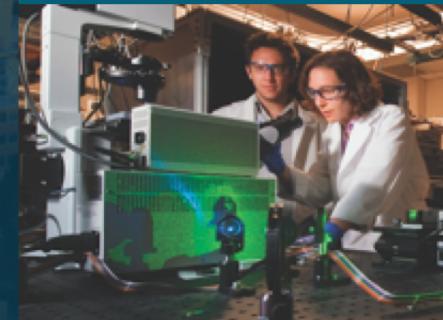


Guest Lecture Stanford ME469: Multiphysics Coupling



PRESENTED BY

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Computational Thermal and Fluid Mechanics

Sandia National Laboratories SAND2018-4536 PE



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Multiphysics Coupling: Outline



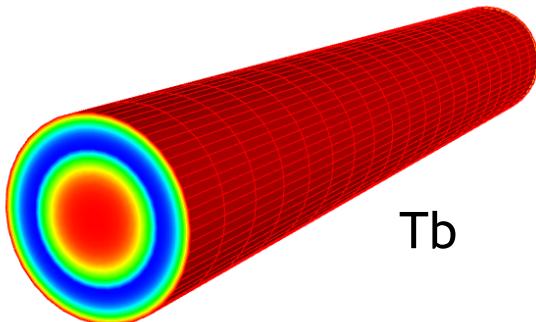
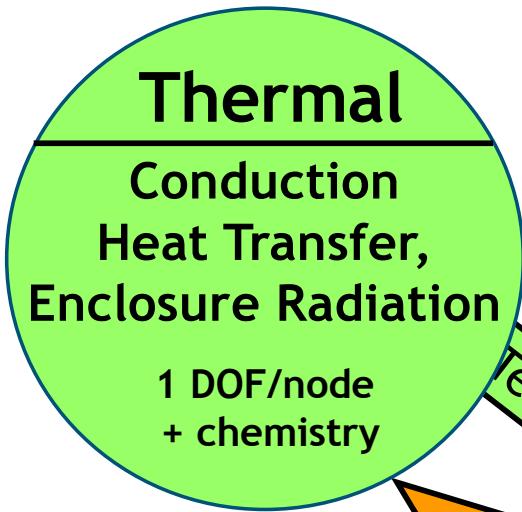
- Examples of multiphysics coupling with emphasis on fluids, PMR, and CHT
- Monolithic vs Operator Split
- Details of PMR/Fluids Coupling
- Details of PMR/Thermal Coupling
- Details of Fluids/Thermal Coupling
- Verification
- Stability
- Conclusions

