The Application of Multi-Phase Flow Models in Simulations of Fluid Structure Interaction

Presented by:

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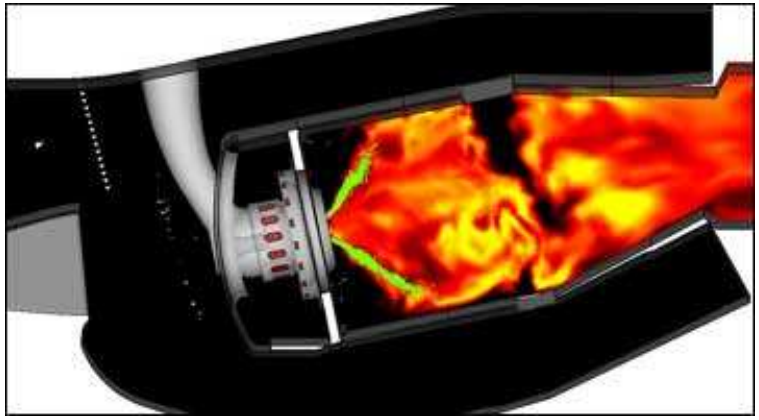
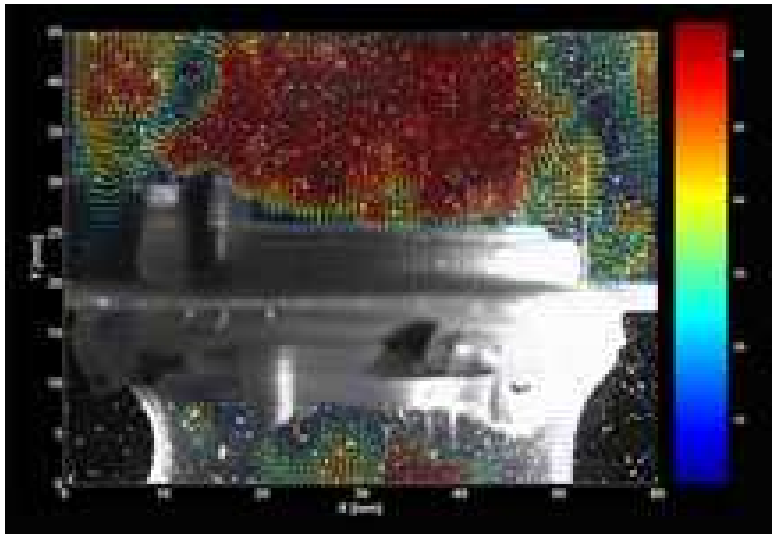
Motivation



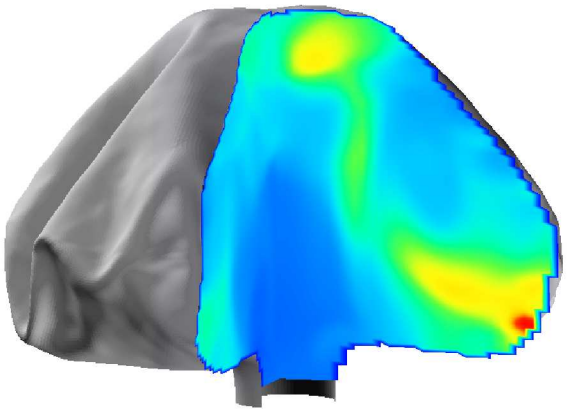
Ham *et al*. (2003)



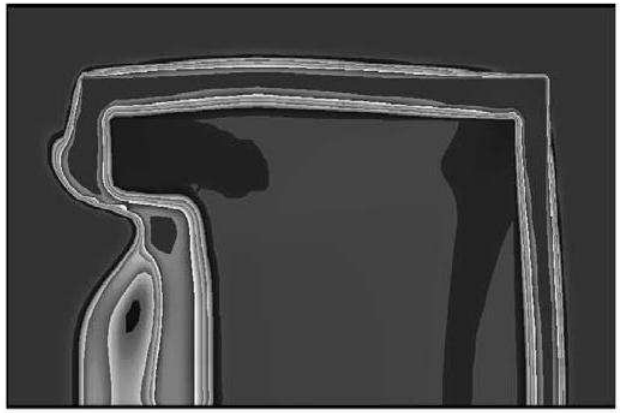
Gharib *et al*. (2007)

- Fluid-structure interaction problem arises in numerous engineering applications:
  - Aerospace (e.g. airplane design, bird strike scenarios, engine blade containment).
  - Automotive (e.g. airbag design, tire performance and hydroplaning).
  - Medical equipment design (e.g. artificial heart valves, lithotryptors).
  - Military and defense (e.g. weapons design, armor design, personnel protection, underwater shock explosion, blast resistance).
  - Failure analysis of structures (e.g. blast loading due to pressure vessel rupture).

