



Influence of Gas Surface Interactions Modeling on Radiative Heat Transfer for Hypersonic Atmospheric Entry

RUSSELL: A New GPU-Accelerated Discontinuous Galerkin Radiation Solver

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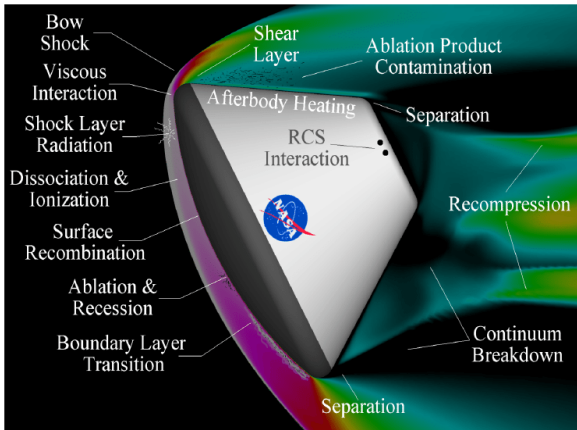


Outline

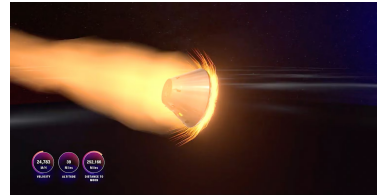
- 1 Motivation
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- 4 Conclusions



Hypersonic atmospheric entry



Aerothermal phenomena around a re-entry capsule. Image credit: NASA.



Artemis II re-entry. Image credit: NASA.



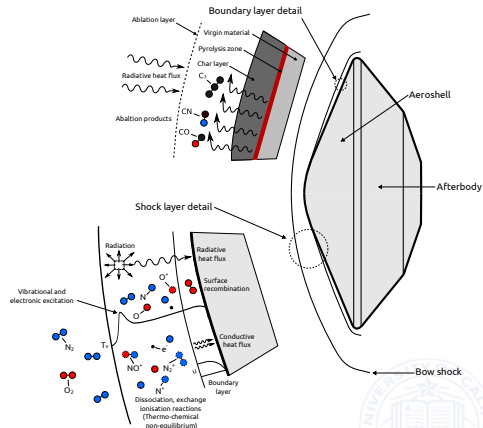
Starship flight test re-entry. Image credit: SpaceX.

A tightly coupled multiphysics problem

In the shock layer multiple physics phenomena interact with each others:

- **Radiation** → **flow**: radiative cooling removes energy from the shock layer, **reducing the stand-off**; reabsorption in the BL can reheat the flow
- **Ablation** → **flow**: injected C, CO, CN cool the boundary layer, soften the near-wall gradient and **increase the BL density**
- **Ablation** → **radiation**: carbon species are strong emitters and absorbers, so they **modify** the radiation field
- **Heat fluxes** → **surface**: convective + radiative flux set T_w , which drives surface chemistry

Everything is coupled — High fidelity simulations require high computational costs.



Aerothermodynamic processes for Earth atmospheric entry.

Potter, D., Ph.D. Thesis, Univ. of Queensland, 2011.

Radiation transport in coupled simulations

$$\mathbf{s} \cdot \nabla I_{\lambda}(\mathbf{x}, \mathbf{s}, \lambda) = j_{\lambda} - \kappa_{\lambda} I_{\lambda}$$

$\mathbf{x}$: space
 10^4 – 10^7 cells

$\mathbf{s}$: direction
 10^2 – 10^3 angles

λ : wavelength
up to 10^6 points

one unknown per cell $\times$ direction $\times$ wavelength $\Rightarrow \gtrsim 10^{12}$ per solve

- **High-speed entry:** radiative load **comparable to convective**, must be evaluated accurately
- **Coupling loop:** CFD **re-converged** after every radiation solve, then radiation called again on the updated flow field
- **Bottleneck:** one RTE solve takes **hours**, the flow solver waits

One radiation solve, MURP on 32 cores (2D-axi)	wall time
Titan entry (Dragonfly)	1 h
Earth entry, 150 groups $\times$ 128 directions	3.5 h
High fidelity, 2000 groups $\times$ 512 directions	> 7 h