We Live in a Multiphysics World



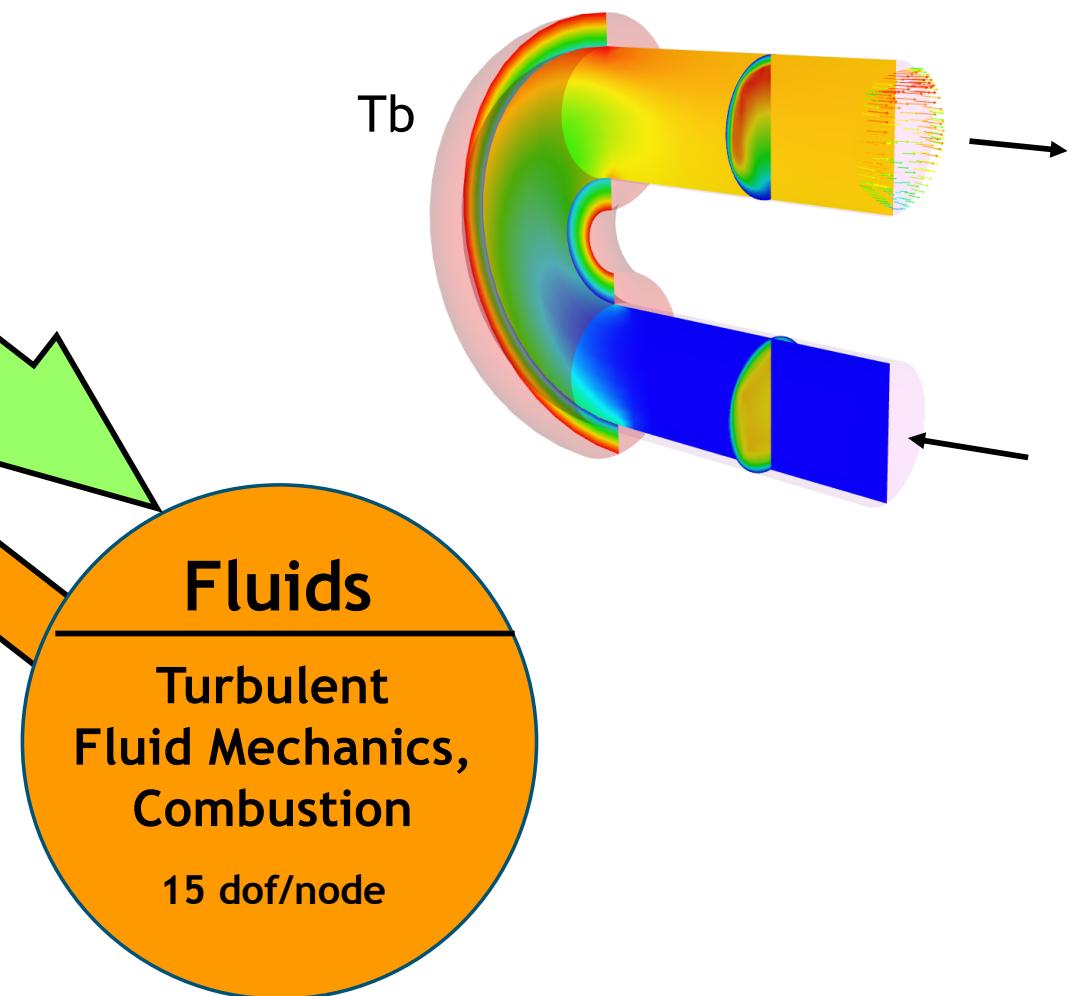
- Fluid/Structure coupling:
 - Wind turbines
 - Wing fluttering, etc.
- Non-isothermal fluids/participating media radiation:
 - Fires,
 - Natural gas and coal combustion,
 - Smelting, ethlyne production, etc.
- Conjugate heat transfer:
 - Object-in-fire
 - Gas turbine fine cooling
- Often times, we note 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 system solve, storage and code design
- For operator split, there can be an “art” in determination of stable couplings due to Eigenvalue spread

Conjugate Heat Transfer Coupling



Turbulent pipe CHT

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



Conjugate Heat Transfer Coupling, Equations



- Favre-averaged static enthalpy equation:

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

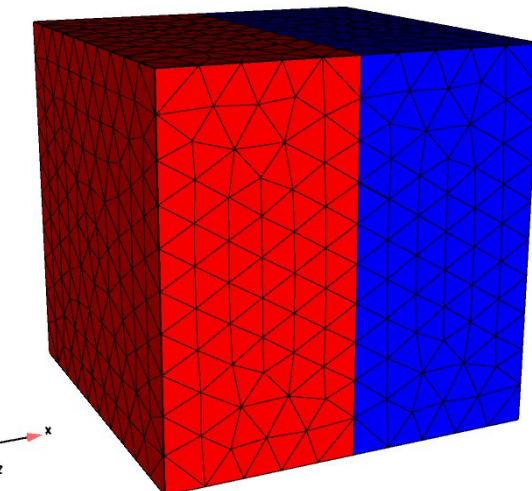
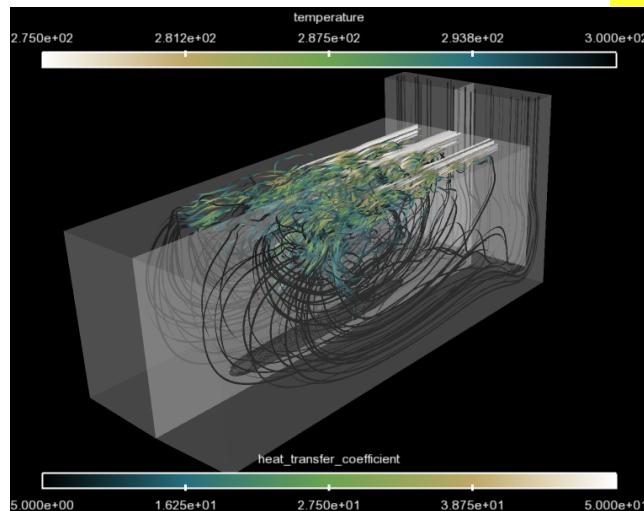
- Thermal heat conduction