Motivation



Cirak and Radovitzky (2005)



Chinnayya *et al*. (2004)

- Examples of simulation techniques for fluid-structure interaction:
  - Coupled Lagrangian-Eulerian methods.
  - Eulerian methods.
  - ALE methods.
  - Particle methods (e.g. SPH).
  - ...
- In the context of eulerian methods:
  - Need to deal effectively with different materials-interface tracking difficult.
  - Materials include solids, fluids or gases.
  - Chemical reactions or phase transitions may also be involved.
- Finite volume Godunov methods well suited for handling multiple materials-***Discrete Equation Method*** (Chinnayya *et al*., 2004).

Discrete Equation Method (DEM)

- ***Key idea (***Abgrall and Saurel, 2003) :
  - Discretize Euler equations at the microscopic level for all pure phases via a Godunov scheme.
  - Average the discretization over the set of all possible realizations to obtain a scheme for the averaged multiphase flow equations.
- Treatment of each phase is Eulerian.
- The original DEM formulation allowed for the treatment of fluids.
- Extended to reactive fluid flows by Chinnayya *et al.* (2003).
- Would like to model materials with strength (solids): need to extend the treatment of the mechanical response to include the deviatoric stress component.

Conservation Equations

mass:

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho \boldsymbol{v}) = 0$$

momentum:

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \mathrm{div}(\rho \boldsymbol{v} \otimes \boldsymbol{v} - \boldsymbol{\sigma}) = 0$$

energy:

$$\frac{\partial \rho (e + \frac{1}{2}\boldsymbol{v}^2)}{\partial t} + \mathrm{div}[\rho (e + \tfrac{1}{2}\boldsymbol{v}^2)\boldsymbol{v} - \boldsymbol{\sigma}\boldsymbol{v}] = 0$$

or

$$\rho \dot{e} = \boldsymbol{\sigma} \cdot \mathrm{grad}(\boldsymbol{v}) \equiv \boldsymbol{\sigma} \cdot \boldsymbol{L}$$

Need closure: material constitutive relations

Material Constitutive Equations

- Relate the stress to some measure of deformation and temperature.
- Must satisfy certain constraints imposed by
  - Thermodynamics (e.g. Clausius-Duhem inequality).
  - Locality.
  - Material frame indifference.
- May also depend on a number of internal (history) variables to track micro-structure development-*inelastic material response*.
- Existence of a Helmholtz free energy functional from which the material response derives is often assumed.
- Commonly the material response split into volumetric (EOS) and isochoric (strength) components.
- Example: $\boldsymbol{\sigma}^{\nabla J} = \boldsymbol{C} : \frac{1}{2}[\boldsymbol{L} + \boldsymbol{L}^{T}]$ - hypoelastic constitutive relation.