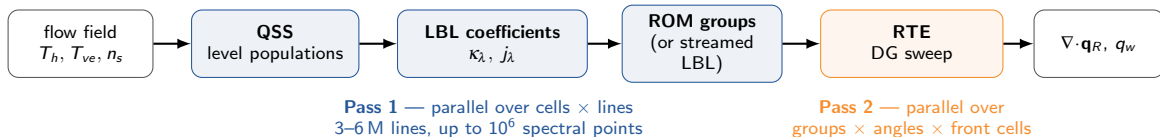


Part I

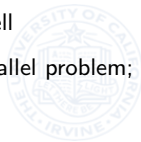
RUSSELL

Radiative Unified Spectral Solver and Emission Line-by-line Library

RUSSELL: a GPU-accelerated DG radiation solver

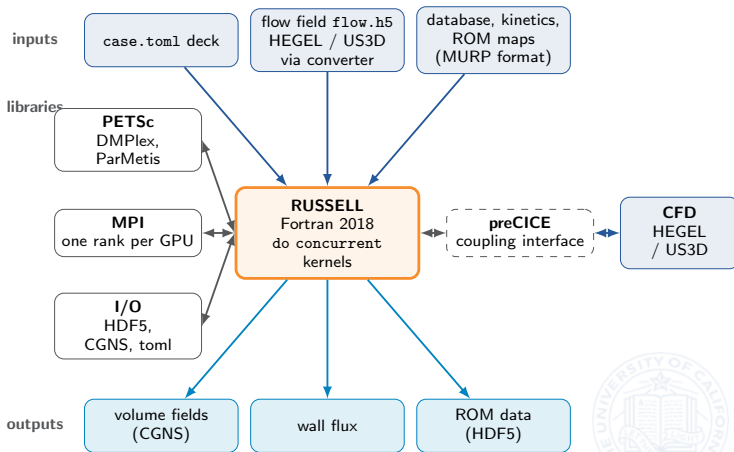


- **High-fidelity spectral library inherited from MURP:** same database, non-Boltzmann (QSS) populations, line-by-line coefficients
- **Advanced ROM grouping:** $\mathcal{O}(10^2)$ groups in place of 10^6 wavelengths
- **Discontinuous Galerkin transport:** conservative in the volume, higher accuracy inside the cell
- **GPU-native code base:** cells, directions and wavelengths are independent — a naturally parallel problem; one Fortran source for CPU and GPU



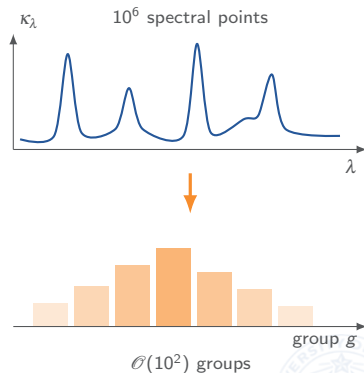
RUSSELL: code structure

- **Mesh:** PETSc DMPLex, ParMetis partitioning
- **Kernels:** every loop a do concurrent; nvfortran for GPU or multicore CPU
- **Parallelism:** MPI, one rank per GPU; mesh and/or spectral decomposition
- **Coupling:** source term and wall flux returned to the CFD solver



Spectral coefficients: from the flow field to group opacities

- **QSS**: non-Boltzmann electronic populations, one dense solve per cell and species
- **Line by line**: κ_λ , j_λ for every line (3–6 M), every wavelength (up to 10^6) and every cell; Voigt profiles [GPU-readable tables: in progress]
- **MBOB grouping**¹: groups cut in coefficient space (j_λ , $\kappa_\lambda j_\lambda$), not in wavelength
 - **100 groups** (10×10) for air11: <5% error vs. line by line
 - **150 groups** (15×10) for ablation mixtures
 - conventional binning needs >1000 groups
- **GPU**: pass 1 parallel over cells $\times$ lines, QSS batched across cells



¹ Sahai et al., *Comparative analysis of reduced-order spectral models and grouping strategies for non-equilibrium radiation*, JQSRT, 2020.