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

- Interface condition

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

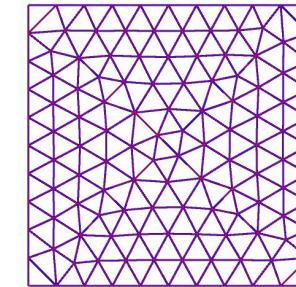
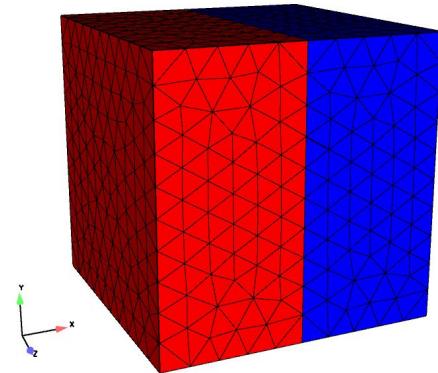
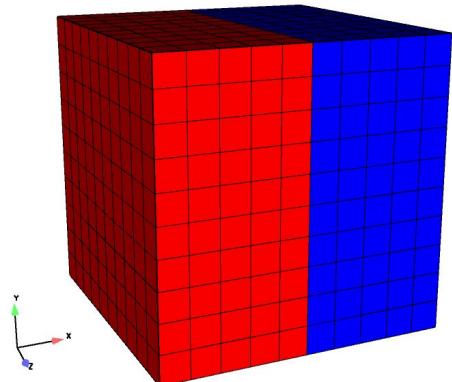
$$q_n = -\lambda \frac{\partial T}{\partial x_j} n_j = h[T - T^\infty]$$



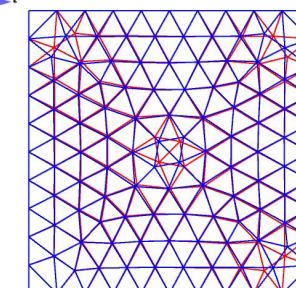
Fluid/CHT Coupling Verification



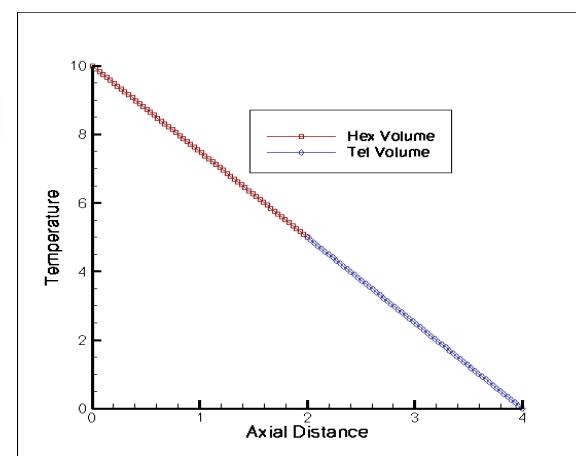
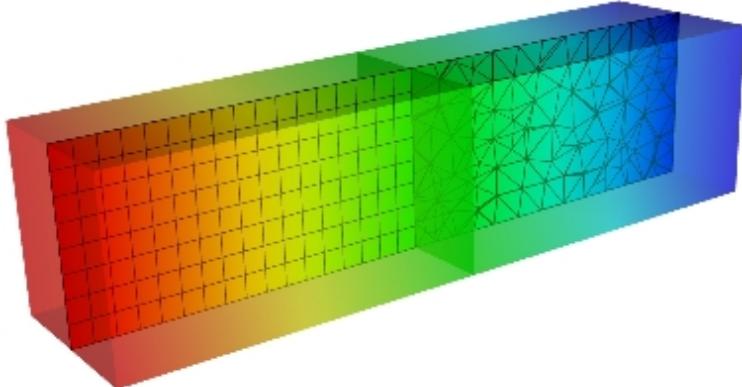
- Unstructured heterogeneous mesh capability
- Arbitrary geometric complexity
- Multi-block domain variable transfer