Acoustic Riemann Solver

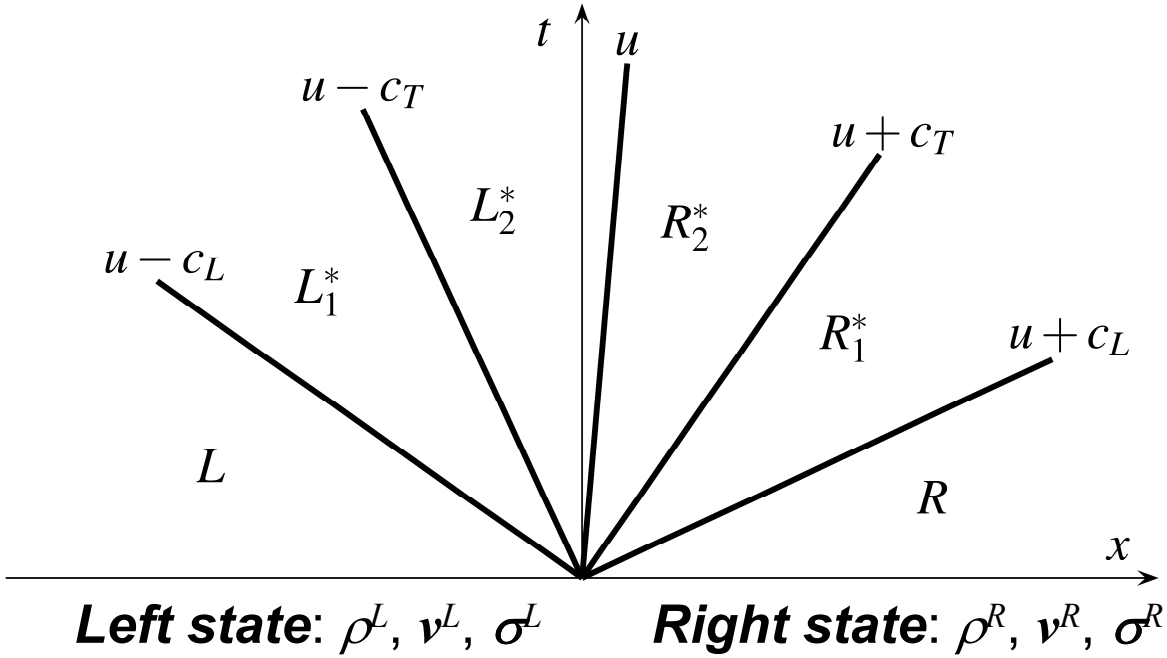
- Need a solution of the Riemann problem to evaluate fluxes of conserved variables.
- Use conservation equations for a solid with *linear elastic* material constitutive relation:

$$\sigma = \lambda \boldsymbol{I} \mathrm{tr}(\varepsilon) + 2\mu\varepsilon$$

where: λ, μ-elastic constants and ε-the infinitesimal strain tensor.

- Non-linear (geometric) effects due to *finite kinematics* neglected.
- Riemann solvers taking into account finite kinematics available (e.g. Garaizar, 1991; Miller and Colella, 2001).

