Impact of radiation transfer modeling on the simulation of the thermal response of ablating spacecraft thermal protection systems

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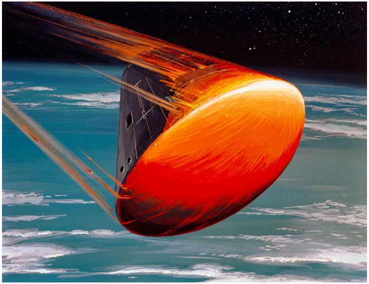
General problem

High velocity atmospheric entry of a spacecraft generates high heat fluxes (up to $10\,\mathrm{MW\,m^{-2}}$, shield temperature up to $3000\,\mathrm{K}$)

Protection of payload requires an appropriate **thermal protection system** (TPS)

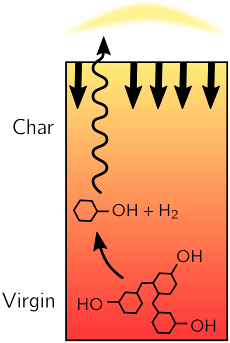
High mission costs: Accurate predictions are essential to reduce safety factors

Lightweight porous carbon/phenolic resin ablators absorb the heat load through an endothermic pyrolysis reaction



Lightweight ablative thermal protection

Essential element of shield design: **Material response modeling**



Coupling with fluid domain

Interface recession

Radiation transfer in hotter regions

Transport and reaction of pyrolysis products

Gas flow

Pyrolysis

Conduction

Multiple, coupled physical phenomena

Challenges and stakes of modeling and material characterization

Model inputs require **medium characterization**

Central element of characterization: **Material testing** (e.g. TGA, LFA, M-DSC)

It is a challenge due to extreme conditions: gathering data for flight conditions is difficult

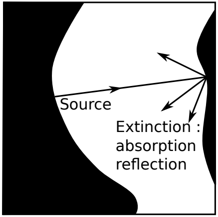
Every addition to a model requires further testing:
the impact has to be assessed

Radiation modeling for TPS

Modeling radiation transfer in porous media

Typical configuration

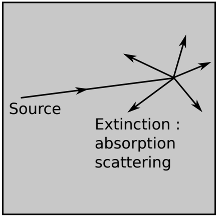
- one opaque phase
- one transparent phase



Multiscale view

- pore-scale: surface radiative interaction
- macro-scale: participating homogeneous medium

Several approaches exist for upscaling (not discussed here)



Common macro-scale models for radiation transfer

- radiation transfer equation (possibly generalized)
- radiative Fourier law

Current model

Fourier $$P^{\mathrm{R}} = \nabla \cdot \left(\mathbb{k}^{\mathrm{R}} \cdot \nabla T \right)$$ "constrained" cheap

$$P^{\mathrm{R}} = -\nabla \cdot \left(\int_{4\pi} I_\nu(\mathbf{r}, \mathbf{u})\, \mathbf{u}\, \mathrm{d}\Omega \right)$$

RTE $$\mathbf{u} \cdot \nabla_{\mathbf{r}} I_\nu (\mathbf{r}, \mathbf{u}) = S_\nu^{\mathrm{e}} (\mathbf{r}, \mathbf{u}) - \beta_\nu (\mathbf{u})\, I_\nu (\mathbf{r}, \mathbf{u}) + \int_{4\pi} \sigma_\nu (\mathbf{u}')\, I_\nu (\mathbf{r}, \mathbf{u}')\, \frac{p_\nu (\mathbf{r}, \mathbf{u}', \mathbf{u})}{4\pi} \mathrm{d}\Omega'$$ "flexible" expensive

Engineering models for spaceraft TPS use the **radiative Fourier law** due to

- cheap computational cost and ease of implementation
- ease of characterization (LFA)

Current model (cont'd)

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
2. Limited variations of temperature

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

κ^{eff}: Effective absorption coefficient accounting for multiple scattering

η: Quantifies "≪ 1" (depends on requested accuracy for Fourier's law)

Problems in the near-interface region

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

Analysis of a simple case

Problem description

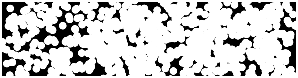
Geometry

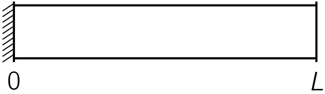
Pore scale:

- Opaque/transparent configuration

Macro scale:

- One-dimensional sample of size $L = 5\,\mathrm{cm}$





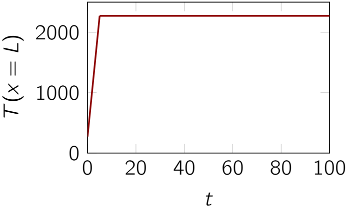
Governing equations

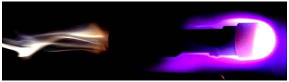
Energy balance (conduction and radiation)