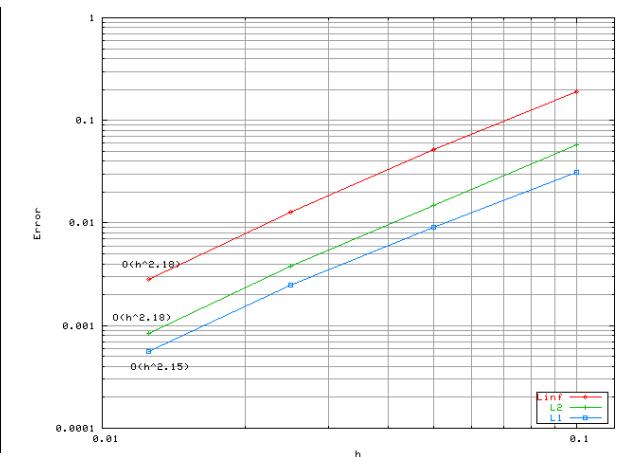
Conforming
interface



Non-
conforming
interface

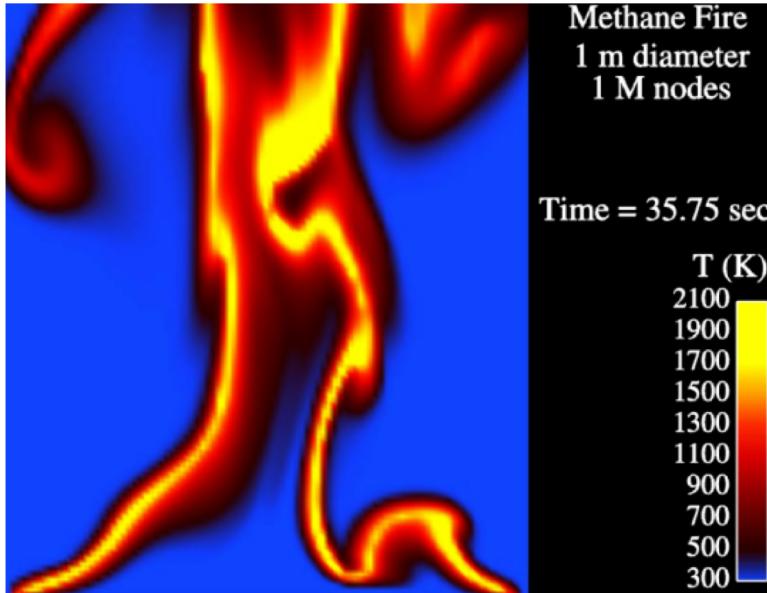


Linear (patch test)

