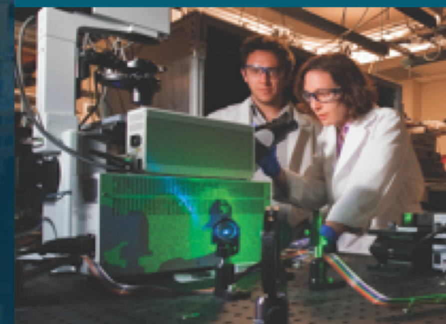
Guest Lecture Stanford ME469: Multiphysics Coupling



PRESENTED BY

Stefan P. Domino

Computational Thermal and Fluid Mechanics

Sandia National Laboratories SAND2018-4536 PE

U.S. DEPARTMENT OF ENERGY NNSA

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Multiphysics Coupling: Outline

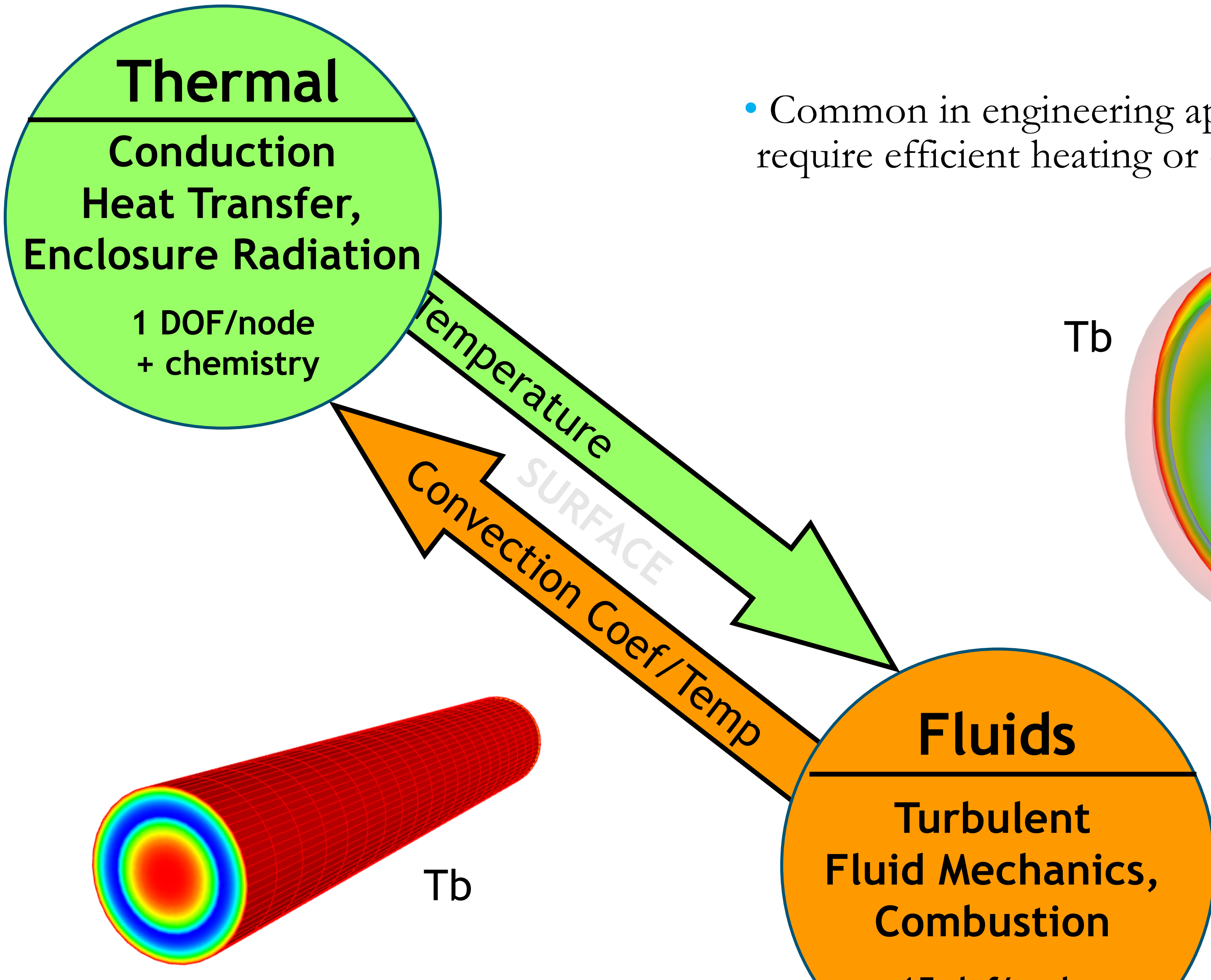
- Examples of multiphysics coupling with emphasis on fluids, PMR, and CHT
- Monolithic vs Operator Split
- Details of PMR/Fluids Coupling
- Details of PMR/Thermal Coupling
- Details of Fluids/Thermal Coupling
- Verification
- Stability
- Conclusions

