Coupled Computation of Fluid and Material Response for Non-charring Ablative Materials in Hypersonic Flow

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Outline

- Project overview
- 2D/Axisymmetric material response code
- Fluid and material response coupling
- IRV-2 results
- Future Work

Project Overview

- Focus on material response modeling of non-charring ablative materials
- Provide high-fidelity estimates of the thermal environment in new light-weight anisotropic TPS materials under realistic hypersonic flow conditions
  - full 3D capability
  - model radiative heat transport within ablative materials
  - couple material response with external flow solver
- Predict thermal stresses Introduced due to thermal gradients
- Provide maximum operating temperatures for a given material selection

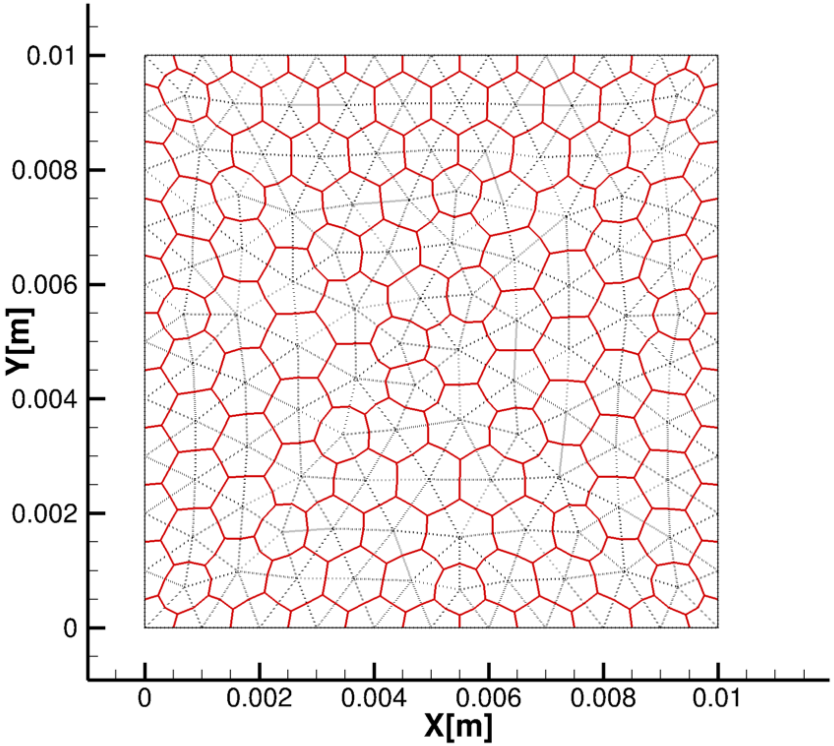
Material Response Code

- Material Response: control volume finite element (CVFEM) code for modeling ablation phenomena:
  - Solves energy equation for 2D/Axisymmetric geometries
  - Handles non-charring anisotropic ablative materials
  - Implicit time integration (Backward Euler -> 1st order in time)
  - Newton's Method with preconditioned GMRES for linear system
  - Can be loosely coupled to a CFD code through an aerodynamic heating boundary condition

$$\underbrace{\int_{cs} \dot{\mathbf{q}}'' \cdot \mathrm{d}\mathbf{A}}_{\text{Conduction}} - \underbrace{\int_{cs} \rho h \mathbf{v}_{cs} \cdot \mathrm{d}\mathbf{A}}_{\text{grid convection}} + \underbrace{\frac{d}{dt}\int_{cv} \rho e \mathrm{d}V}_{\text{Energy Content}} = 0$$