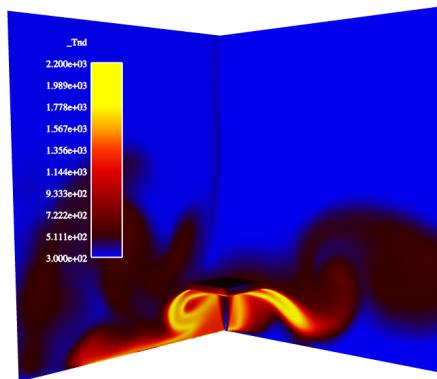


Trigometric MMS

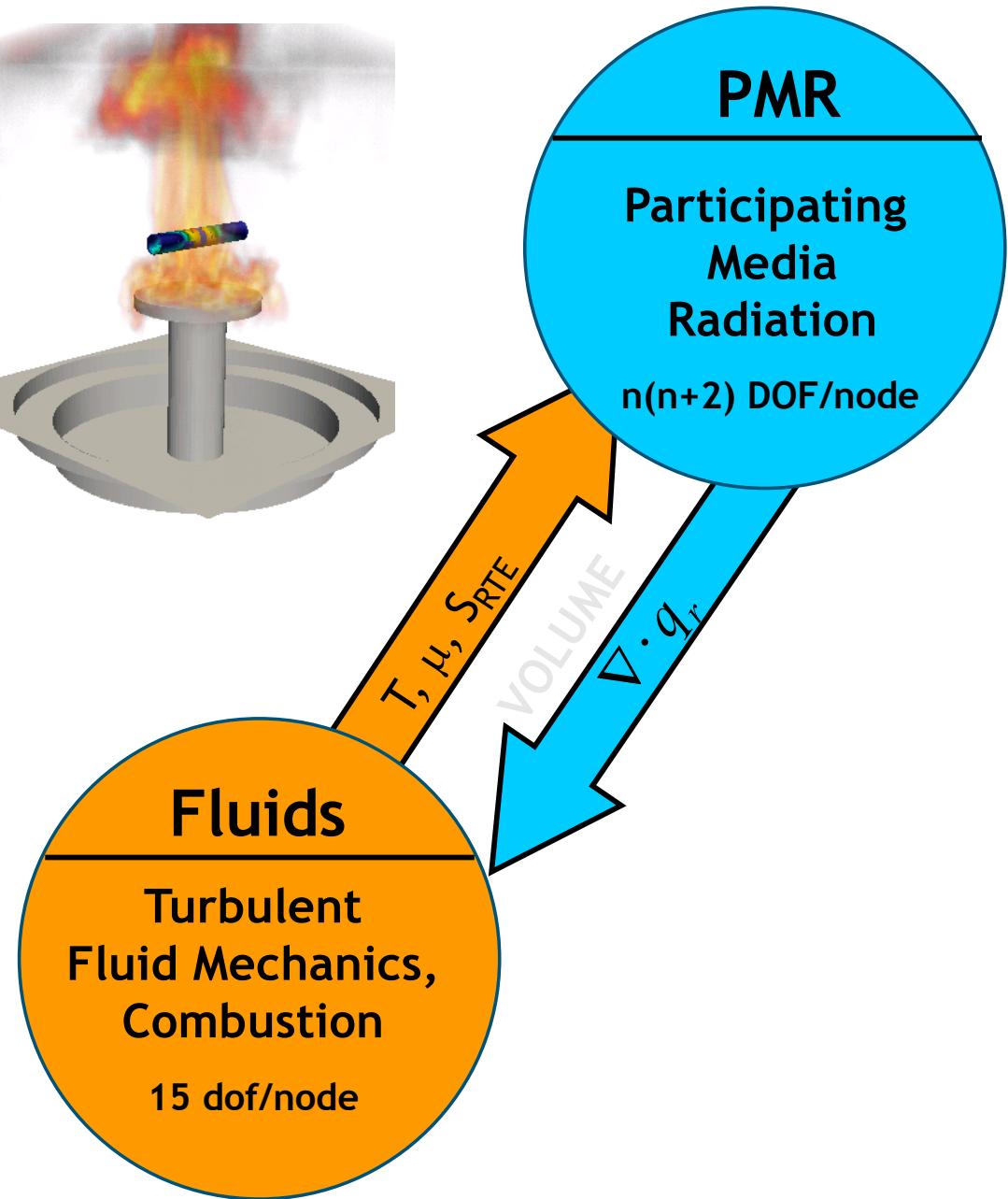
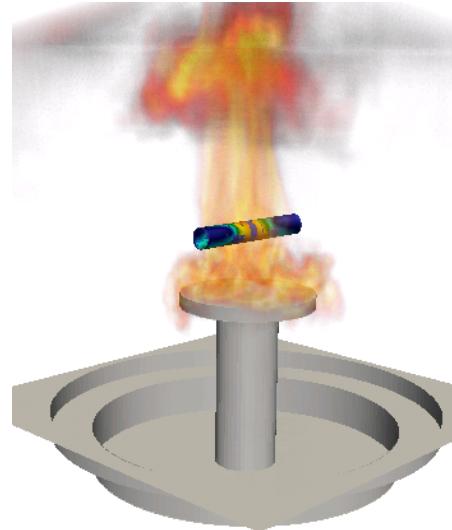
Fluids/PMR Coupling



