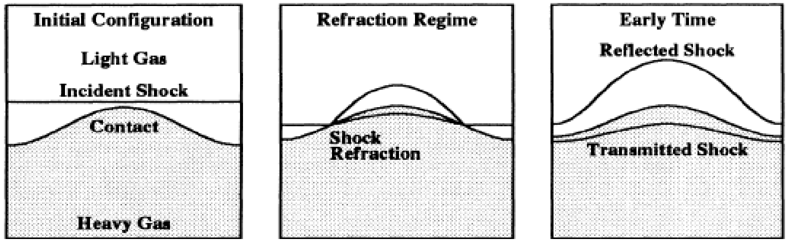
Richtmyer-Meshkov Instability

Shock propagation

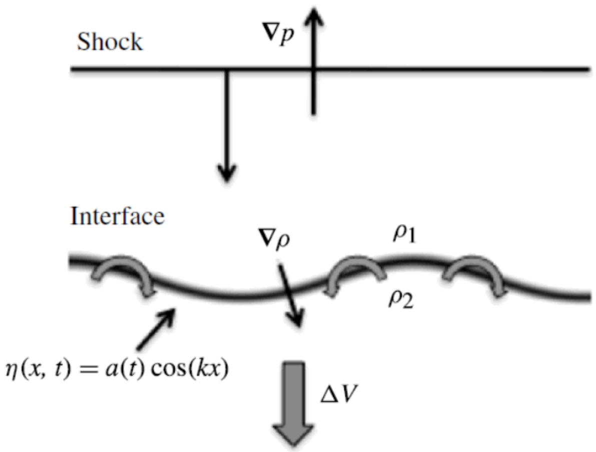
- Incident shock travels down in upper gas
- Transmitted shock travels down in lower gas
- Reflection behavior depend on Atwood number
  - Positive results in reflected shock
  - Negative results in reflected rarefaction

Interface motion

- Interface is accelerated to constant velocity
- Travels in same direction as shock
- Vorticity generated baroclinically at interface
  - Density & pressure gradients misaligned



Grove et al.

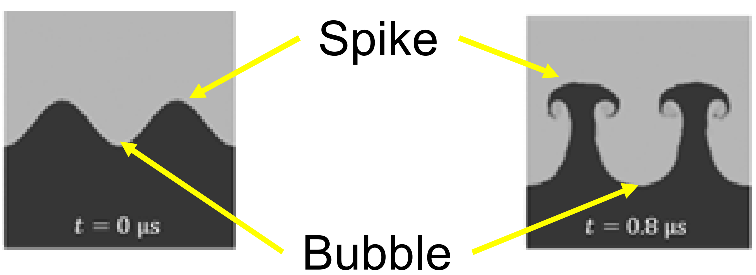


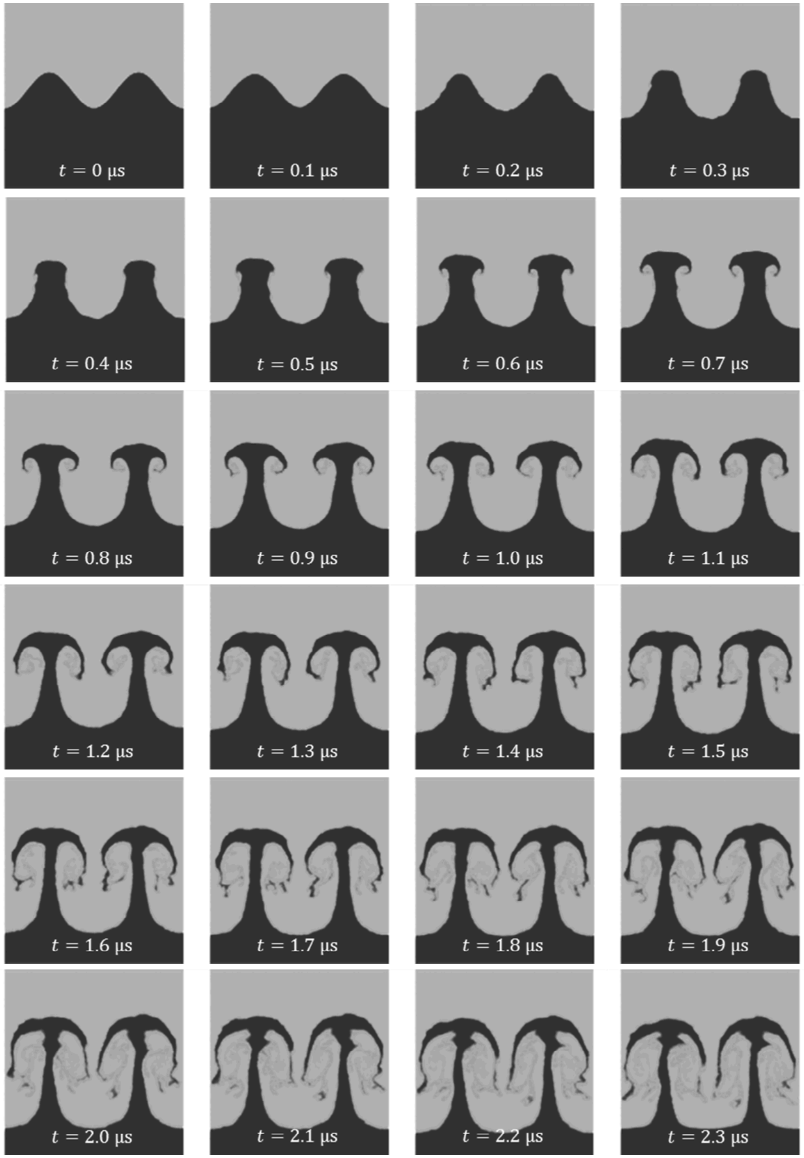
Morgan et al.

Richtmyer-Meshkov Instability

Perturbation growth

- Initially, amplitude growth is linear with time
- Later, amplitude growth becomes nonlinear
  - When amplitude is similar to wavelength
- Spikes features begin to roll-up and gain other disturbances





Gallis et al.

Computational Methods

Navier-Stokes: US3D

- Developed by Graham Candler et al. at the University of Minnesota
- Reacting, 3D NS equations based on finite volume formulation
- Many spatial flux evaluation and time advancement methods
  - 3^{rd} order Runga-Kutta time advancement
  - 6^{th} order KEC spatial fluxes with 2^{nd} order MSW dissipation
- Thermal equilibrium or T-Tv thermal non-equilibrium

DSMC: SPARTA

- 1D, 2D, 2D-axisymmetric or 3D, serial or parallel
- Cartesian, hierarchical grid
  - Oct-tree (up to 16 levels in 64-bit cell ID)
  - Multilevel, general NxMxL
- Triangulated surfaces cut/split the grid cells
  - 3D via Schwartzentruber algorithm
  - 2D via Weiler/Atherton algorithm
- C++, but really object-oriented C
  - Exascale-capable (scales to 1.6 Million cores, GPUs, Threading)
  - The code has been extensively verified and validated.
  - Includes advanced collision/chemistry models, boundary conditions, etc.