We Live in a Multiphysics World

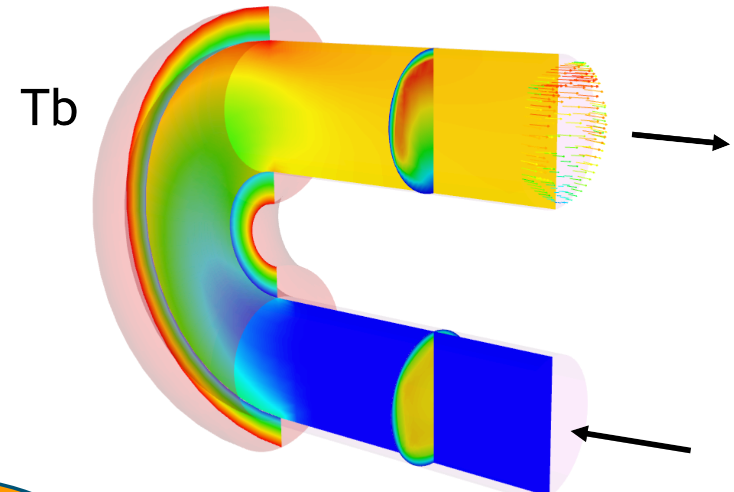
- Fluid/Structure coupling:
  - Wind turbines
  - Wing fluttering, etc.
- Non-isothermal fluids/participating media radiation:
  - Fires,
  - Natural gas and coal combustion,
  - Smelting, ethlyne production, etc.
- Conjugate heat transfer:
  - Object-in-fire
  - Gas turbine fine cooling
- Often times, we note a time and length scale disparity
  - For example, consider heating a pan on a home burner
- The coupling architect must generally choose between monolithic and split
- For monolithic, the equations are provided, therefore, the challenge becomes managing a monolithic sytem solve, storage and code design
- For operator split, there can be an "art" in determination of stable couplings due to Eignevalue spread

Conjugate Heat Transfer Coupling

- Common in engineering applications that require efficient heating or cooling of objects



Turbulent pipe CHT



Conjugate Heat Transfer Coupling, Equations

- Favre-averaged static enthalpy equation:

$$\frac{\partial \rho h}{\partial t} + \frac{\partial \rho u_j h}{\partial x_j} = -\frac{\partial q_j}{\partial x_j} + \frac{\partial p^t}{\partial t} - \frac{\partial q_j^R}{\partial x_j}$$