Domain Discretization

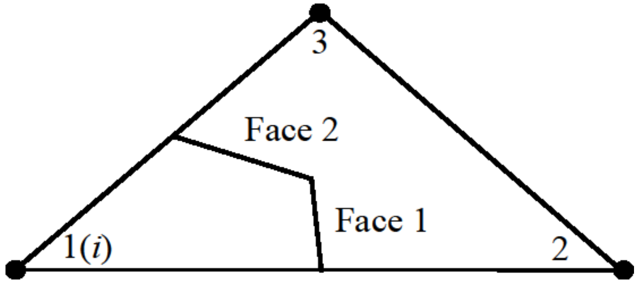
- Dual mesh formed from initial triangular mesh
- Linear shape functions used to interpolate nodal data
- Global sensitivity matrix assembled element by element



$$\phi(x,y) \simeq \sum_{i=1}^{3} N_i(x,y)\phi_i$$

$$\frac{\partial \phi}{\partial x} = N_{1x}\phi_1 + N_{2x}\phi_2 + N_{3x}\phi_3$$

$$\frac{\partial \phi}{\partial y} = N_{1y}\phi_1 + N_{2y}\phi_2 + N_{3y}\phi_3$$



Boundary Conditions

- Supported boundary conditions
  - Specified temperature
  - Specified heat flux
  - Radiation

$$\dot{q}''_{rad} = \epsilon\sigma(T^4_{bnd} - T^4_{res})$$

  - Aerodynamic heating

$$\dot{q}''_{ah} = \rho_e u_e C_h (h_w - h_r)$$

- Thermochemical ablation model

$$\dot{q}''_{abl} = \rho_s \dot{s} h_w$$

$$\dot{m}''_{abl} = \rho_s \dot{s} = \rho_e u_e C_m B'_c$$

  - *B'_c* is determined from user generated thermochemistry table
  - The surface recession rate determines a nodal velocity along the boundary, which can be used to calculate new nodal position

Mesh Deformation

- Treat the mesh as a linear elastic solid and solve equilibrium equations with zero body force (Lynch et. al. 1980) (Hogan et. al. 1996) (Dec 2010)
  - Equilibrium equations can be written in terms of displacements by using constituitive equations and strain definitions
  - Poisson’s ratio is only necessary material property and it can be arbitrarily chosen (taken as 0.0 for this work)
  - Boundary displacements from thermochemical ablation model
  - GMRES used to solve system of equations

Equilibrium equations

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z} = 0$$

$$\frac{\partial \sigma_{yx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{yz}}{\partial z} = 0$$

$$\frac{\partial \sigma_{zx}}{\partial x} + \frac{\partial \sigma_{zy}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} = 0$$

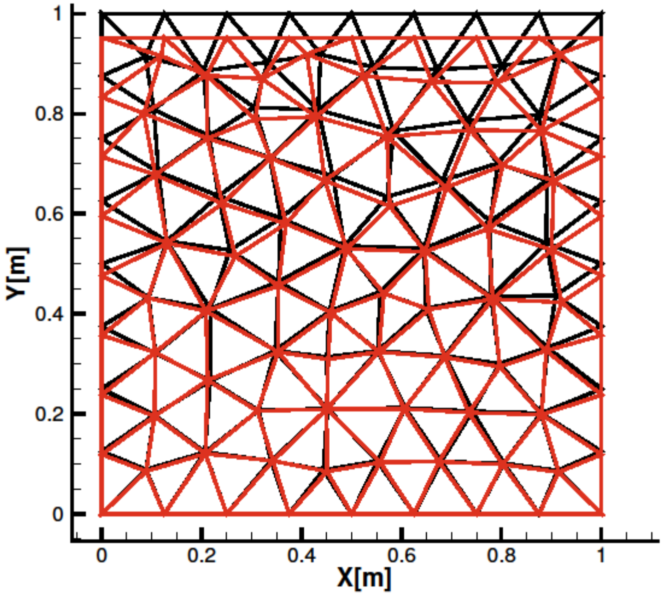
Boundary conditions

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} \dot{s}\Delta t n_x \\ \dot{s}\Delta t n_y \\ \dot{s}\Delta t n_z \end{bmatrix}$$

Mesh Deformation Cont.