Acoustic Riemann Solver

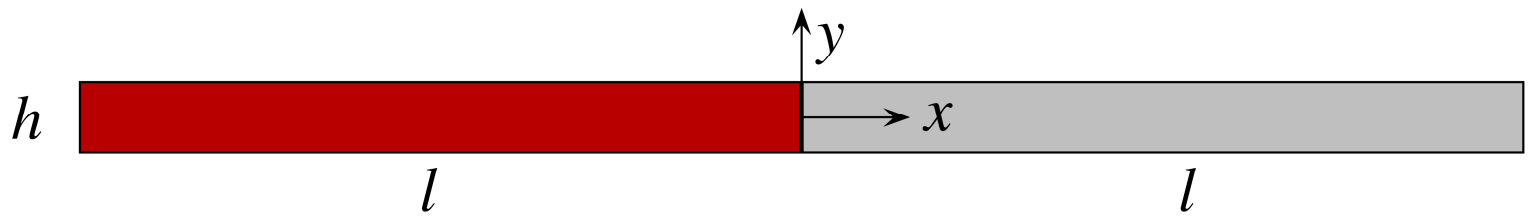


$$c_L = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

$$c_T = \sqrt{\frac{\mu}{\rho}}$$

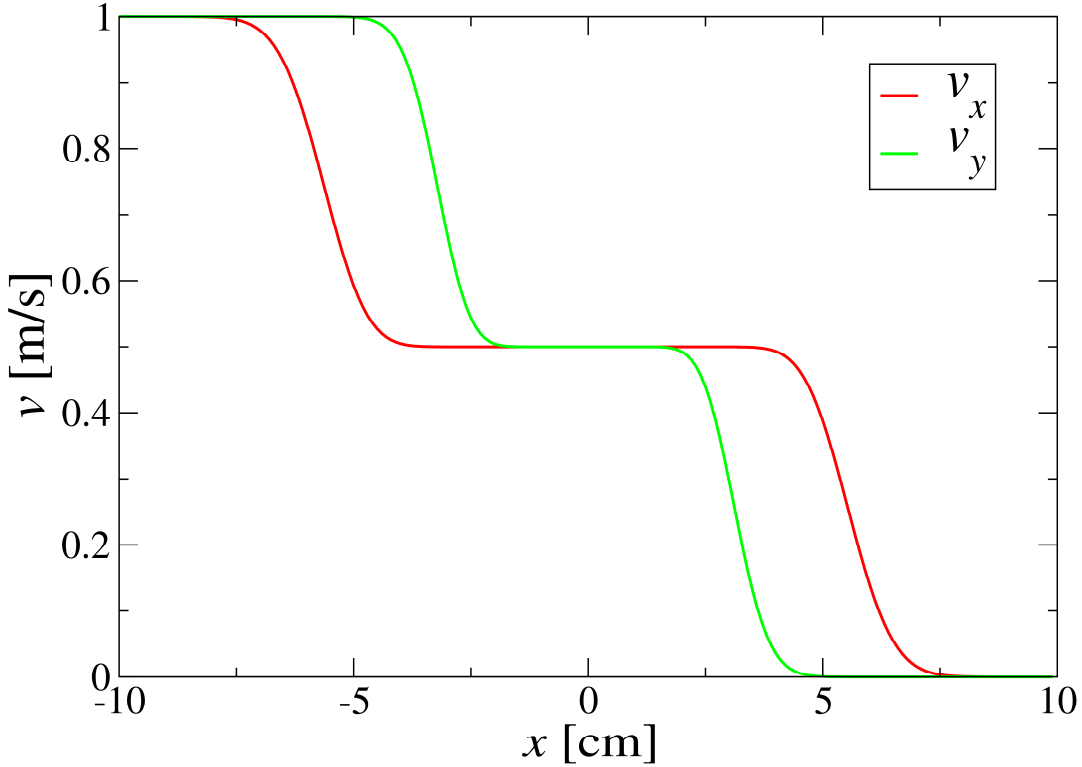
- Two elastic waves: longitudinal (c_L) and tangential (c_T).
- Treatment of tangential waves analogous to longitudinal waves.
- Quantities discontinuous across shear waves: (σ_{12},v_2) and (σ_{13},v_3).

1D Example-Validation



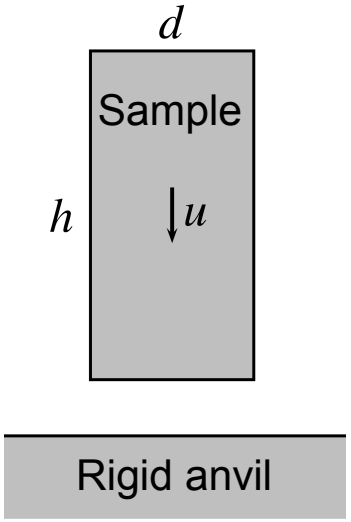
- Rod: $l = 10$ cm and $h = 1$ cm.
- Discretization: 1 zone per h and 100 zones per l.
- Periodic boundary conditions in y,z-directions.
- Outflow boundary conditions at both ends.
- Initial conditions: velocity of 1 m/s in both x and y-directions applied to left half of the rod ($x < 0$).
- Material: linear elastic steel $\lambda = 87$ GPa and $\mu = 80$ GPa.
- Elastic wave velocities: $c_L = 0.563$ cm/μs and $c_T = 0.320$ cm/μs.

1D Example-Validation



- Velocity solutions at $10\ \mu s$.
- Two-elastic-wave structure present in the solution.
- Elastic wave velocities match ***exactly*** those computed from the elastic constants.