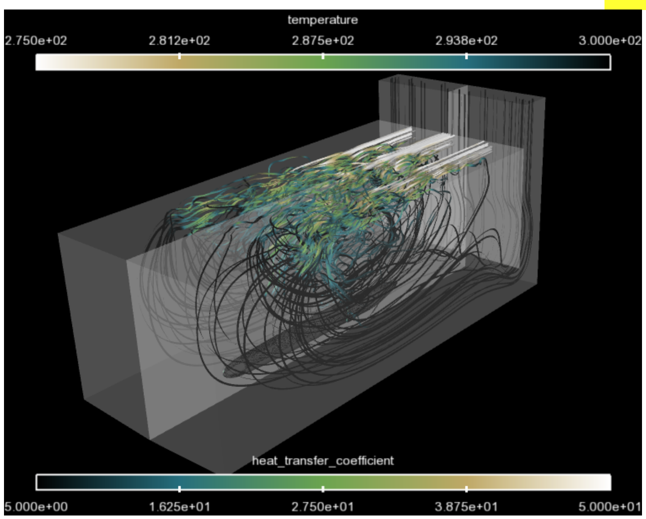
- Thermal heat conduction

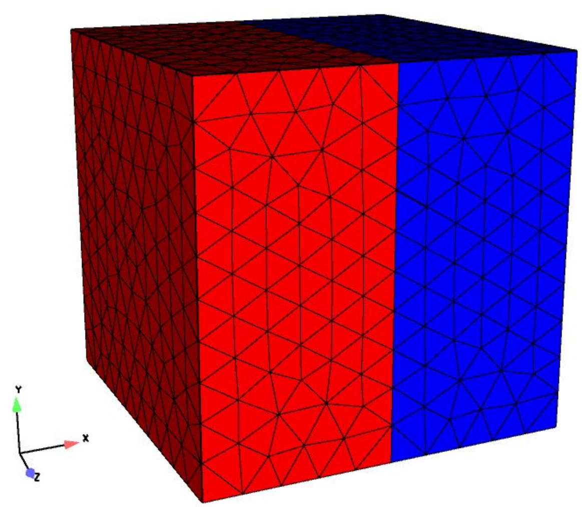
$$\rho C_p \frac{\partial T}{\partial t} - \frac{\partial}{\partial x_j}\lambda\frac{\partial T}{\partial x_j} = \rho C_p \frac{\partial T}{\partial t} + \frac{\partial}{\partial x_j} q_j^{HC} = 0$$

- Interface condition

$$q_j^{HC} n_j = q_j n_j$$

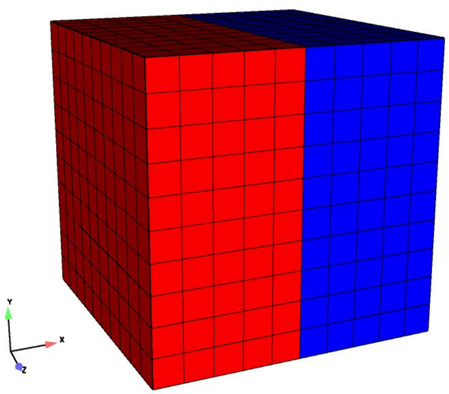
$$q_n = -\lambda \frac{\partial T}{\partial x_j} n_j = h[T - T^\infty]$$

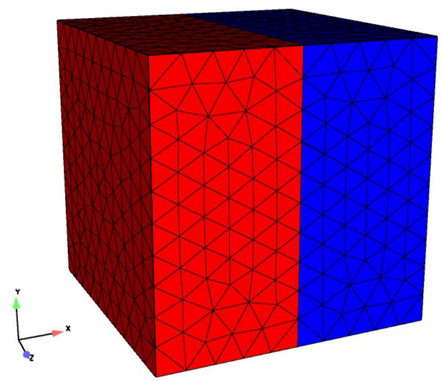


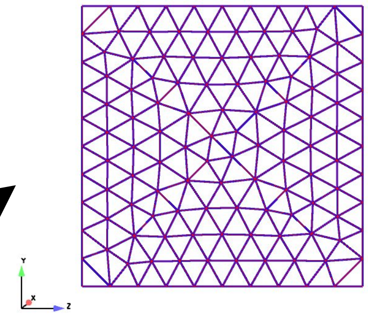


Fluid/CHT Coupling Verification

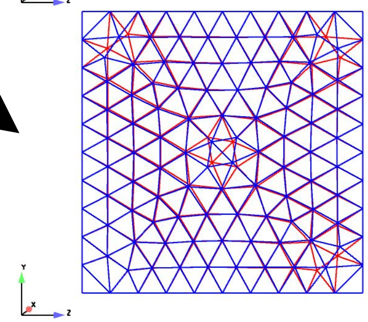
- Unstructured heterogeneous mesh capability
- Arbitrary geometric complexity
- Multi-block domain variable transfer