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k^{\mathrm{eff}} \frac{\partial T}{\partial x}\right) + P^{\mathrm{R}}$$

Boundary conditions ($\sim$ plasmatron test):

- Zero flux at $x = 0$
- $T = \begin{cases} 273\,\mathrm{K} & \text{at } t = 0 \\ 2273\,\mathrm{K} & \text{at } t \geq 5\,\mathrm{s} \end{cases}$ at $x = L$





Implementation

Material properties

Fictitious lightweight ablator designed for code benchmarking: TACOT 3.0 (Lachaud et al., 2012)

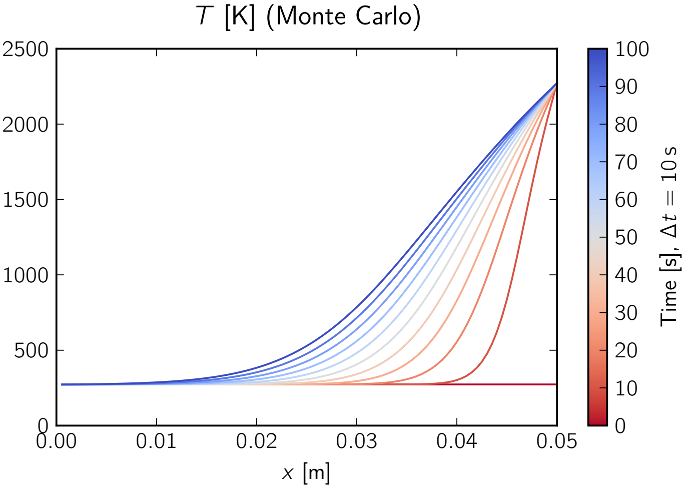
Conduction code

- OpenFOAM solver
- Finite volume discretization, explicit time stepping

Radiation code

- Monte Carlo ray tracing code (C++)
- Reciprocal Monte Carlo method with deterministic absorption
- Supports isotropic Beerian absorption and scattering
- Client-server architecture for convenient coupling based on MPI

Temperature field analysis



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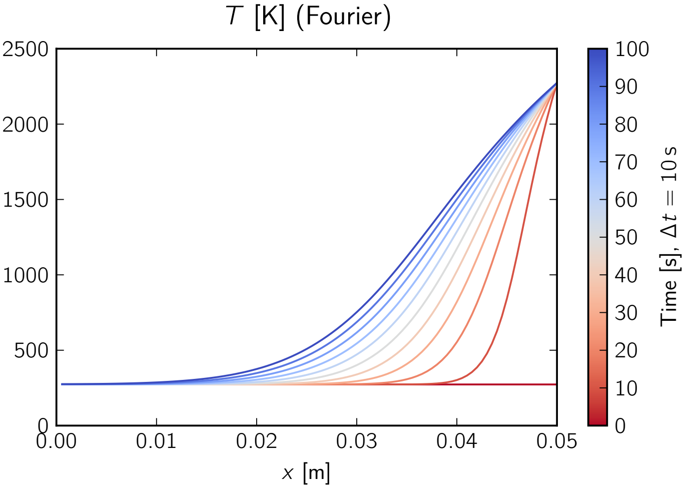
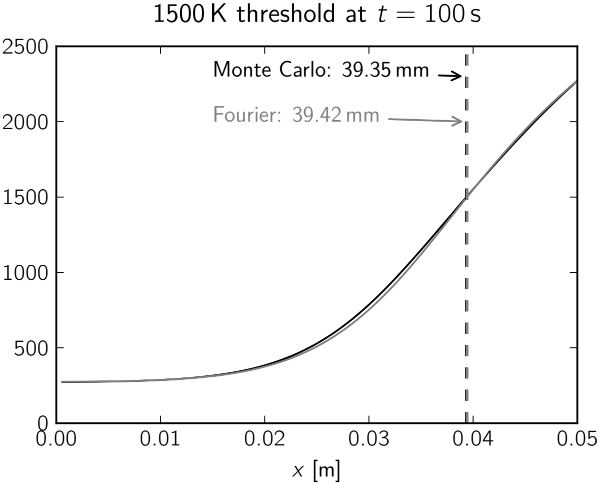
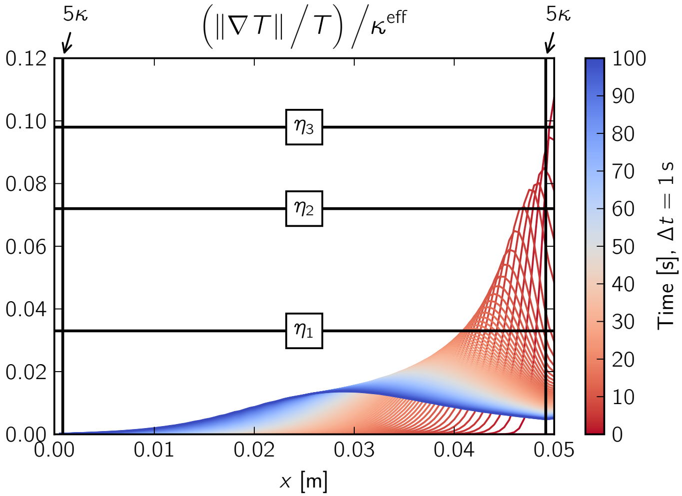