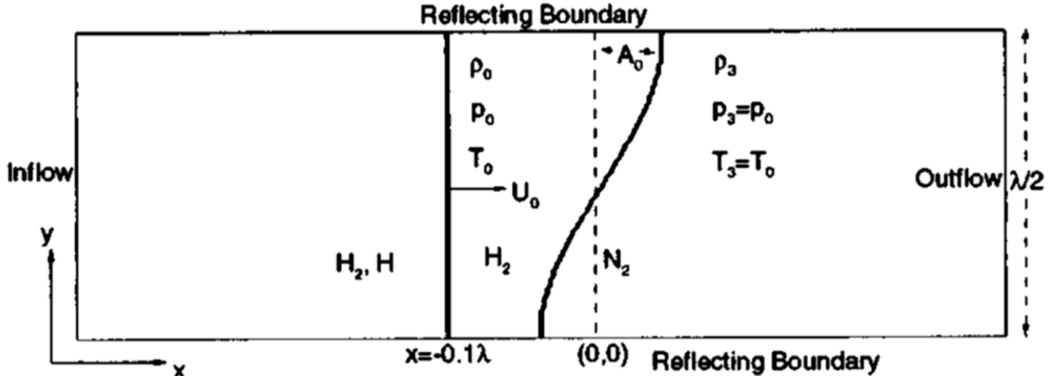
NS Verification Study

Code-to-Code Comparison

- Use a previous simulation to verify the NS solver to calculate a high-Mach number RMI

Samtaney and Meiron

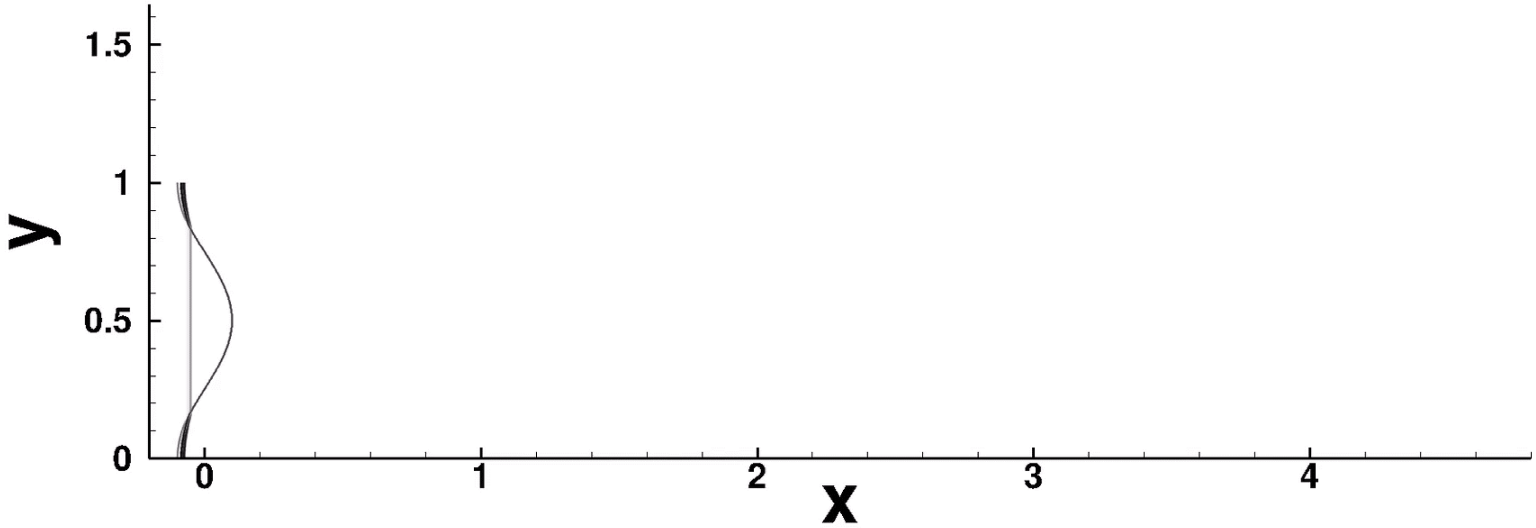
- Inviscid, non-reacting Mach 10 H_2- N_2 interface, A = 0.867
- Mimic conditions in the Caltech T5 shock tunnel
- Pressure P_0=P_3 = 0.1 atm; Temperature T_0=T_3 = 298.0 K
- Disturbance: wavelength = 0.1m; initial amplitude A_0 = 0.01m
- 2nd-order accurate method range of grids
  - 500x50; 1000x100; **2000x200**; 4000x400



RMI Simulation

Density gradient magnitude video

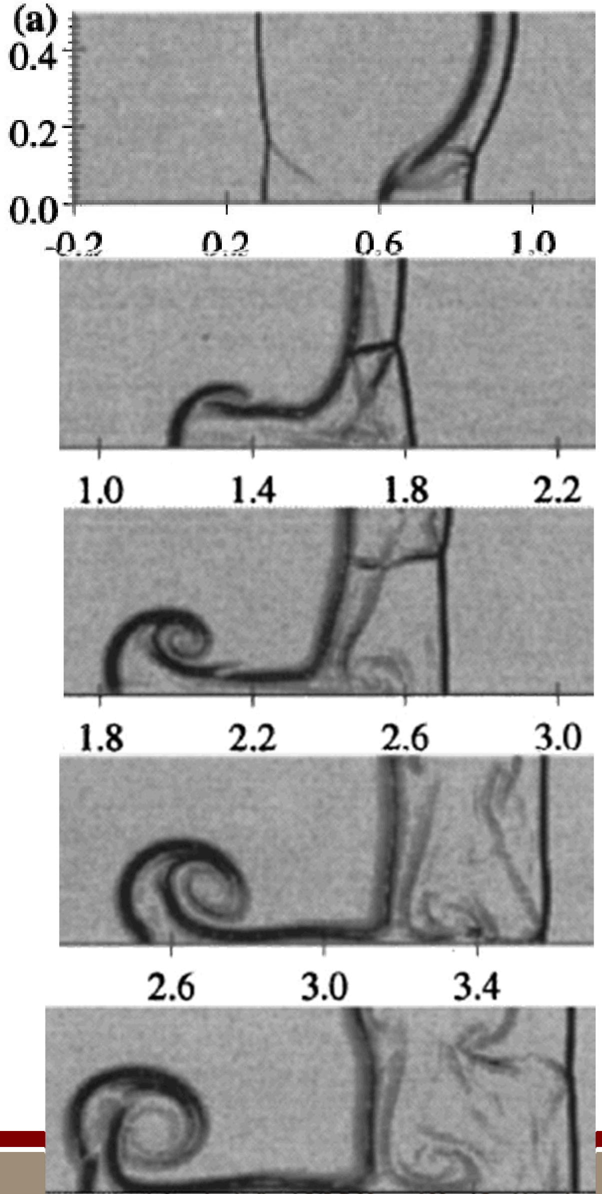
- Experimental data is often taken by shadowgraph
- Computational shadowgraph can be approximated with density gradient magnitude