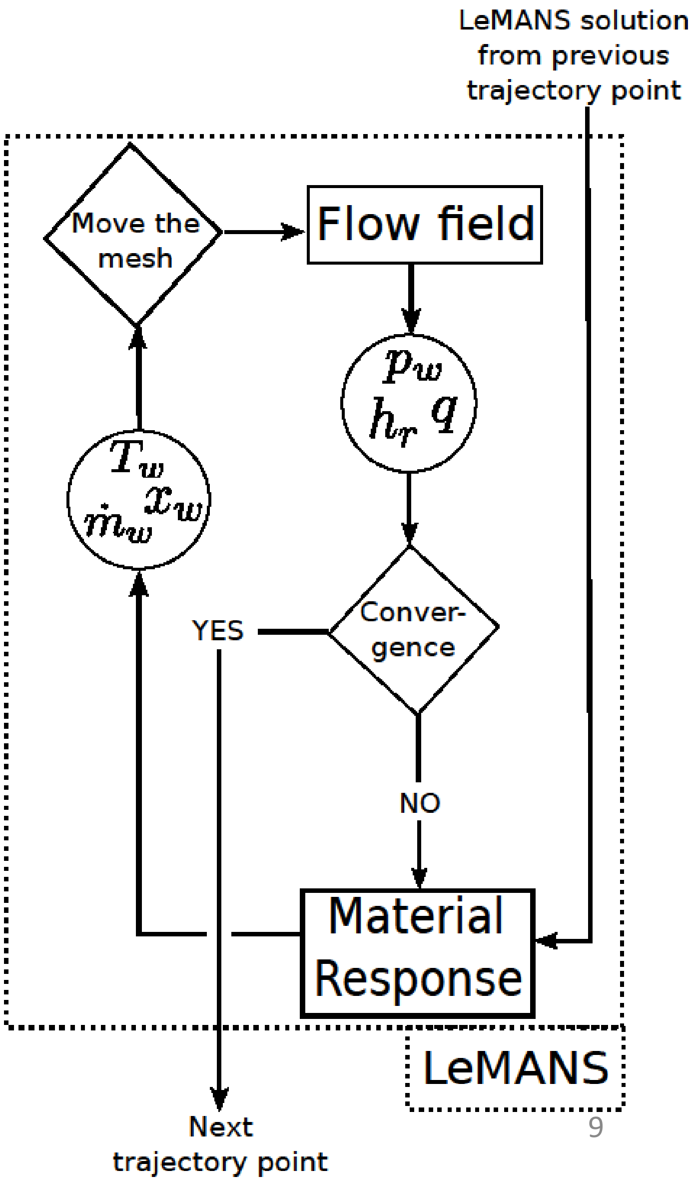
- To advance the solution a time step the method of Hogan, Blackwell, and Cochran is used (Hogan et. al. 1996)
  - Move the mesh based on $\dot{s}^i$
  - Update temperatures
  - Calculate $\dot{s}^{i+1}$ based on new temperatures
  - Compute average change of temperature between *i* and *i+1* for ablating nodes to determine temperature and recession rate convergence

$$\epsilon = \frac{1}{M}\sum_{j=1}^{M}|T_j^{i+1} - T_j^i|$$



Coupling with CFD

- Current coupling implementation
  - The material response code and CFD provide boundary conditions for each other
  - Boundary values are interpolated between codes
  - After material response has converged, the flow field mesh is adjusted and the CFD code is run with updated boundary values