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

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

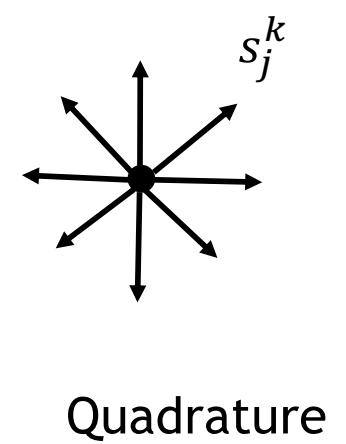
- Scalar Flux,

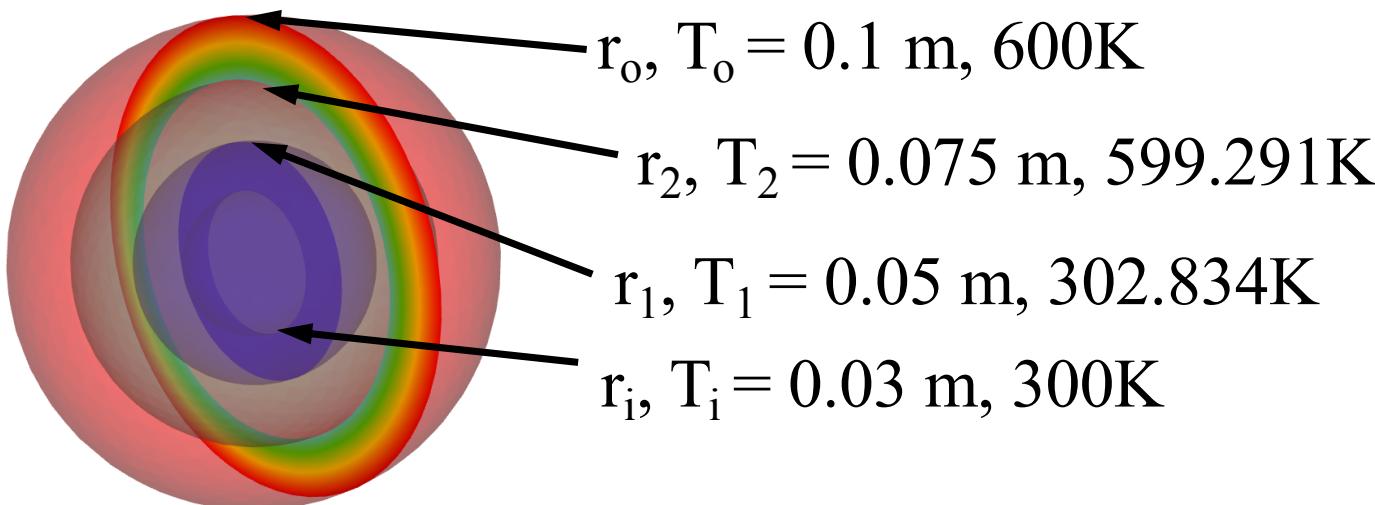
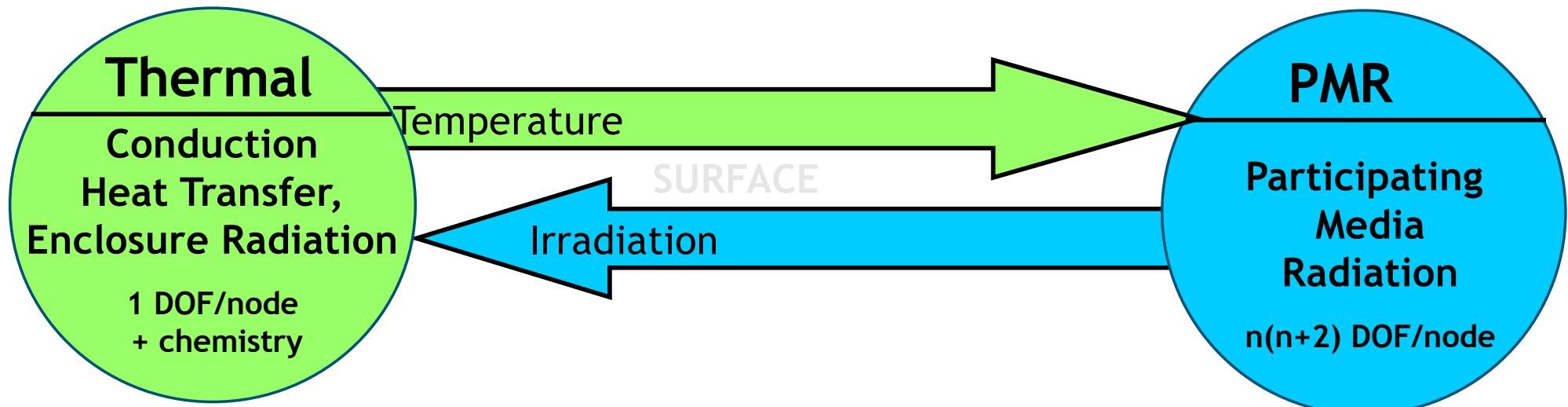
$$G \approx \sum_k w_k I^k$$