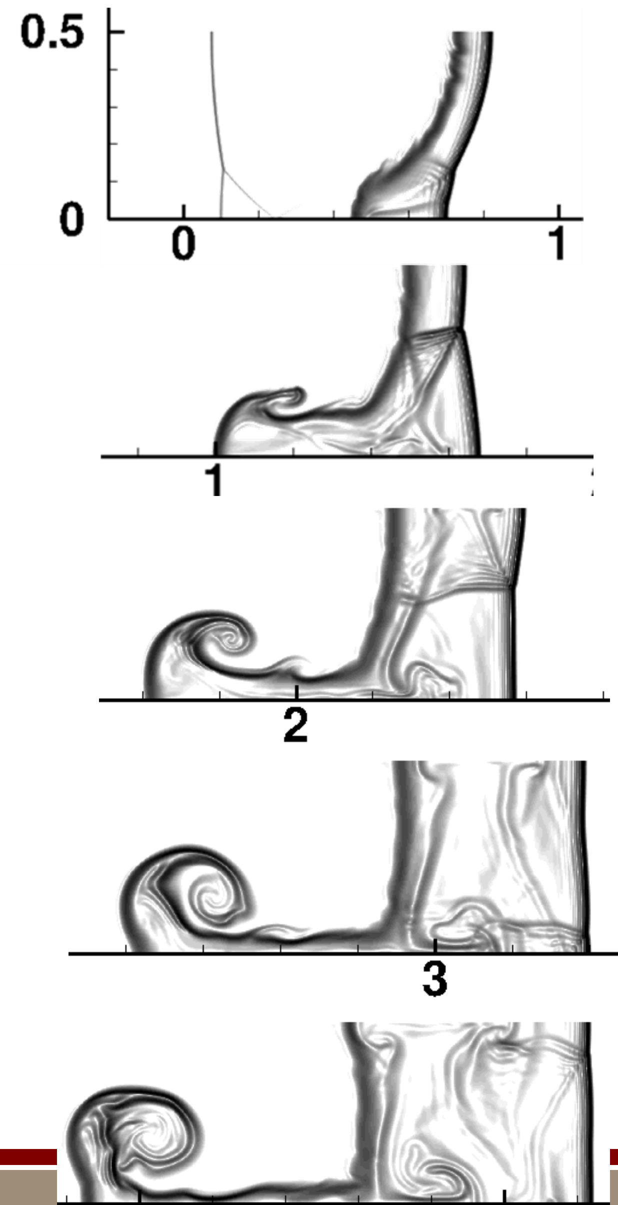
Dimensions normalized by wavelength

Simulation Comparison

Samtaney and Meiron



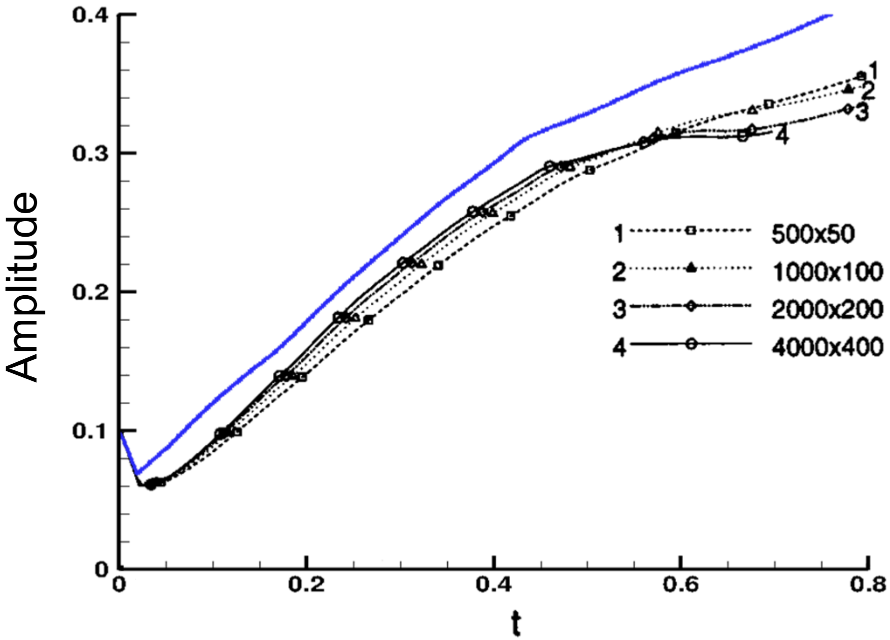
Current



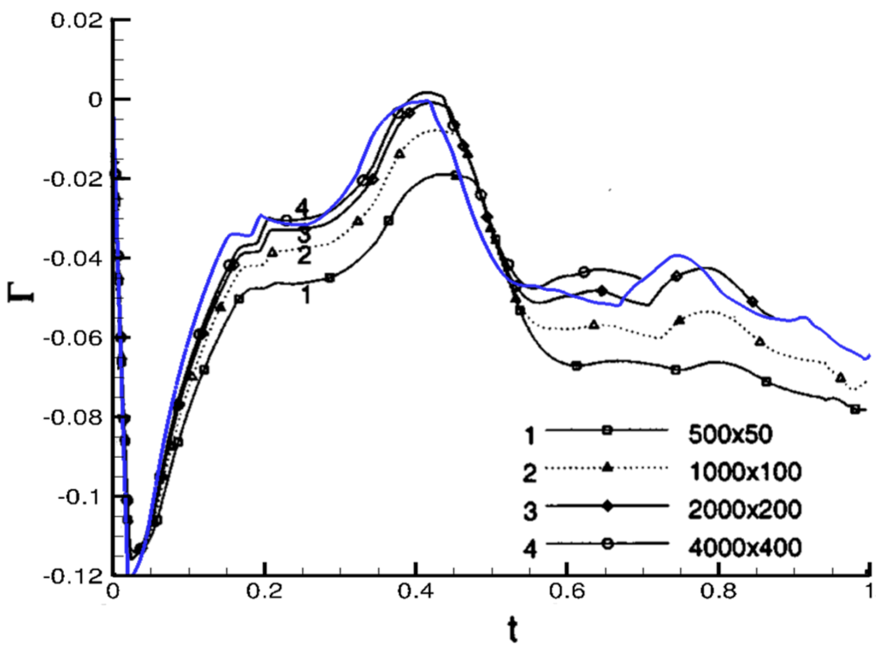
Simulation Comparison

Quantitative comparison

- Disturbance amplitude
  - Higher in the current study
  - Amplitude growth similar
- Circulation
  - Similar to previous work
  - Wave speed difference evident