From the RTE to the DG cell system

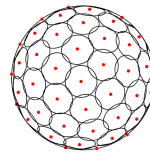
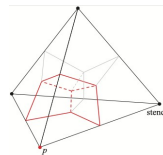
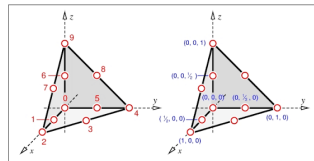
RTE, per direction $\mathbf{s}_m$ and wavelength λ

$$\mathbf{s}_m \cdot \nabla I_m + \kappa_\lambda I_m = j_\lambda, \quad \nabla \cdot \mathbf{q}_R = \int_0^\infty \left[4\pi j_\lambda - \kappa_\lambda \int_{4\pi} I_\lambda d\Omega \right] d\lambda$$

Weak form on each cell K , $b \in \mathbb{Q}^p(K)$, upwind trace $\hat{I}_m$

$$-\int_K I_m (\mathbf{s}_m \cdot \nabla b) dV + \int_{\partial K} (\mathbf{s}_m \cdot \mathbf{n}) \hat{I}_m b dS + \int_K \kappa I_m b dV = \int_K j b dV$$

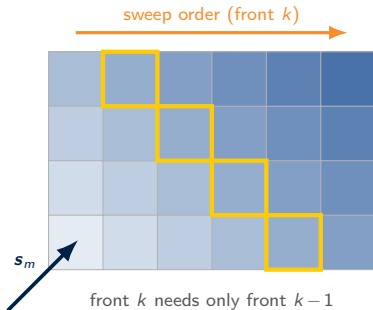
$$(S_m + F_m^+ + \kappa_K M) \mathbf{I}_{m,K} = M \mathbf{j}_K + \mathbf{g}_{m,K}^-$$



- Dense $N_p \times N_p$ block per cell and direction, $N_p = (p+1)^d$; $\mathbf{g}^-$ collects the upwind neighbours
- $p=0 \equiv$ finite-volume update of MURP; $\nabla \cdot \mathbf{q}_R$ conserved cell by cell for any p



One sweep is the exact solve



Cells ordered along $s_m \Rightarrow$ block lower-triangular operator:

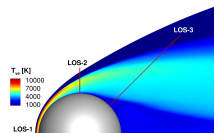
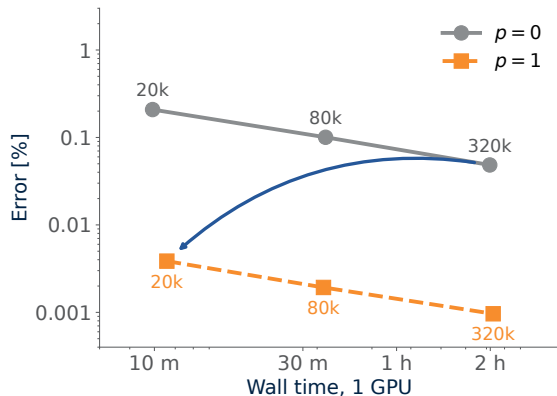
$$\mathbf{L}_m = \mathbf{D} - \mathbf{N}, \quad \boxed{(\mathbf{D}^{-1}\mathbf{N})^L = 0}$$

Forward substitution *is* the exact solve: one pass per direction, no iteration.

- One pass per direction; the cells of a front are **independent**
- Unstructured meshes: Kahn topological sort per direction; closed loops cut and lagged
- Verified against point-Jacobi and assembled LU (PETSc) solvers



Second order on the same sweep

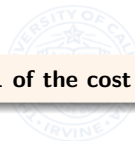


Sphere, 14 km/s: temperature field.

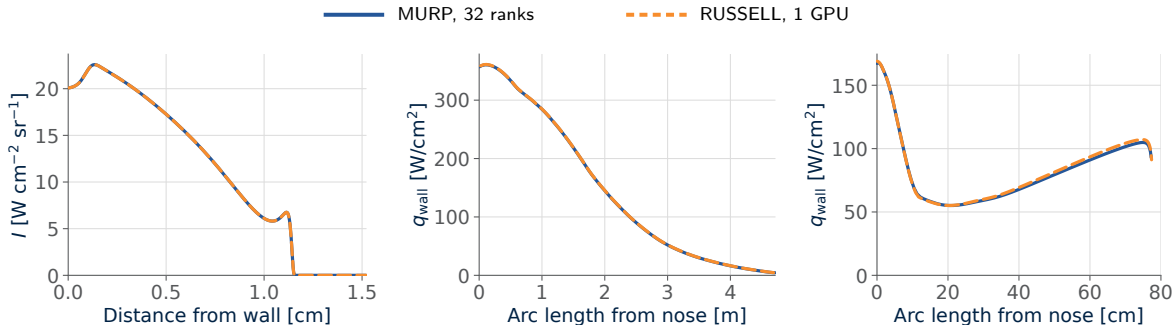
- $p=1$: nodal Q^1 , 4 (2D) or 8 (3D) DOFs per cell
- Positivity limiter¹, conservation preserved
- Sphere, 14 km/s: nested 20k / 80k / 320k cells, 500 groups $\times$ 128 directions

$p=1$ is 12 $\times$ more accurate at 1/11 of the cost

¹ Yuan, Cheng & Shu, SIAM J. Sci. Comput., 2016.