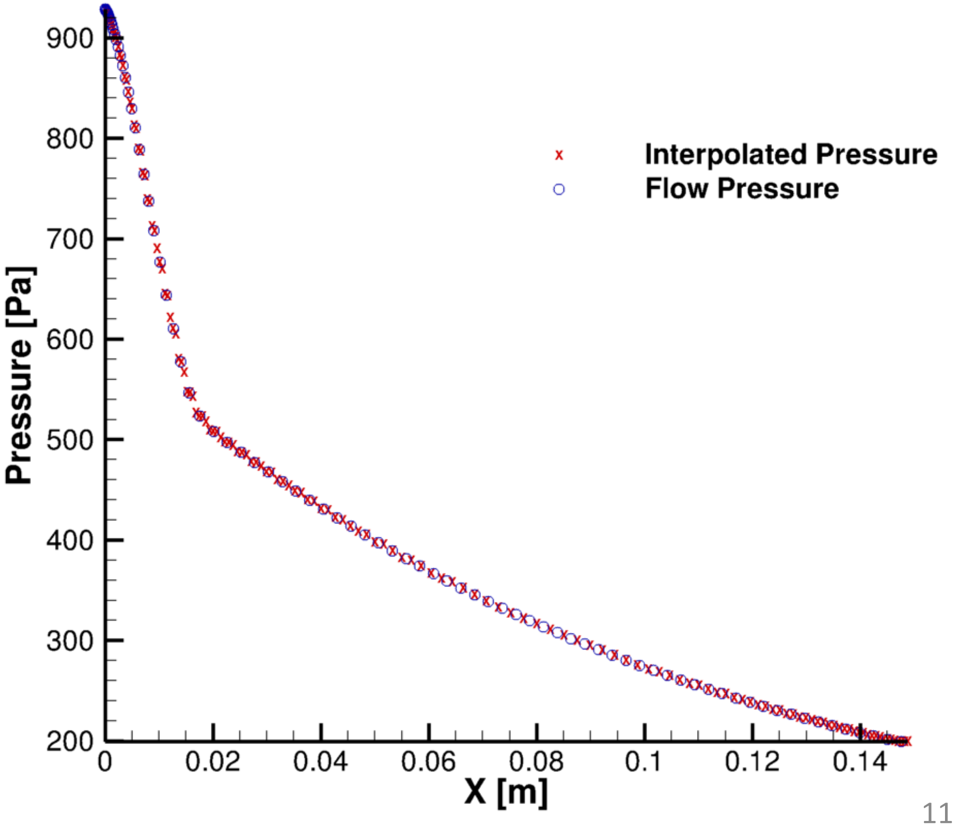
Coupling Continued

- LeMANS: finite volume Navier-Stokes solver for hypersonic flows developed at the University of Michigan (Martin et. al. 2012)
  - Handles 2D, 3D, and axisymmetric configurations
  - Can compute weakly ionized flow with thermal (trans/rot/vib) and chemical nonequilibrium
  - Time integration using a point or line implicit method
  - Can move mesh for 2D/axisymmetric geometries if modeling ablation
  - Has previously been coupled to the 1D material response code, MOPAR (Martin et. al. 2009)

Coupling Continued

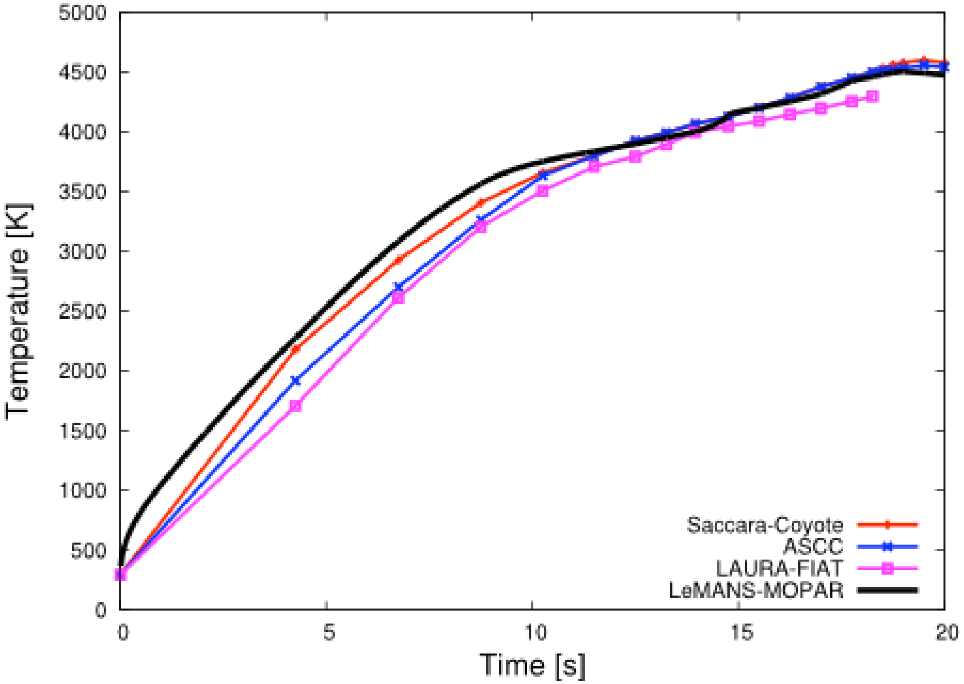
- Shepard's Method for code-to-code interpolation (Franke 1982)
  - Inverse distance weighting method that works in both 2D and 3D
  - A minimum number of points within a radius, *R*, are used for weighting