Normalized Disturbance Amplitude

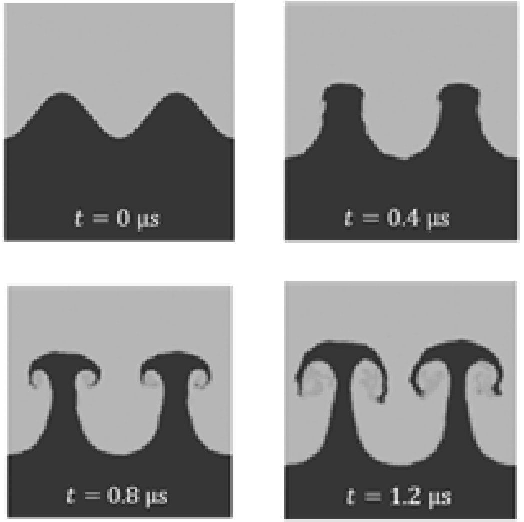


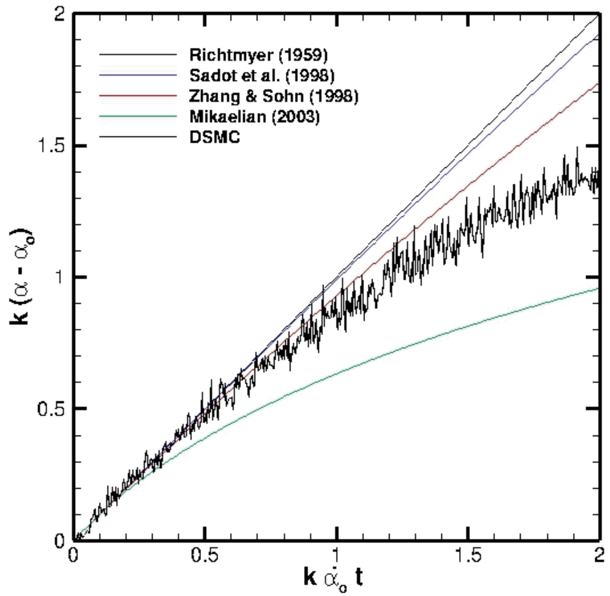
Normalized Circulation

SPARTA Verification

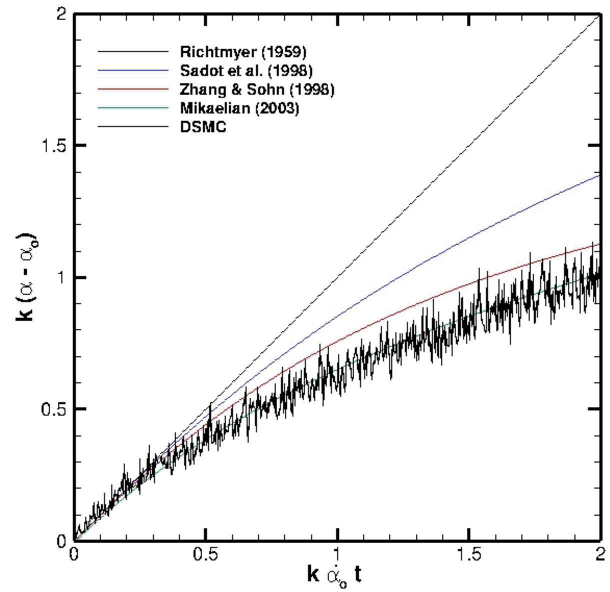
Gallis et al. Physics of Fluids 2015

- Series of lower Mach RMI simulations
- Compared against various theories
  - Early time compressible
  - Late time incompressible
  - Limit of A → 0





Ar/He A=0.82



Ar/Ne A=0.33

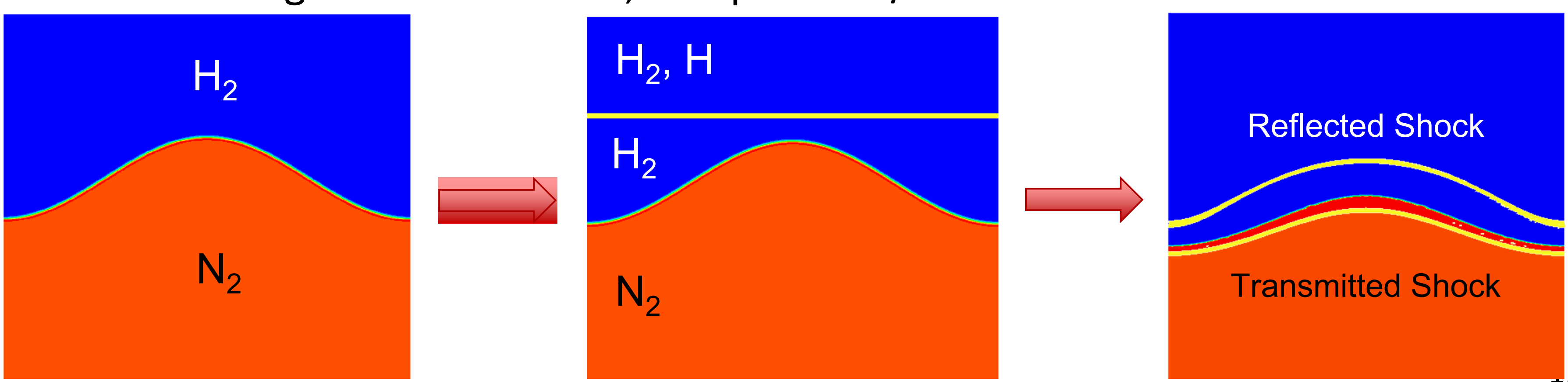
Reacting RMI Comparison

Compare the NS simulations to DSMC

- Evaluate differences in flowfield development
- Determine what NS can learn from DSMC simulations

Similar conditions to Samtaney and Meiron

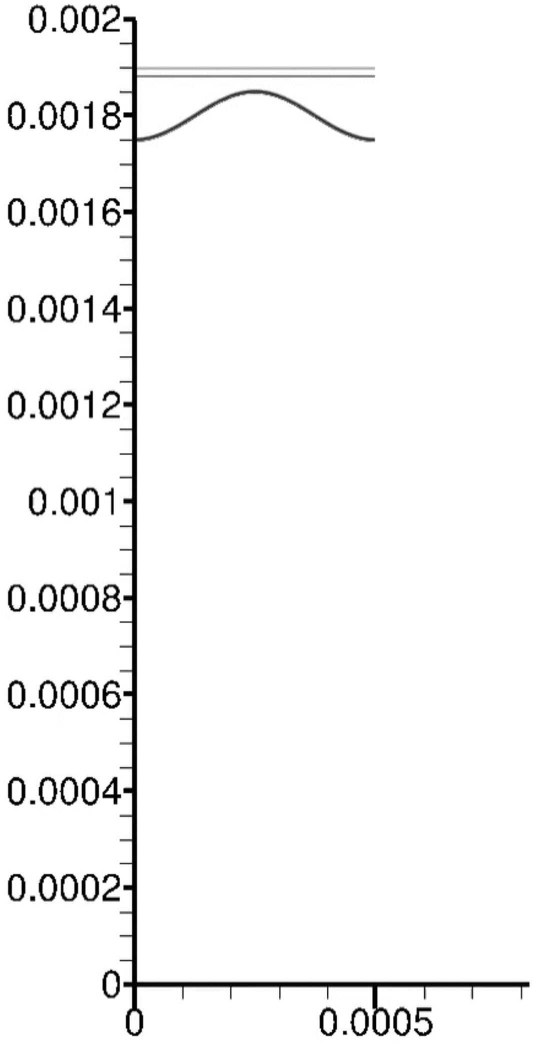
- Viscous, **dissociating** Mach ~ 10 H_2- N_2 interface, A = 0.867
- Pressure P_0=P_3 = 101.4 kPa; Temperature T_0=T_3 = 278.15 K
- Disturbance: wavelength = 0.5 mm; initial amplitude A_0 = 0.05 mm
- Nominal grid: 1000x4000 cells; Refined grid: 2000x8000 cells
- DSMC grid 10000x40000; 100 particles/cell



CFD Simulation

Simulation Characteristics

- Similar flow features to Samtaney and Meiron
  - Different scale
  - Shock refraction
  - Vorticity generation leading to roll-ups
  - Highest temperatures confined to interface region
- Addition of viscosity adds
  - Diffusion of the interface
  - More Kelvin-Helmholtz features