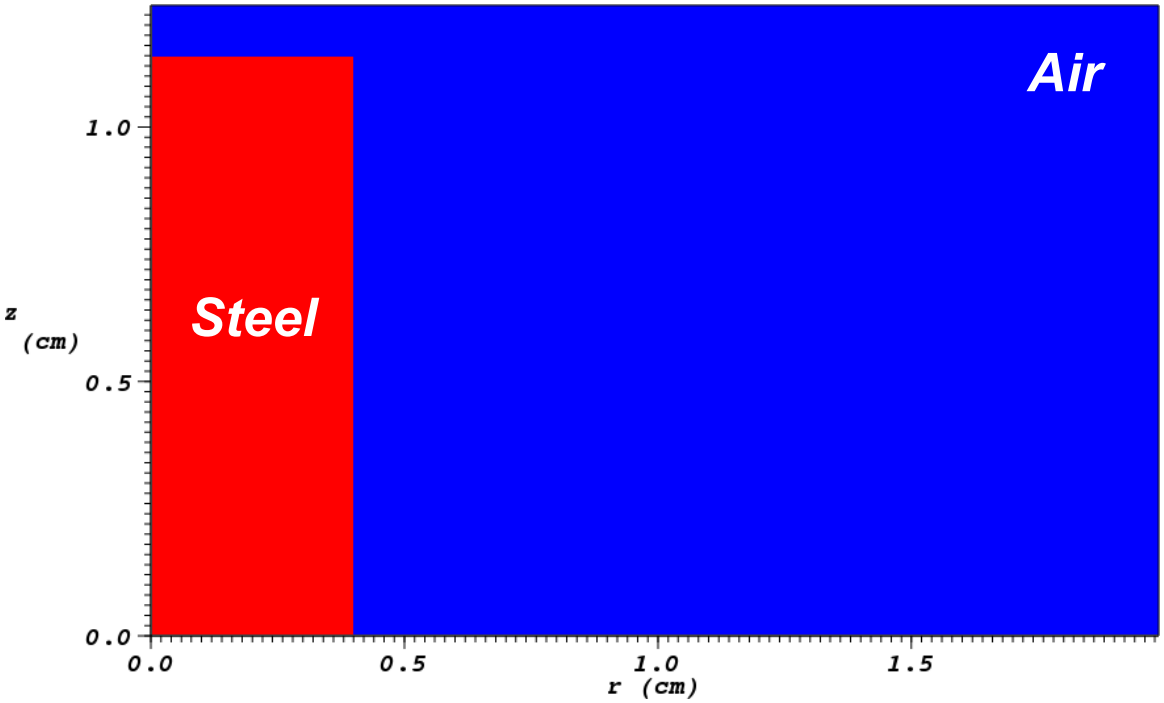
Taylor Impact Test



Wang *et al*. (2003)

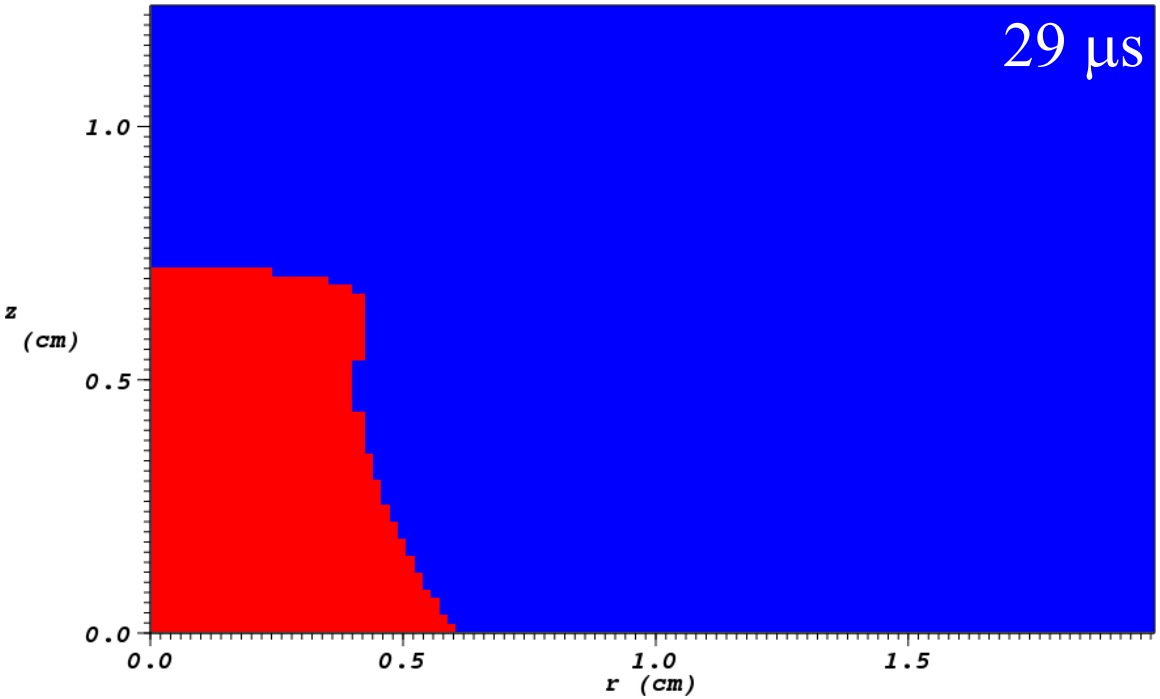
- Fundamental test for characterizing the inelastic mechanical response of structural materials (plastic deformation, shear band formation and fracture).
- Experimental data: House *et al*. (1995).
- Material: 4340 low strength steel.
- Sample dimensions: $d = 7.595$ mm, $h = 11.39$ mm.
- Impact velocity: 285 m/s.
- Final length: 9.3 mm.
- Mushroom diameter: 10.9 mm.