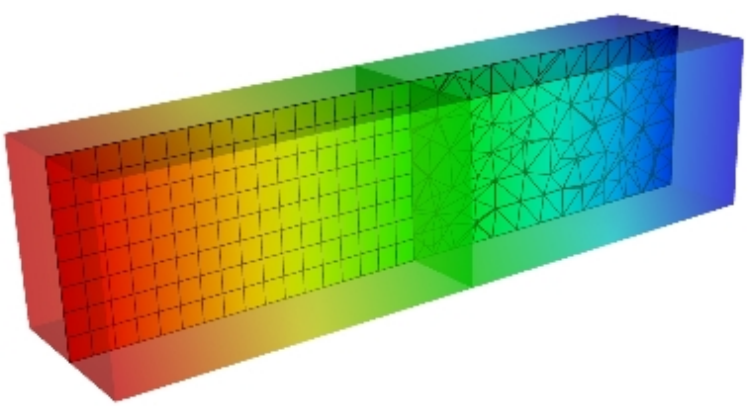


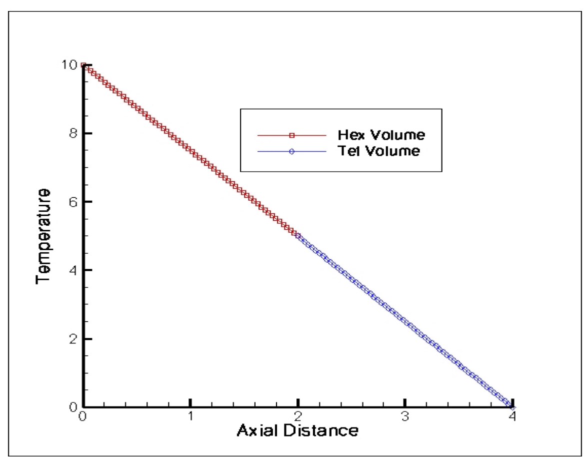


Conforming interface

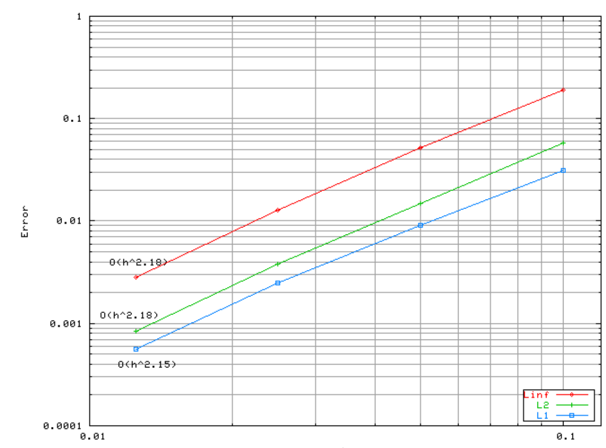


Non-conforming interface



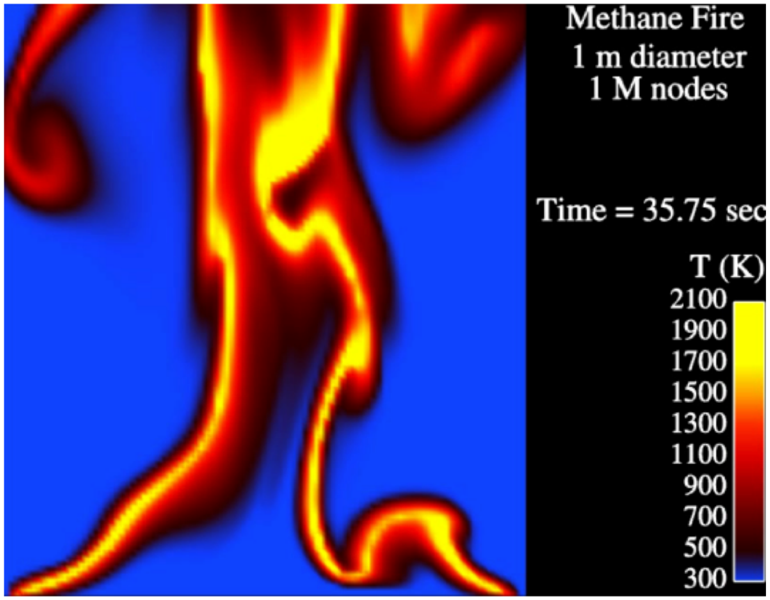


Linear (patch test)