$$w_k(\mathbf{x}) = \left(\frac{R - d(\mathbf{x}, \mathbf{x}_k)}{R d(\mathbf{x}, \mathbf{x}_k)} \right)^2$$

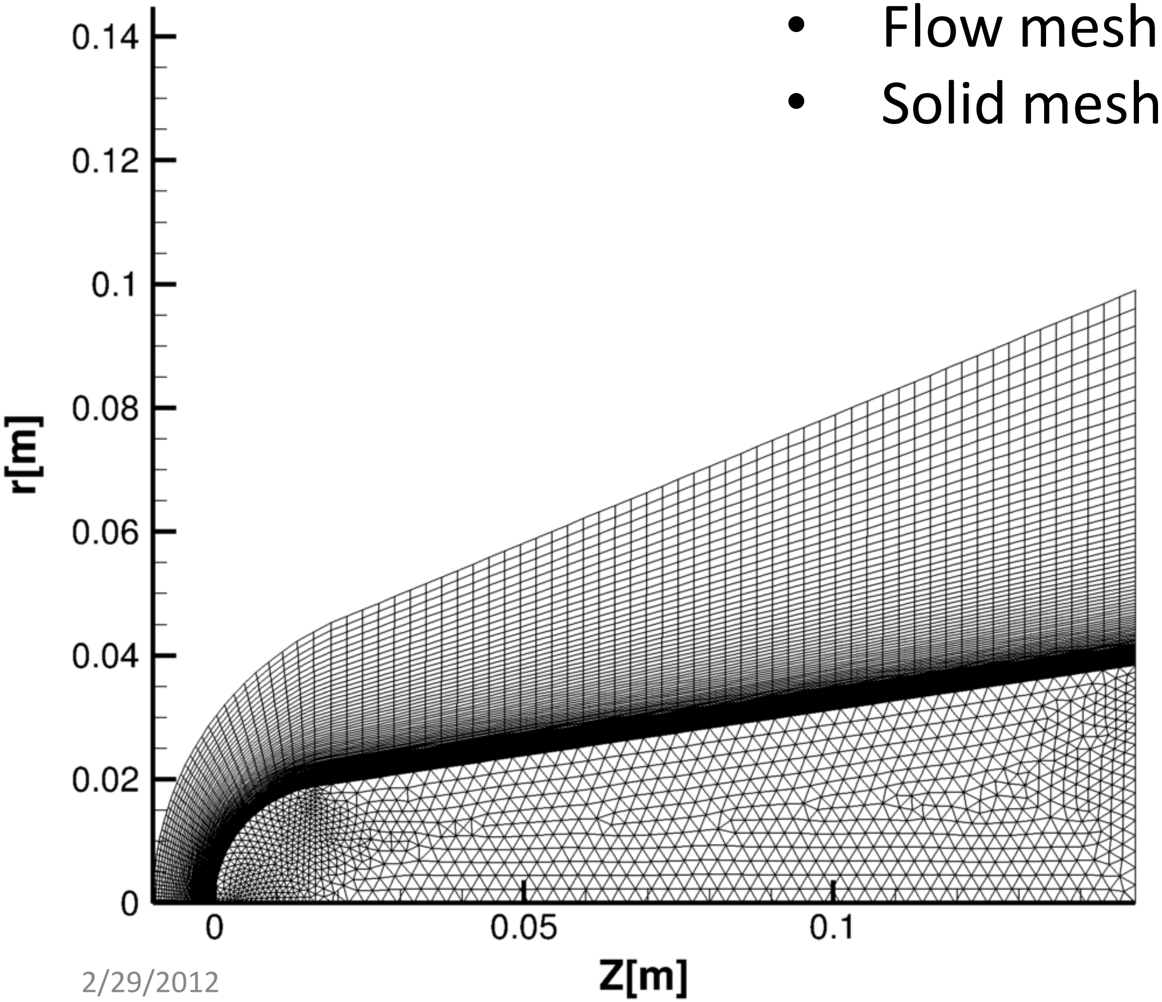


IRV-2

- Well documented re-entry simulation (Hassan et. al. 2001)
