Quantitative Guidelines on Radiation Model Selection for Material Response Simulation

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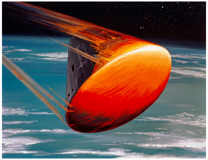
Radiation in Porous Media

A critical modeling point

- In lightweight ablative TPS: radiation has an impact close to conduction *starting from* $\sim 1000\,\mathrm{K}$
- Only basic modeling in common simulation tools



Modeling approaches

- Radiation Transfer Equation
- Differential approximations (moment methods)
- Radiative Fourier law

Material Response Code Features

Current implementation in material response codes

- **Radiative Fourier law** in the medium $P^{\mathrm{R}} = \nabla \cdot \left(\mathbb{k}^{\mathrm{R}}(T) \cdot \nabla T\right)$
- **Opaque-body** radiative BCs $\boldsymbol{q}^{\mathrm{R}} = \varepsilon \sigma_{\mathrm{SB}} \left(T_{\mathrm{w}}^4 - T_{\infty}^4\right)$

Model benefits and drawbacks

✓ Very cheap numerically

✗ Strong modeling hypotheses

Input data

- $\mathbb{k}^{\mathrm{R}}$ accessed through LFA
- No immediate experimental separation from conductive contribution

Is our radiation model good enough?

Are improvements necessary?

What should be improved?

Models

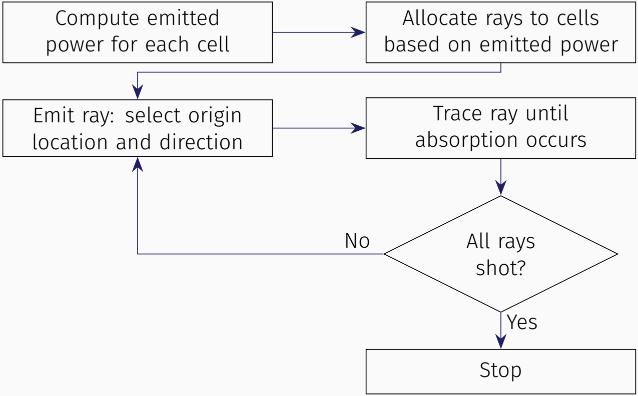
Material response model

- "Type 2" material response model (Lachaud et al., 2011)
- Solver: PATO
- Based on OpenFOAM
- Uses Mutation^{++} for chemistry and gas properties

Radiation transfer model

- Non-scattering medium $\Rightarrow \beta = \kappa$, $\kappa^{\text{eff}} = \kappa$
- No radiative property variation
- RTE solver: Monte Carlo ray tracing

Monte Carlo ray tracing principles



Test Case

Basic setup

- 1 D sample
- Size $L = 5\,\mathrm{cm}$
- Flux-driven BC (CMA) at $x = L$
- Zero-flux BC at $x = 0$
- Properties: TACOT 2.2, modified conductivity values

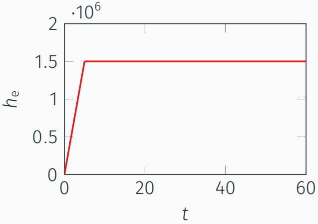
Boundary conditions

$\sim$ Ablation Test Case 2.2:

$$h_e = \begin{cases} 0\,\mathrm{J\,kg^{-1}} & \text{at } t = 0 \\ 1.5 \times 10^6\,\mathrm{J\,kg^{-1}} & \text{at } t \geq 5\,\mathrm{s} \end{cases}$$

Blackbody temperature:

$$T_e = 1750\,\mathrm{K}$$



Initial conditions

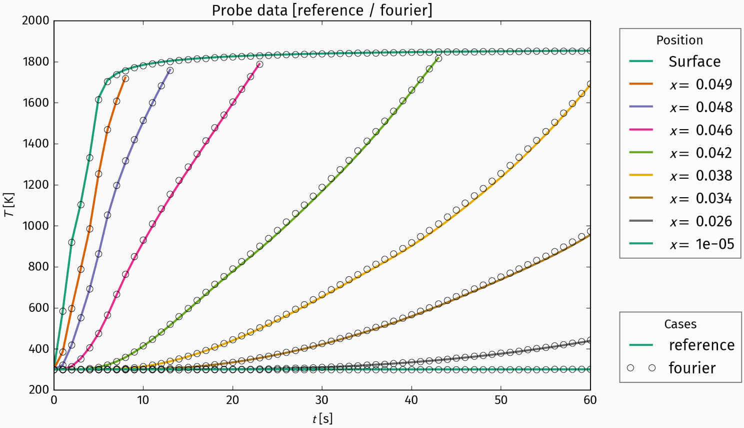
$T = 300\,\mathrm{K}$

Test case breakdown

1. Reference (original PATO model)
2. Fourier law
3. RTE with Monte Carlo ray tracing

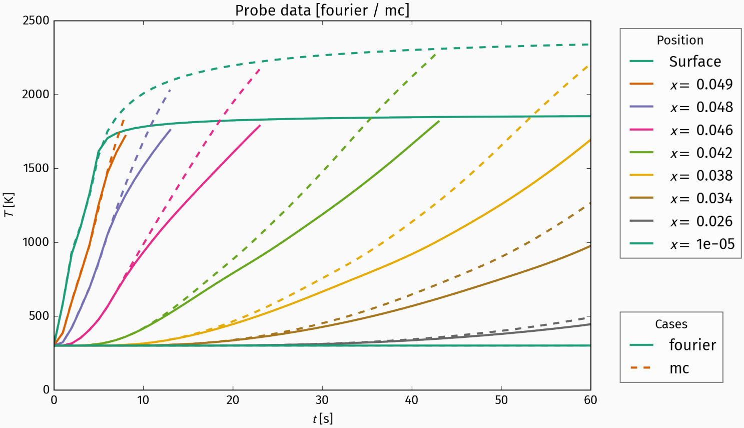
Probe positioning

Fourier



Probe data [reference / fourier]
T [K]
t [s]
2000
1800
1600
1400
1200
1000
800
600
400
200
0
10
20
30
40
50
60
Position
Surface
x= 0.049
x= 0.048
x= 0.046
x= 0.042
x= 0.038
x= 0.034
x= 0.026
x= 1e−05
Cases
reference
fourier

Monte Carlo RTE



Conclusions

Summary

- Reasonable accuracy of the radiative Fourier law **outside the radiative boundary layer**
- Improving models for the radiative boundary layer is critical

Future works and perspectives

- Testing for a wider variety of cases
- Modeling in the radiative boundary layer (near-interface region)

Questions?

PATO: `https://software.nasa.gov/software/ARC-16680-1`

Mutation^{++}: `https://sync.vki.ac.be/mpp/mutationpp`

Backup Slides

Material Response Model

Type 2 material response model main features (Lachaud et al., 2011)

- Momentum conservation (Darcy law)
- Pyrolysis
- Finite-rate gas chemistry
- Element-based gaseous species mass conservation
- CMA boundary condition

Implementation: PATO (Lachaud, 2017)

- Based on OpenFOAM
- Open source
- Implements Type 2+ features
- Uses Mutation^{++} for gas properties

Radiation Transfer Model

Main hypotheses

- Non-scattering medium $\Rightarrow \beta = \kappa$, $\kappa^{\text{eff}} = \kappa$
- No radiative property variation

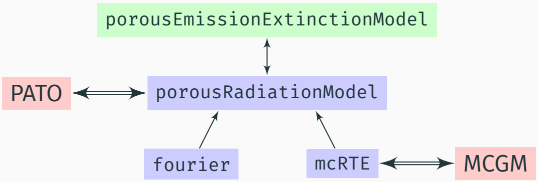
Implementation: MCGM (Monte Carlo solver for Gray Media)

- RTE solver implemented in C++
- Client-server parallel architecture (MPI)
- One-dimensional
- Fully reciprocal method
- Validated on multiple test cases

Coupling with Material Response Code

Custom OpenFOAM radiation library

- Intermediate abstraction level
- Uses runtime selection mechanism for better extensibility
- Supported models: Fourier law and RTE *via* interface with MCGM



Model Accuracy Quantification

Validity criterion for the Fourier law (Gomart and Taine, 2011)