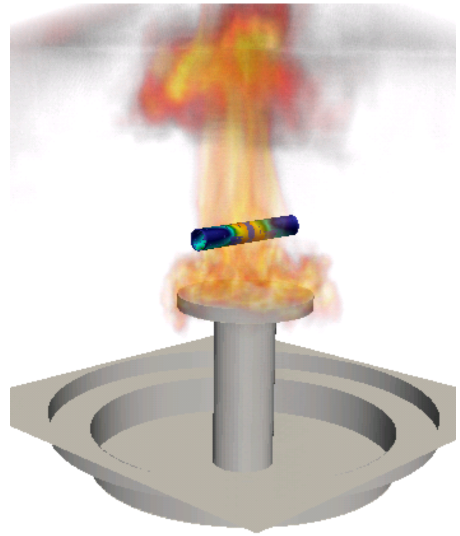


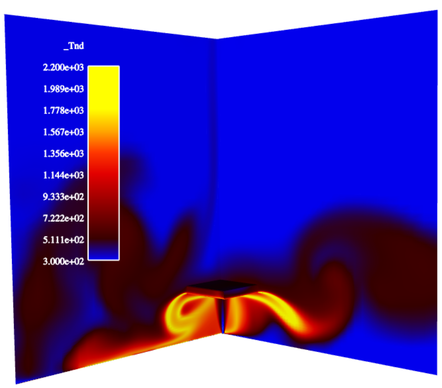
Trigometric MMS

Fluids/PMR Coupling

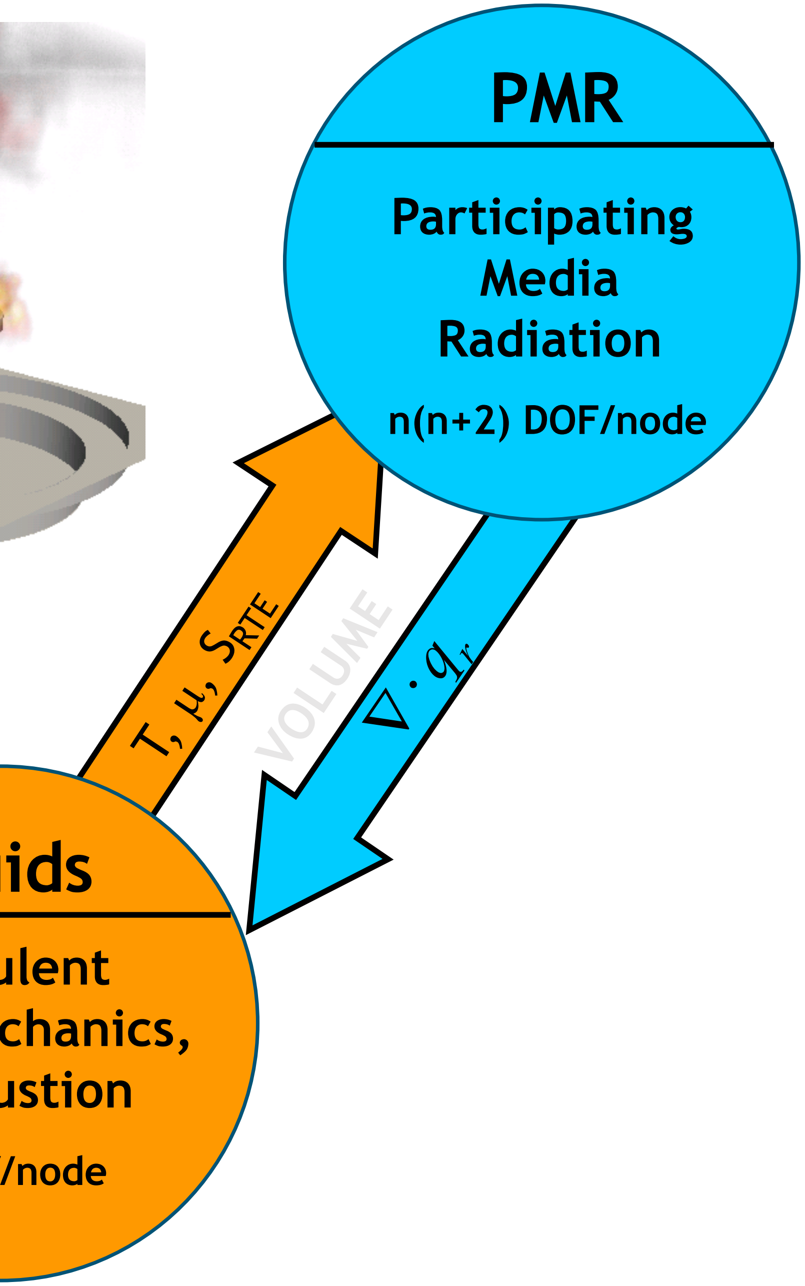


Pool fire





Deflected reacting jet



Fluids/PMR Coupling Equations

- Favre-averaged static enthalpy equation:

$$\frac{\partial \rho h}{\partial t} + \frac{\partial \rho u_j h}{\partial x_j} = -\frac{\partial q_j}{\partial x_j} + \frac{\partial p^t}{\partial t} - \frac{\partial q_j^R}{\partial x_j}$$

- Steady, non-scattering Radiative Transport Equation

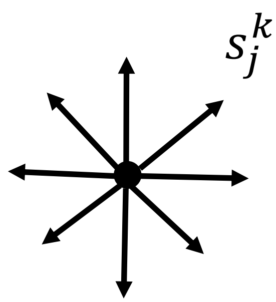
$$s_j^k \frac{\partial I^k}{\partial x_j} + \mu_a I^k = \mu_a \sigma \frac{T^4}{\pi}$$