Taylor Impact Test



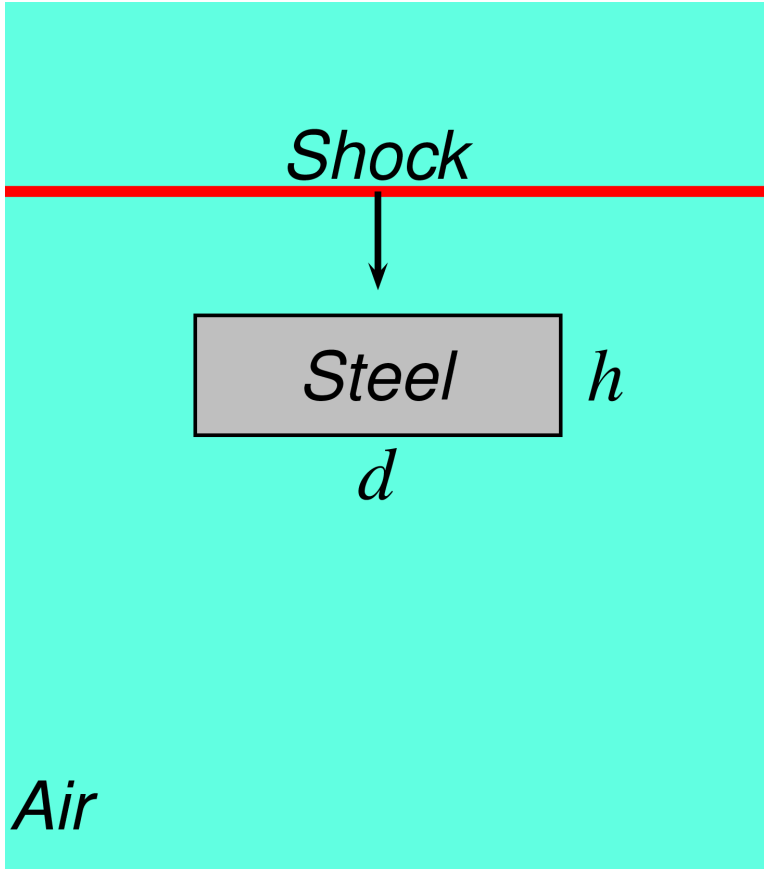
- 4340 steel material model:
  - EOS: 7-term polynomial.
  - Strength: conventional J_2-plasticity, no strain hardening.
- Air material model: γ-law gas EOS. No strength.
- Quarter configuration modeled (3D).
- 139,194 total number of zones.