- Divergence of radiative flux,

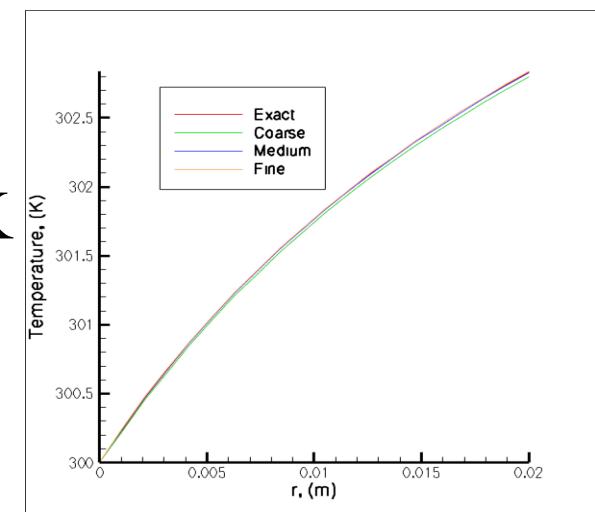
$$q_j^R \approx \sum_k w_k I^k s_j^k$$

$$\frac{\partial q_j^R}{\partial x_j} = \mu_a [4\sigma T^4 - G]$$





PMR:Conduction through concentric spheres



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



- 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),

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

- 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,

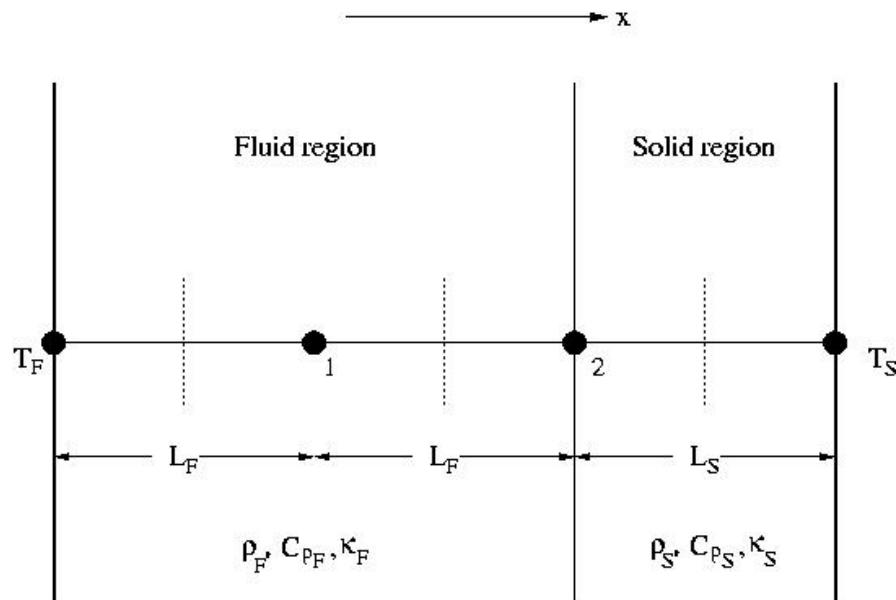
$$q_n = -\lambda \frac{\partial T}{\partial x_j} n_j = \varepsilon [\sigma T_e^4 - H]$$