- Scalar Flux,

$$G \approx \sum_k w_k I^k$$

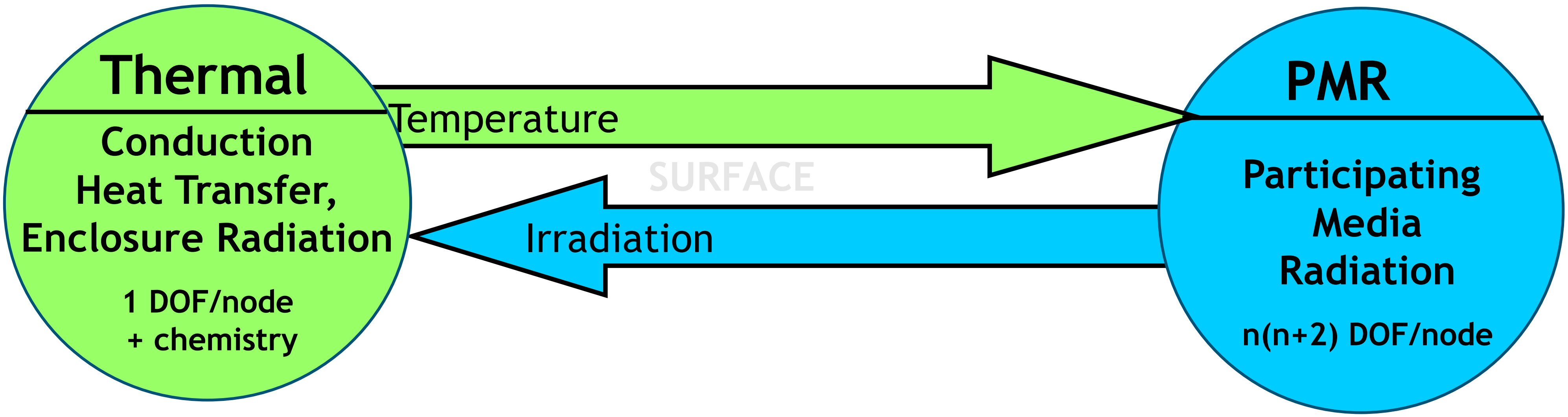
- Divergence of radiative flux,

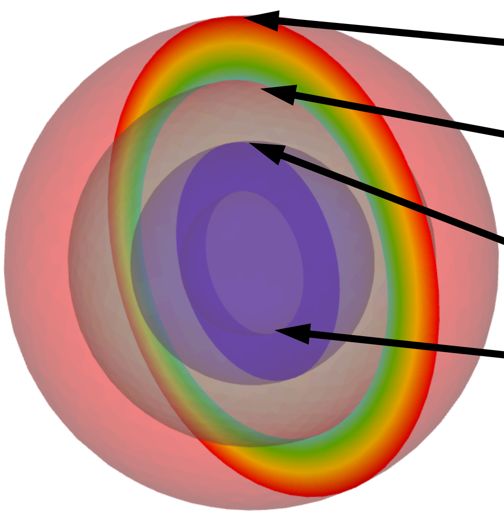
$$q_j^R \approx \sum_k w_k I^k s_j^k \qquad \frac{\partial q_j^R}{\partial x_j} = \mu_a [4\sigma T^4 - G]$$



Quadrature

PMR/Thermal Coupling





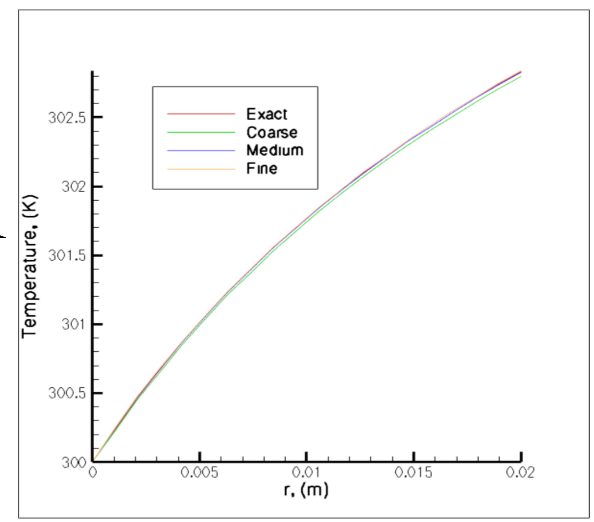
r_o, $T_o = 0.1$ m, 600K

r_2, $T_2 = 0.075$ m, 599.291K

r_1, $T_1 = 0.05$ m, 302.834K

r_i, $T_i = 0.03$ m, 300K

PMR:Conduction through concentric spheres



O(1.8) with faceting,
O(2) without

PMR/Thermal Coupling Equations

- Steady, non-scattering Radiative Transport Equation

$$s_j^k \frac{\partial I^k}{\partial x_j} + \mu_a I^k = \mu_a \sigma \frac{T^4}{\pi}$$