1. **Not in the radiative boundary layer**
   Works only in the core of the shield $\Rightarrow$ thickness $= 5/\kappa$
2. **Limited variations of temperature**

$$\frac{1}{\kappa^{\text{eff}}} \frac{\|\nabla T\|}{T} < \eta \qquad \text{with } \kappa \leq \kappa^{\text{eff}} \leq \kappa + \sigma(1-g)$$

Effective absorption coefficient accounting for multiple scattering "Radiative mean-free-path"

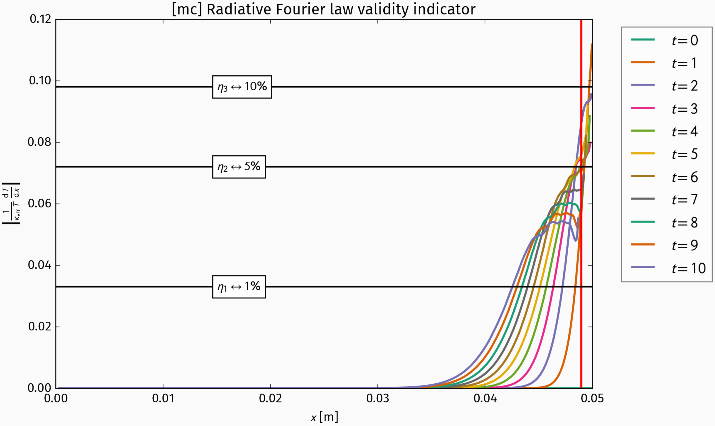
Quantifies "$\ll 1$" (depends on requested accuracy for Fourier law) Available from theoretical study

Problems in the near-interface region

- Hottest region $\Rightarrow$ Radiation transfer is more intense
- Close interface & higher porosity $\Rightarrow$ Increased chance to invalidate crit. 1
- Steep temperature gradients $\Rightarrow$ Increased chance to invalidate crit. 2

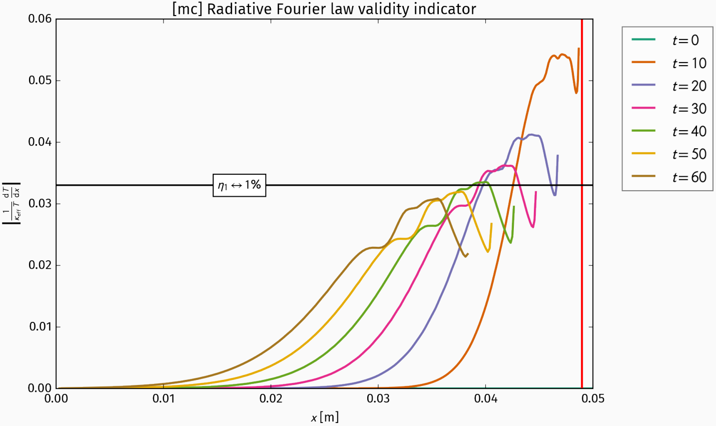
Validity Criterion

Monte Carlo RTE



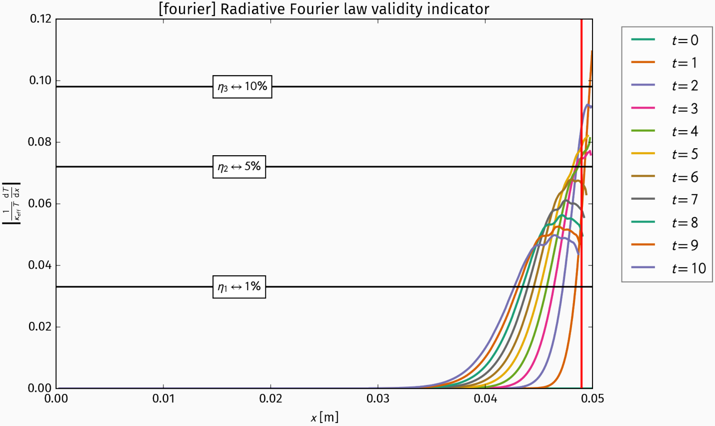
Validity Criterion

Monte Carlo RTE



Validity Criterion

Fourier



Validity Criterion

Fourier