Density Gradient Magnitude

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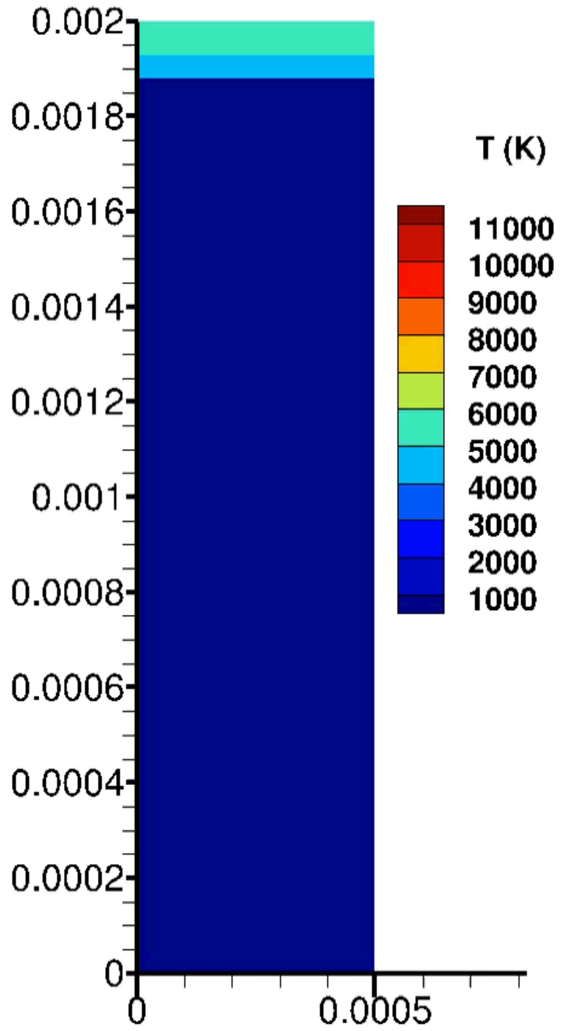
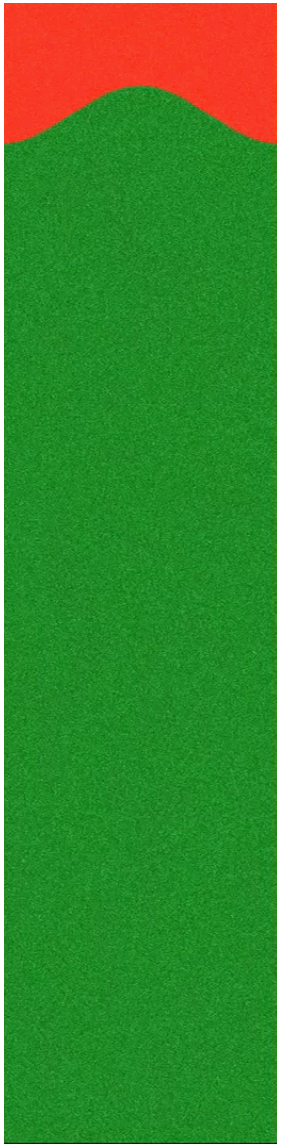


Temperature Contours

DSMC Simulation

Simulation Characteristics

- Shocked interface is different
  - Immediately has a larger range of scales compared to CFD
  - Pockets of dissociation coincide with small scale fluid fluctuations
- Similar features to CFD
  - Shock refraction still visible
  - Vorticity generation leading to roll-ups
  - Highest temperatures confined to interface region
  - Diffusion of the interface



Contours of most prevalent molecule
Colored by: N_2 N H_2 H

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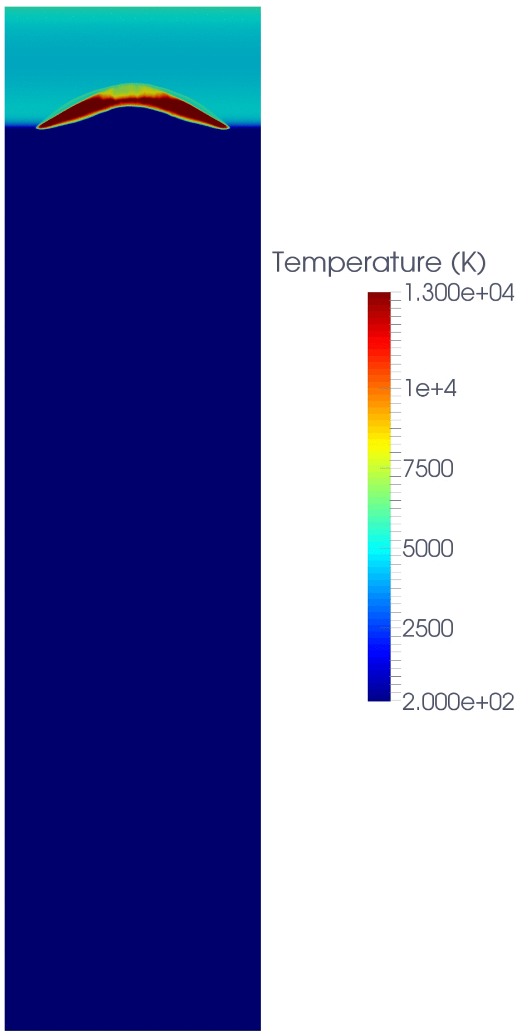
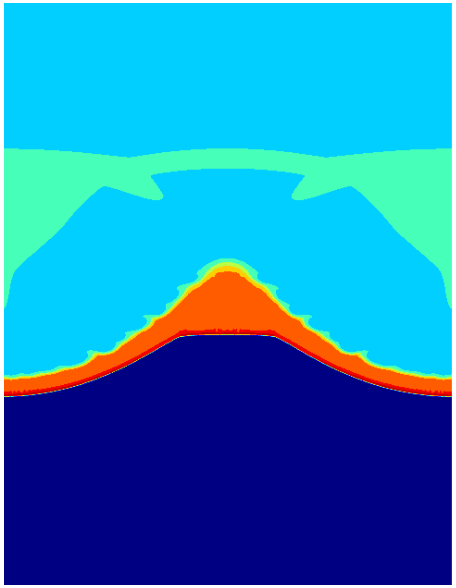


Temperature Contours

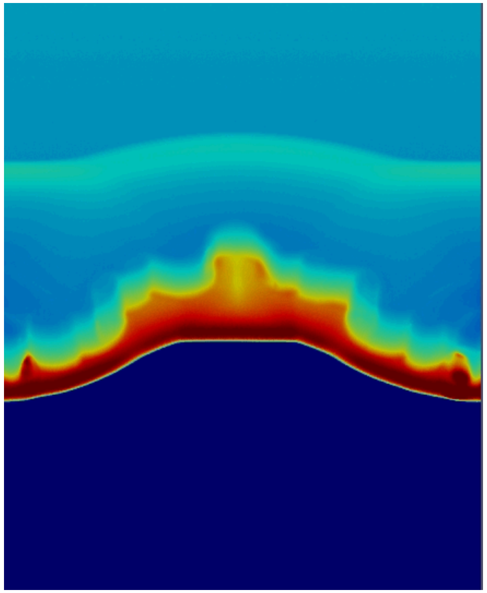
Method Comparisons

Compare solutions at 80 nanoseconds

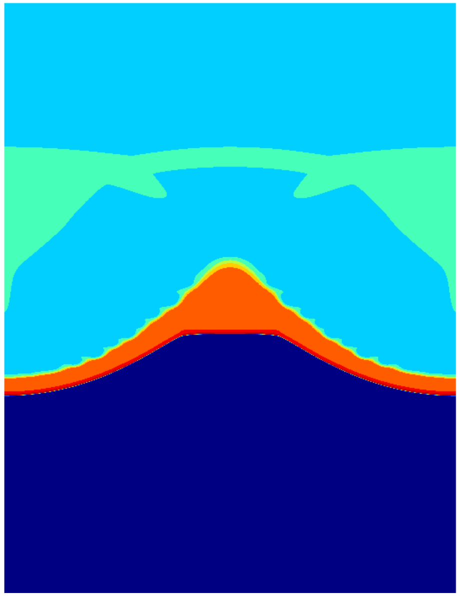
- Simulations show similar behavior
  - Similar wave speeds and disturbance amplitudes
- DSMC shows a more feature-rich interface
  - Most likely due to particle information