- Irradiation (incoming),

$$H \approx \sum_{n_j s_j^k > 0} w_k I^k \left| n_j s_j^k \right|$$

- Grey, diffuse boundary condition (given transmissivity, τ, emissivity ε, and reflectivity, ρ

$$I = \frac{1}{\pi}[\tau\sigma T_e^4 + \varepsilon\sigma T^4 + \rho H]$$

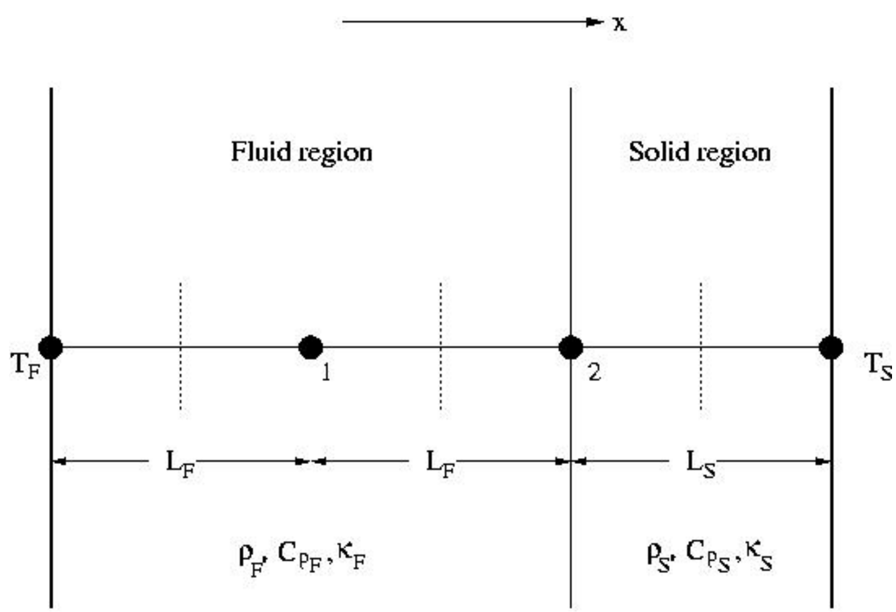
- With boundary condition,

$$q_n = -\lambda \frac{\partial T}{\partial x_j} n_j = \varepsilon[\sigma T_e^4 - H]$$

$$\rho C_p \frac{\partial T}{\partial t} - \frac{\partial}{\partial x_j} \lambda \frac{\partial T}{\partial x_j} = 0$$