- Non-charring carbon-carbon ablator
- Will allow comparison to 1D MOPAR results (Martin et. al. 2009)



IRV-2 Mesh



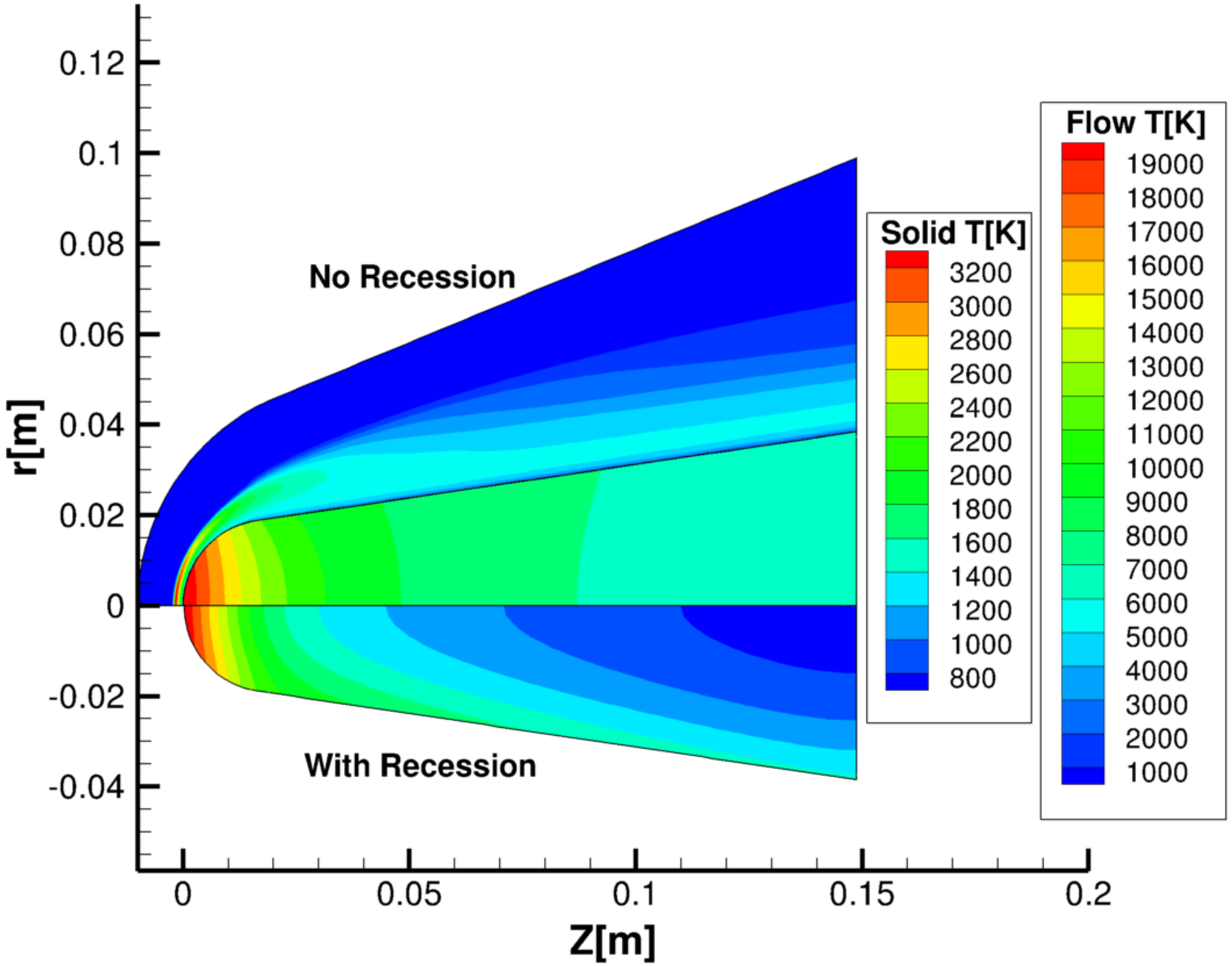
- Flow mesh: 8448 cells
- Solid mesh: 1106 nodes