Nominal NS



DSMC



Refined NS

Data from Experiments

Smooth interface is not realistic

- Data from Morgan et al. show higher frequency content compared with primary disturbance
- NS method late-time behavior would improve if it could mimic this initial condition

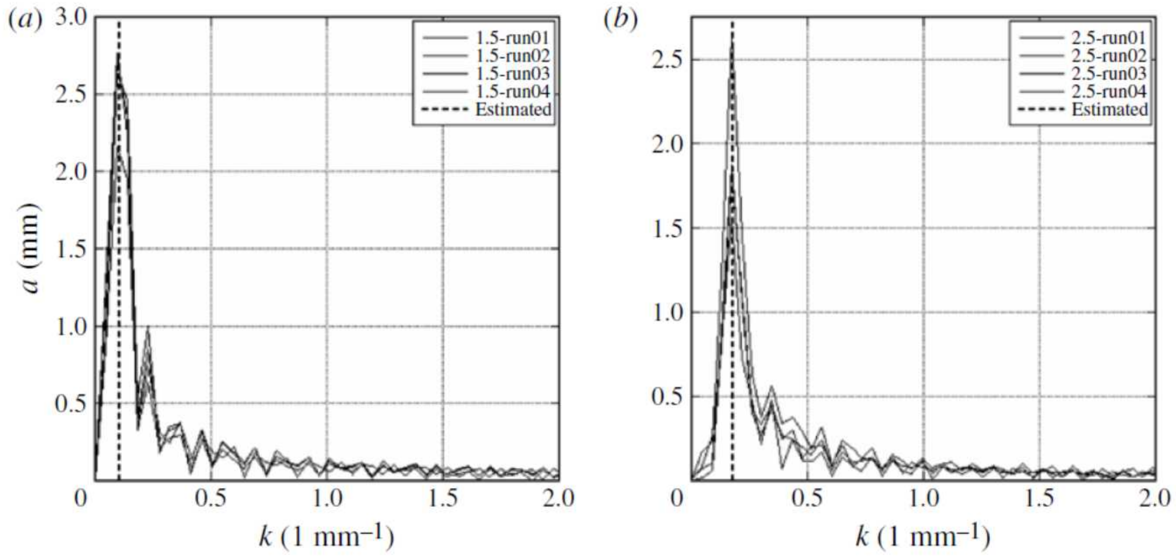


FIGURE 6. Spectra of wavenumbers present in the initial perturbation of Mie scattering experiments: (*a*) 1.5 wavelengths; (*b*) 2.5 wavelengths. Both sets of spectra exhibit weak higher harmonics and a strong peak near the desired wavenumber.

Morgan et al.

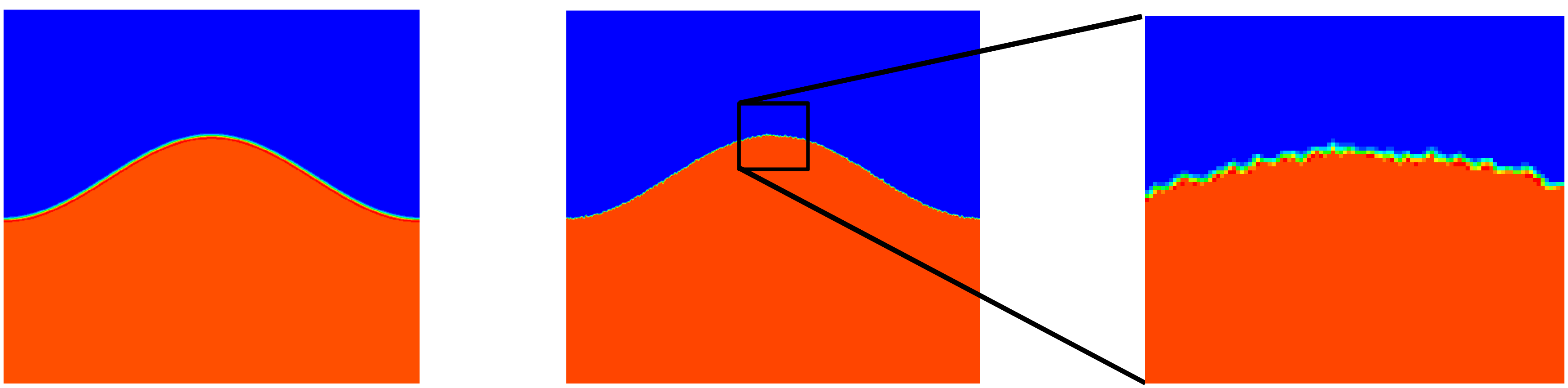
Random noise description

Smooth vs. fuzzy interface

- DSMC simulations produce a more feature-rich interface
- Test to determine if NS method can reproduce something similar
- Apply random noise to interface in the NS simulations

Same conditions as before

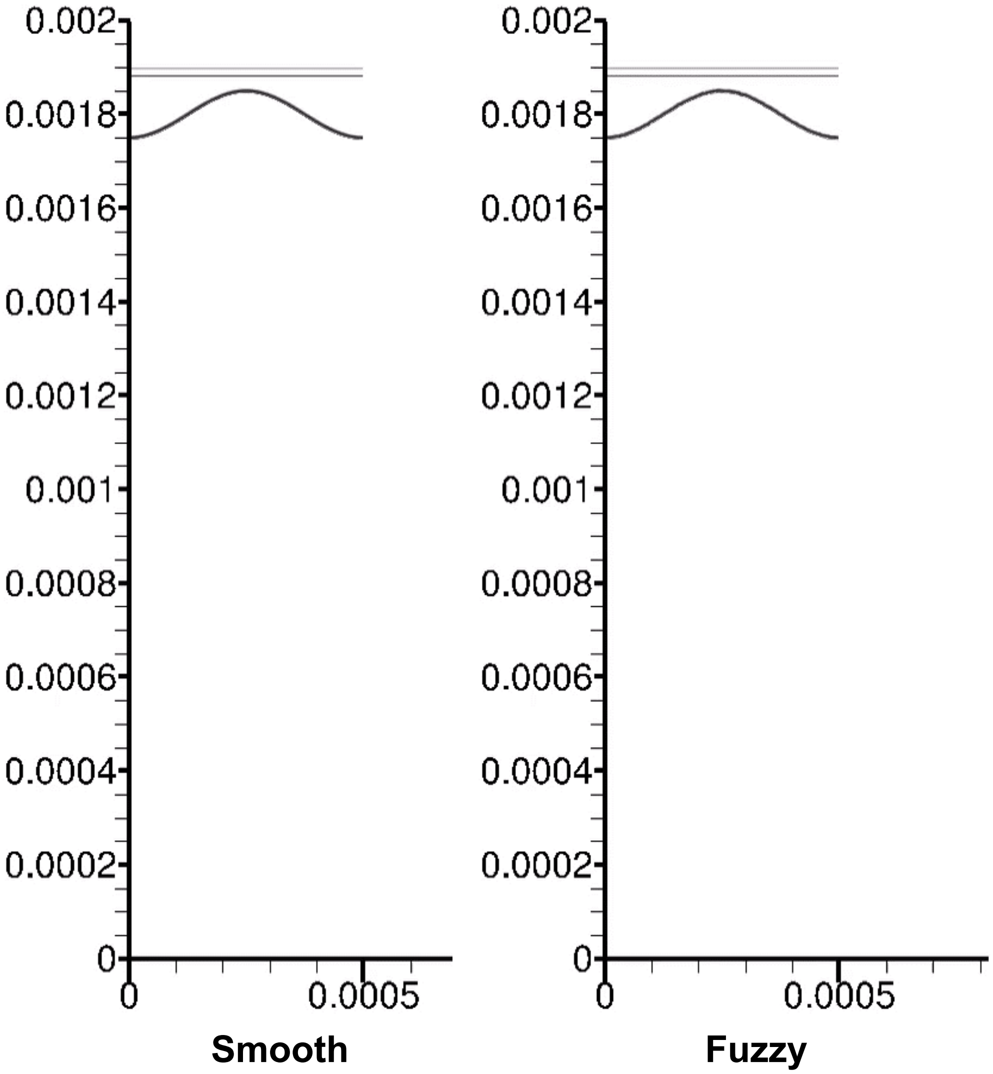
- Viscous, **dissociating** Mach ~ 10 H_2- N_2 interface, A = 0.867
- Pressure $P_0=P_3$ = 101.4 kPa; Temperature $T_0=T_3$ = 278.15 K
- Disturbance wavelength = 0.5 mm; initial amplitude A_0 = 0.05 mm
- Grid size 1000x4000 cells