Conjugate Heat Transfer Stability

- Consider a simple CHT problem



Simplified 1D geometry with 2 nodes for stability analysis of CHT

$$q_n = -\lambda \frac{\partial T}{\partial x_j} n_j = h[T - T^{\infty}]$$

- Compute amplification factor

$$\mathbf{T}^{n+1} = \lambda \mathbf{T}^{n}$$

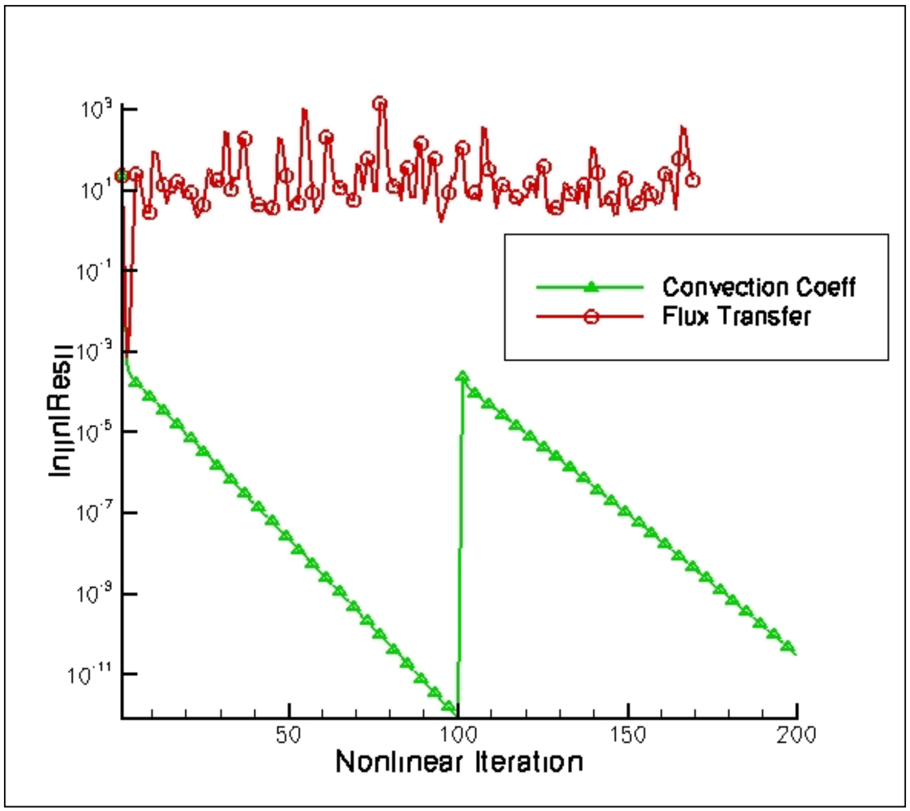
- Requiring:

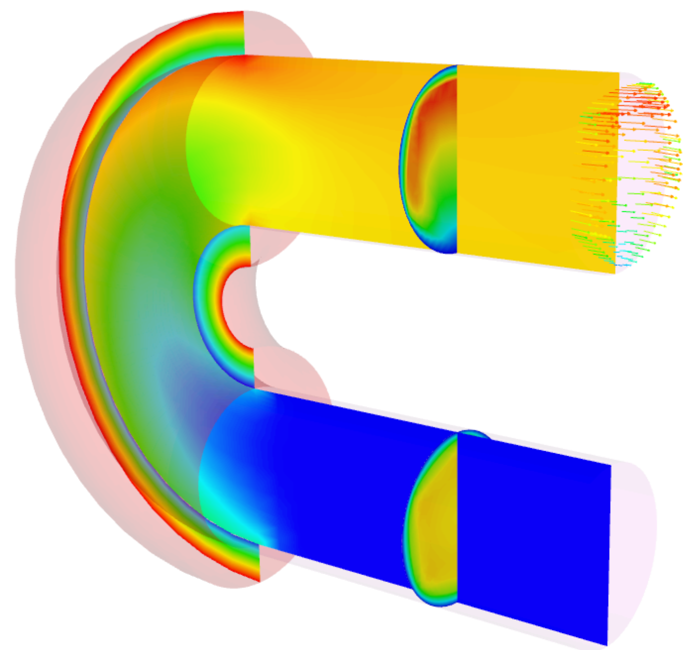
$$|\lambda| \leq 1$$

- CHT via flux transfer:
  - Explicit RHS
  - Unstable for certain time steps and material properties
- CHT via convection coefficient:
  - Implicit LHS
  - Unconditionally stable

Conjugate Heat Transfer Stability, In Practice

- Transient heated laminar pipe in a 180 degree bend
  - Water, Re = 2000, inflow T = 300
  - Copper jacket, boundary – 350K





Other Linearization Procedures

- PMR and heat conduction radiative boundary condition:

$$q_n = -\lambda \frac{\partial T}{\partial x_j} n_j = \varepsilon[\sigma T^4 - H] \qquad lhs \propto \frac{\partial}{\partial T}\varepsilon[\sigma T^4 - H] = 4\varepsilon\sigma T_e^3$$

- PMR and fluids coupling, linearized divergence of the radiative flux,

$$\frac{\partial q_j^R}{\partial x_j} = \mu_a[4\sigma T^4 - G] \qquad lhs \propto \frac{\partial}{\partial T}\mu_a[4\sigma T^4 - G] = 16\mu_a\sigma T^3 \frac{1}{C_p}$$

- In practice, such procedures enhance stability for the multi-physics coupling
- In the case of Fluids/CHT, one could possibly monolitically couple the systems
- In the case of Fluids/PMR, monolithic coupling is not practical as the intensity system is ~ N^2, where N is generally O(8)

Multiphysics Coupling: Conclusions

- Multiphysics applications are abundant in engineering applications
- Turbulent, reacting flow with PMR and CHT requires a wide range of length and time scale resolution
- Monolithic approaches are ideal from a splitting perspective, however, can be prohibitively expensive when considering systems such as PMR
- Linearization can augment time step stability and should be exploited when possible