Taylor Impact Test



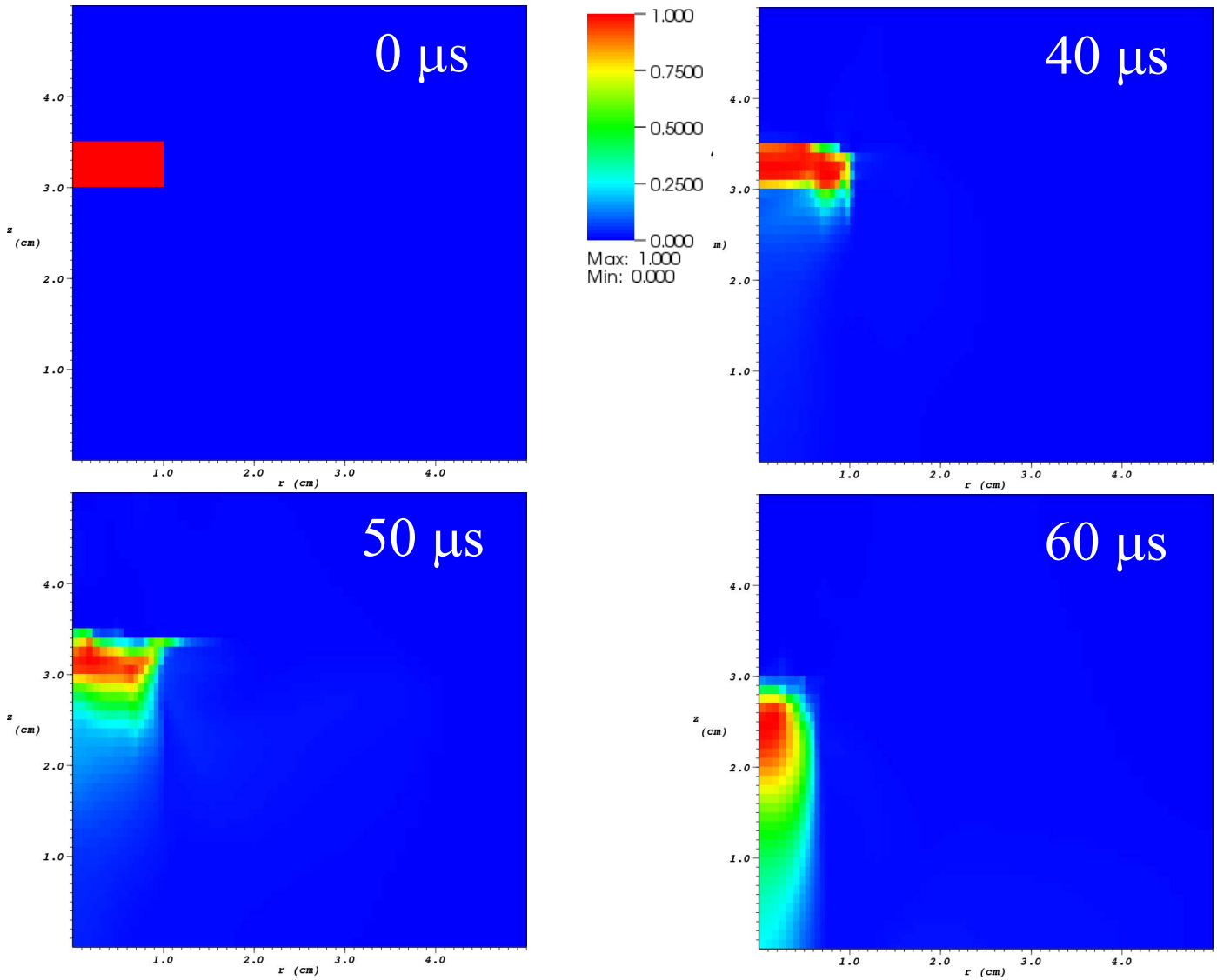
- Final simulated cylinder length: 7.02 mm (experiment: 9.3 mm).
- Mushroom diameter: 12.1 mm (experiment: 10.9 mm).
- Very good agreement with the experimental data.
- Need to include strain hardening effects to obtain a better match!

In Progress-Momentum Trap



- Investigate interaction of a shock wave with a solid body.
- $d = 20$ mm, $h = 5$ mm.
- 5 Mach shock.
- Steel modeled as:
  - EOS: 7-term polynomial.
  - Strength: J_2-plasticity, no strain-hardening.
- Air modeled as:
  - EOS: γ-law gas.
  - No strength.
- Quarter configuration modeled (3D).
- Discretization: 31,164 zones.

In Progress-Momentum Trap



Summary

- Extended the DEM-based multi-phase flow approach of Chinnayya *et al*. to materials with strength.
- The necessary changes confined to an acoustic Riemann solver.
- The validity of our multi-phase flow model for solids verified on a simple 1D dimensional problem.
- Multi-phase flow model applied to a Taylor problem involving a steel cylinder impacting a rigid anvil. Good agreement with experimental measurements.
- The effort on modeling an interaction of a shockwave with a steel plate ongoing.
- Future work: ballistic impact and penetration, modeling of the effects of blast-waves on solids and structures.