Smooth vs Fuzzy

Simulation differences

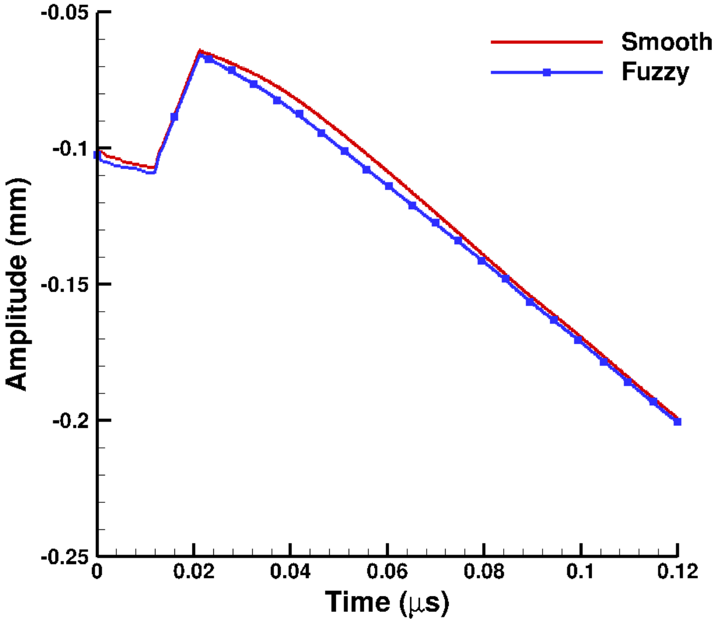
- Fuzzy interface produces asymmetries
- Fuzzy interface has more secondary disturbances



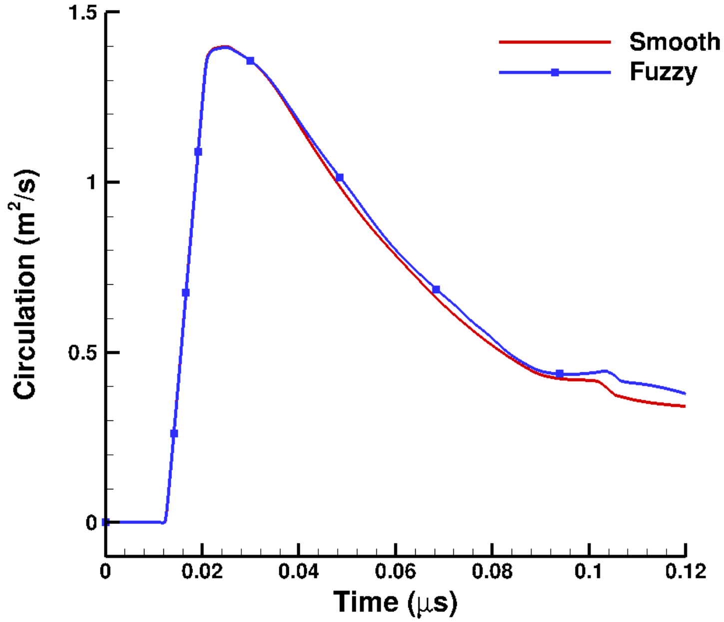
Smooth vs Fuzzy

Solution comparison

- Addition of the interface noise produces a small change in amplitude and circulation



Disturbance Amplitude

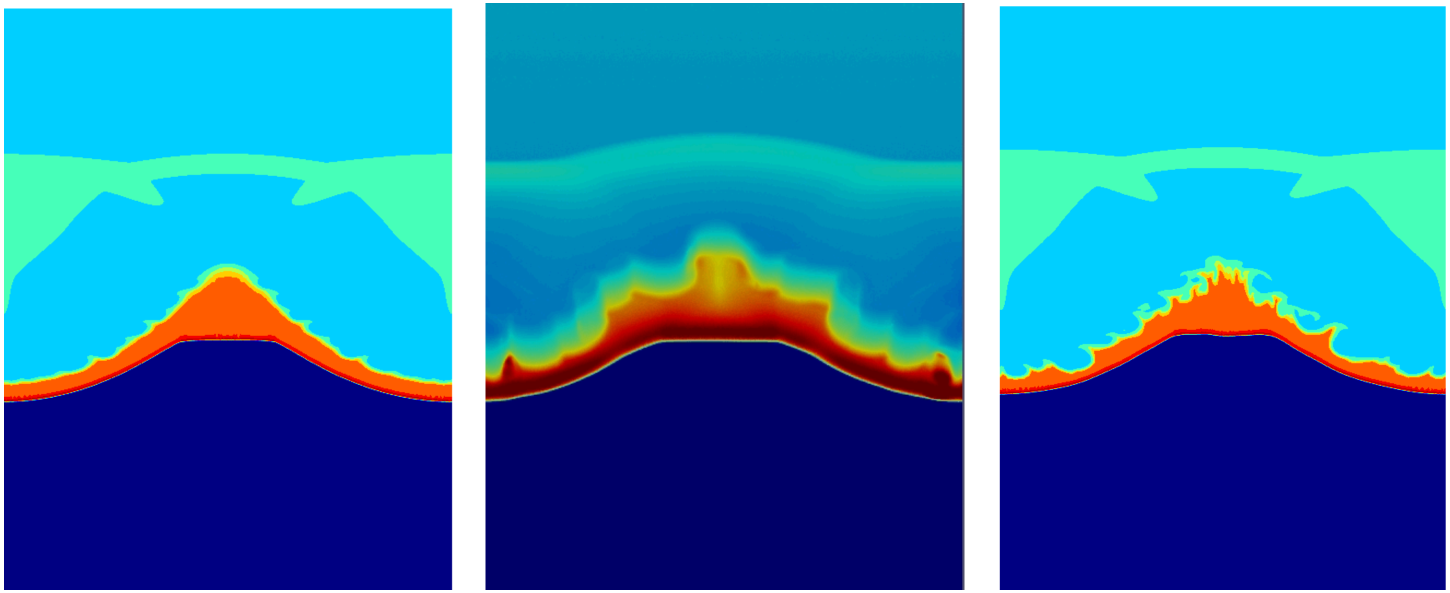


Circulation

Method Comparisons

Compare solutions at 80 nanoseconds

- Fuzzy interface in the NS simulation produces an interface more similar to the DSMC simulation