Temperature field analysis



Temperature field analysis



Fourier law accuracy [%]	
η_3	10
η_2	5
η_1	1

Conclusions

Conclusions

Summary

- Validity criterion is ideal for the selection of a model
- Overall effect on a non-reacting sample is very limited in the conditions considered

Future works

- Testing in a high-temperature case
- Impact on the recession rate for a reacting sample
- Design of a hybrid radiation code if relevant

Questions?

Backup slides

Ablative C/P shield phenomenology

Macroscopic phenomenology

Long distance effects
- Radiation$^{\#}$

Material/flow coupling
- Boundary layer transfers (heat and mass)$^{\#}$
- Recombination/catalicity$^{\#}$
- Ablation (oxidation, sublimation, spallation)

Interface phenomena: Heat and mass balance*,
Subsurface phenomena
- In-depth ablation^{++}
- Penetration of radiation$^{\#}$
- Gas flow entering into the material$^{\#}$

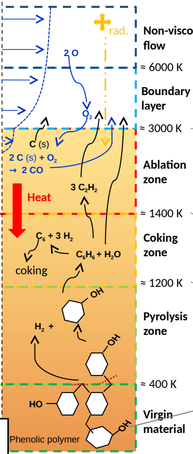
- Conduction heat transfer*
- Radiation heat transfer (empirical*, modeled^{++})
- Finite-rate chemistry of the pyrolysis gases^{++}
- Coking^{++}

- Multi-component diffusion^{++} (atm. gas/ pyro. gas)
- Convective transport (Darcy^{+}, Klinkenberg^{++})
- Charring process (evolution of the density*, porosity^{+}, tortuosity^{++}, permeability^{+}, effective conductivity*, effective surface area^{++})

- Phenolic-decomposition products^{++}
- Phenolic-decomposition rate*

* : type 1 (e.g. CMA)
$^{+}$: type 2 (PAM_2)
$^{++}$: type 3 (PAM_3)
: research in progress (elementary analysis modules – e.g. COACO for carbon-fiber ablation)

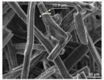
Macroscopic illustration



Chemistry mechanisms (simplified illustration)

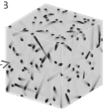
Microscopic illustration

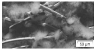
Gas/surface Interactions in porous fibrous media:
- ablation$^{\#}$
- erosion$^{\#}$
- recombination$^{\#}$
- convective heating$^{\#}$
- radiative heating$^{\#}$



Scanning Electron Microscopy (SEM) : Carbon preform

3D simulation of the ablation of a carbon/phenolic composite [Lachaud, 2010]





SEM: carbon/phenolic (virgin) [Stackpoole, 2008]

3D numerical reconstitution of a carbon/phenolic composite

(Lachaud et al., 2011)

Verification through ground testing

Ground testing (e.g. plasma torch + longshot) can be used for verification

(Helber, 2016)

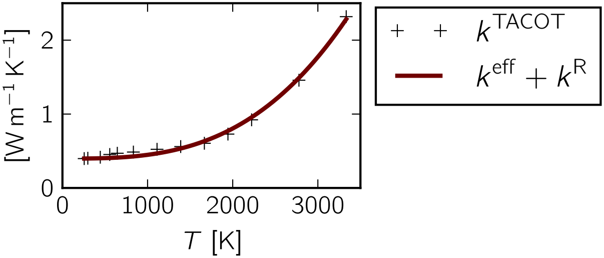
Material properties

Thermophysical properties

- $\varepsilon = 0.85$
- $\rho = 2.6 \times 10^2\,\mathrm{kg\,m^{-3}}$
- $c_p = 1.8 \times 10^3\,\mathrm{J\,kg^{-1}\,K^{-1}}$
- $k^{\mathrm{eff}} = 0.40\,\mathrm{W\,m^{-1}\,K^{-1}}$ (isotropic)

Radiative properties

- $k^{\mathrm{R}} = CT^3$ with $C = 5.1 \times 10^{-11}\mathrm{SI}$
- no scattering: $C = \dfrac{16\sigma_{\mathrm{S}}}{3\kappa}$
- $\kappa = 5.9 \times 10^3\,\mathrm{m^{-1}}$



Values obtained from properties of charred-state TACOT 3.0 (Lachaud et al., 2012)

Fictitious lightweight ablator designed for code benchmarking