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

Conjugate Heat Transfer Stability



- Consider a simple CHT problem



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

- Compute amplification factor

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

- Requiring:

$$|\lambda| \leq 1$$

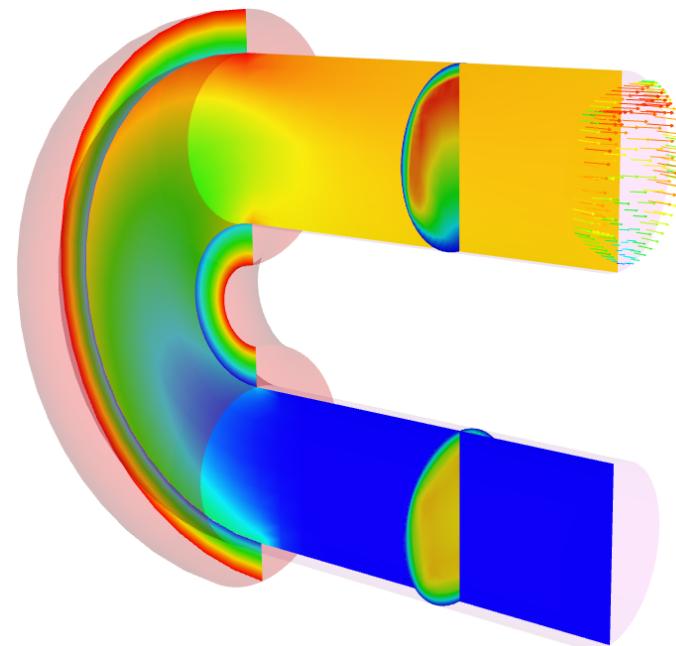
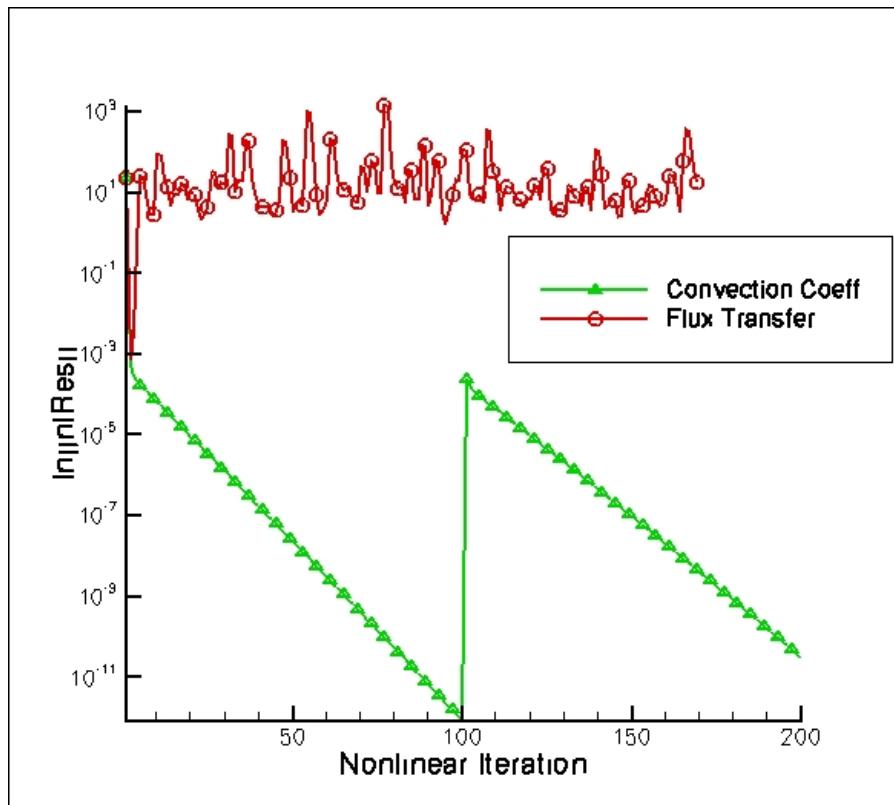
- CHT via flux transfer:
 - Explicit RHS
 - Unstable for certain time steps and material properties
- CHT via convection coefficient:
 - Implicit LHS
 - Unconditionally stable

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

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:

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

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

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

- In practice, such procedures enhance stability for the multi-physics coupling
- In the case of Fluids/CHT, one could possibly monolithically couple the systems
- In the case of Fluids/PMR, monolithic coupling is not practical as the intensity system is $\sim N^2$, 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