Smooth NS DSMC Fuzzy NS

Summary and conclusions

Comparisons show DSMC viable method for reacting hypervelocity RMI simulations

- DMSC produce a more realistic, feature-rich interface due to particle information at the interface

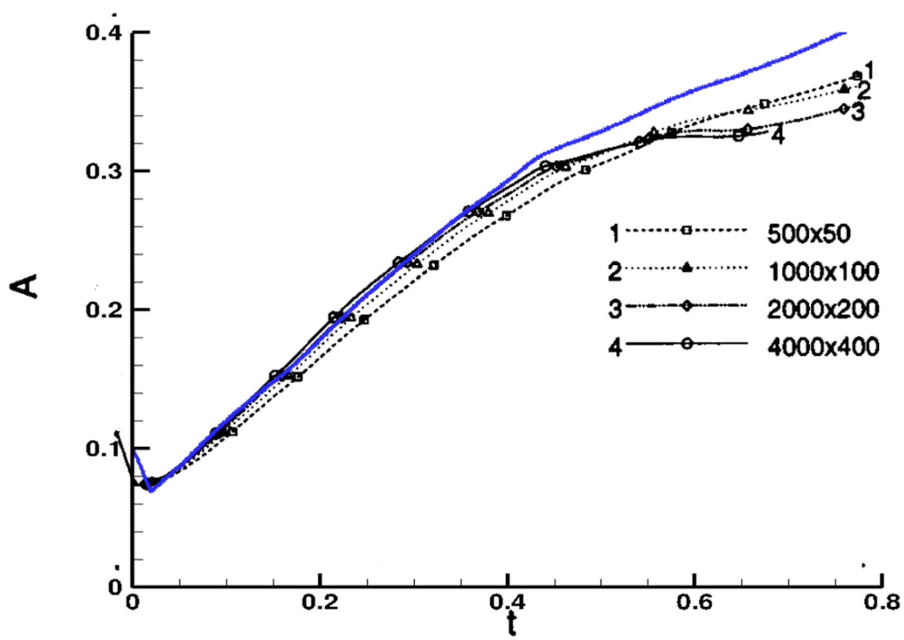
Work in progress

- Continuing development of NS interface information to better reproduce DSMC behavior
- Need experimental data at reacting gas conditions to benchmark both codes against

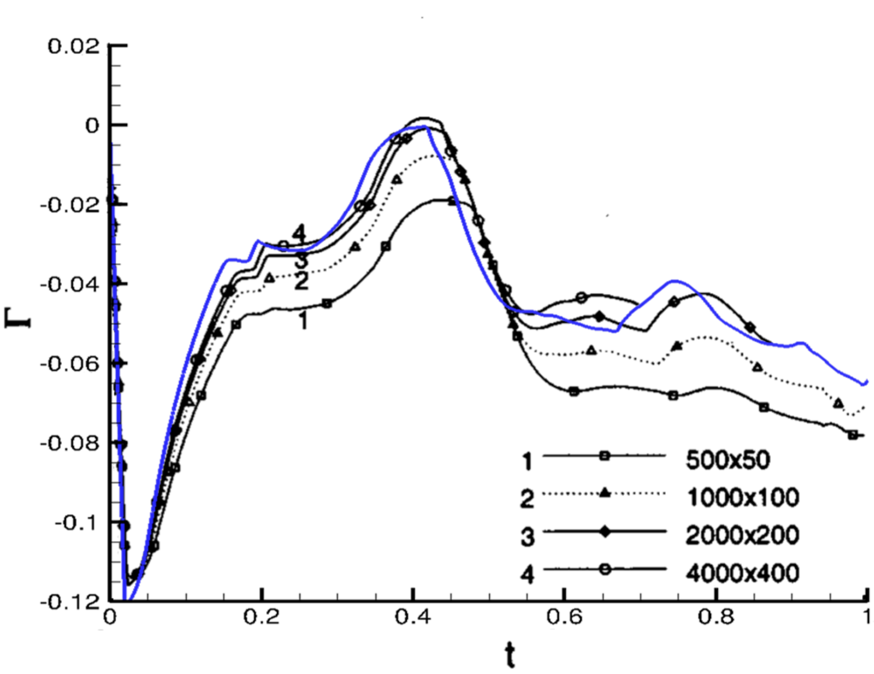
Questions?

Quantitative Comparisons

Interface Amplitude



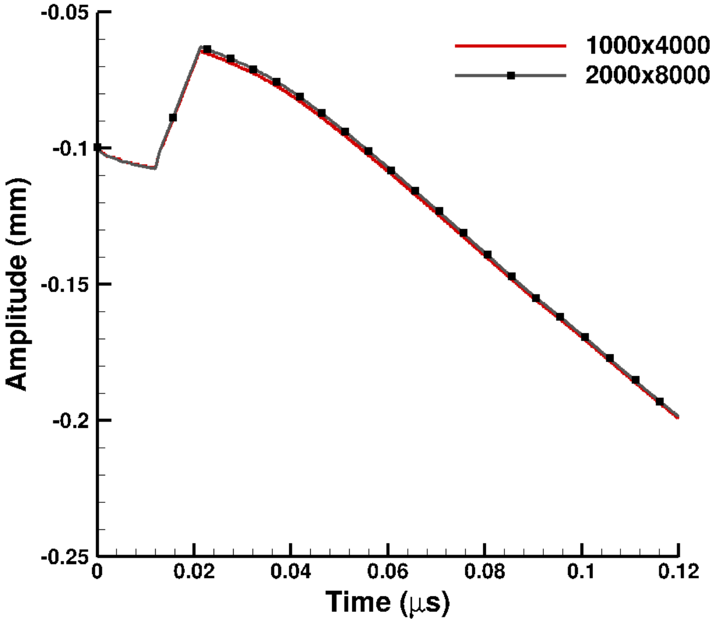
Circulation



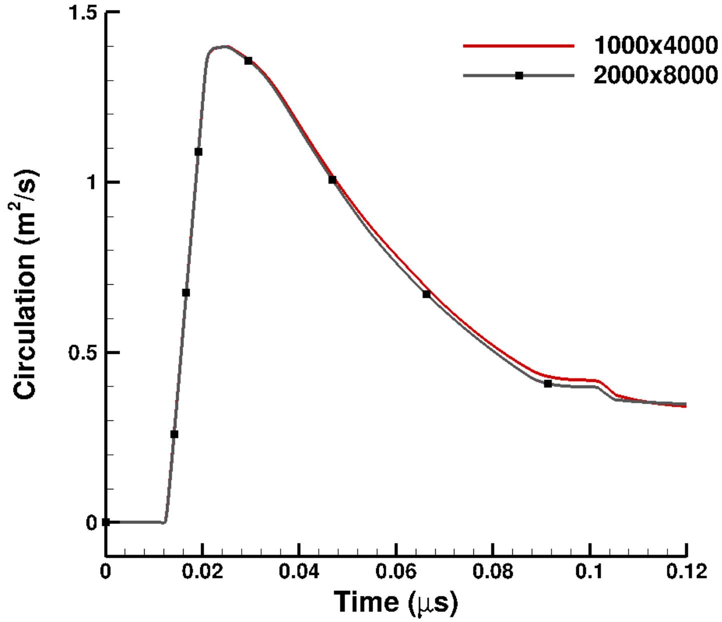
Grid Convergence

Solution comparison

- CFD solution shows minimal difference between nominal and refined grids



Disturbance Amplitude



Circulation