IRV-2 Conditions

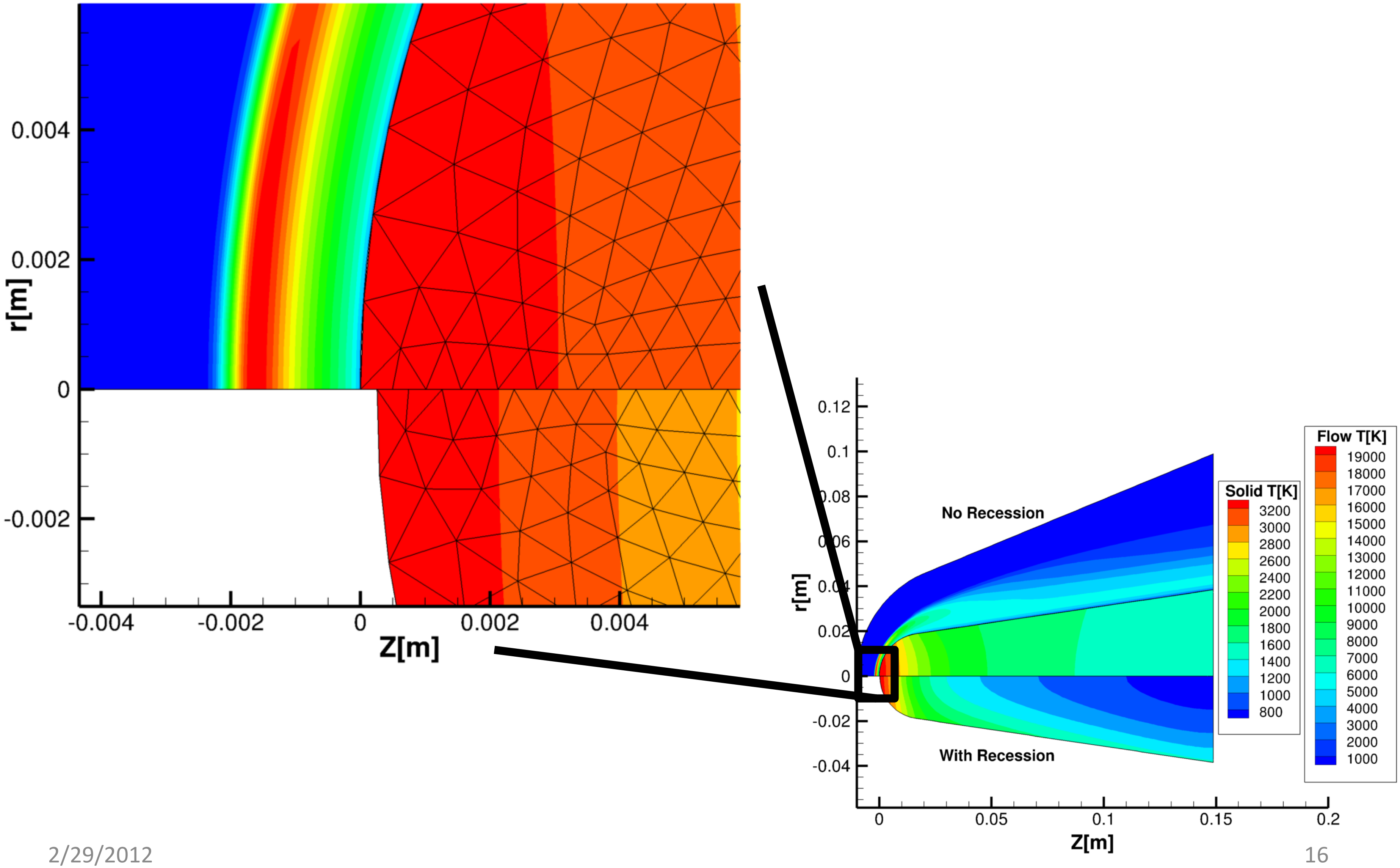
- Two simulations performed
  - No recession (i.e. $B'_c = 0$), radiative boundary
  - Recession included, radiative boundary
- Procedure
  - Run trajectory point 0 with no material response
  - Run trajectory point 1 with the flow field initialized to the point 0 solution, and the solid initialized to 300 K
  - Call material response every 100 flow iterations
  - Monitor convergence of flow field residual
- 5 species air chemistry model

Trajectory point	Time [s]	Altitude [m]	Velocity [m/s]	Temperature [K]	Density [kg/m^3]
0	0.00	66700	6780	228	1.25×10^{-4}
1	4.25	56000	6790	258	5.05×10^{-4}

IRV-2 Results

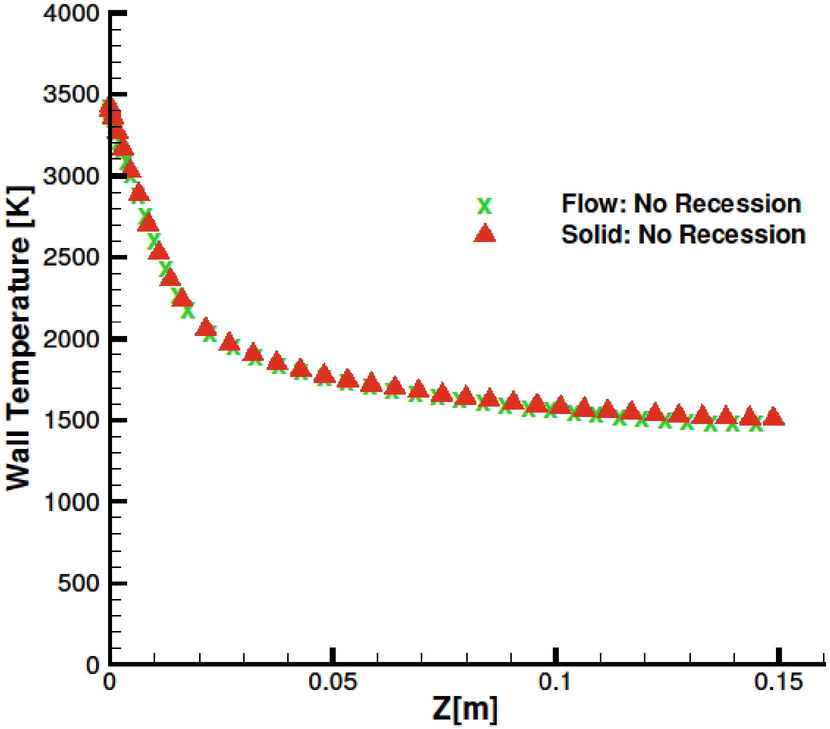


IRV-2 Results Cont.



IRV-2 Results Cont.

- Internal temperatures are much higher than published 1D data
- Grid deformation scheme appears robust and maintains a smooth surface profile
- Wall temperatures calculated by LeMANS and the material response code show good convergence



Summary

- A multidimensional material response code is being developed at the University of Michigan
- The material response code has been loosely coupled to the hypersonic CFD code, LeMANS
- Preliminary results for an axisymmetric coupled simulation of the IRV-2 vehicle have been shown

Future Work

- Continue code verification and validation
  - IRV-2
  - PANT
- Extend material response and CFD coupling to 3D
- Include thermal stress calculations in the material response code

Questions?

References

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