Verification against MURP



1D line of sight, 10 km/s, 10^6 wavelengths

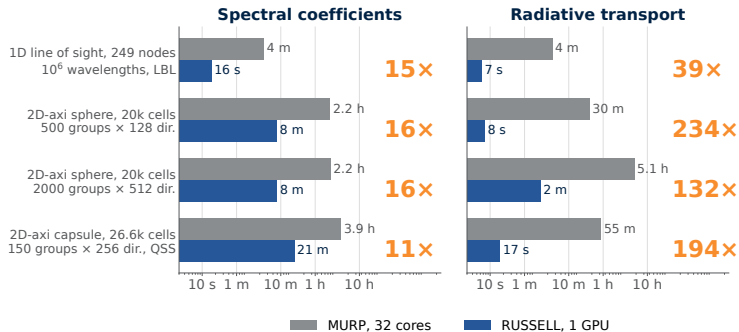
2D-axi sphere, 14 km/s, 500 groups $\times$ 128 dir.

2D-axi PICA capsule, 10 km/s, 500 groups $\times$ 400 dir.

- **Coefficients:** same database, QSS and ROM maps as MURP; pointwise agreement to 10^{-10}
- **Transport:** integrated fluxes agree to 10^{-3} in parity builds



Speed-up: 1 GPU vs. 32 CPU cores

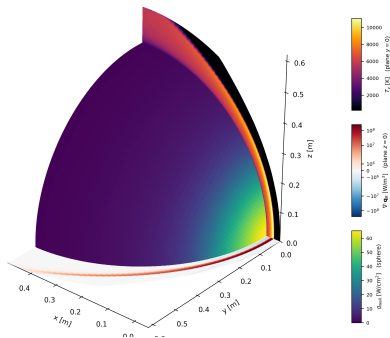


- Transport: **two orders** of magnitude
- Coefficients: one order (memory bound)
- Full solve: up to **40x**
- **No tables**: all coefficients line by line

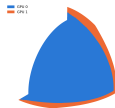
MURP: 32 MPI ranks, Intel Xeon w9-3495X. RUSSELL: 1x NVIDIA RTX 6000 Ada, 48 GB.



Towards coupled 3D simulations

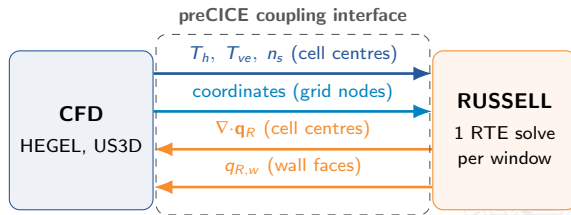


MIRKA sphere, 7.4 km/s: T_v , $\nabla \cdot \mathbf{q}_R$ and wall flux.



2 GPUs [s]	Setup	Coeff.	RTE	Total
$p = 0$	359	2568	34	2962
$p = 1$	382	2566	159	3108

790k hex cells, 100 groups $\times$ 128 directions; bitwise identical to the single-GPU result



RUSSELL: future developments

- **Spectral tables** readable on the GPU
- **Angular discretization study:** DG in angle, quadratures, RPAD
- **Higher-order accuracy:** $p \geq 2$
- **Full ray-tracing implementation** and comparison
- **Scattering**



Part II

Impact of GSI models on flow–radiation coupled simulations

All cases re-solved with RUSSELL

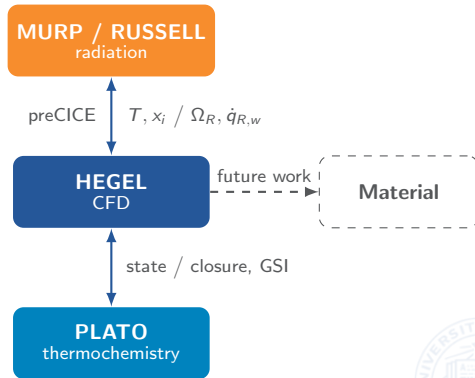
Coupled high-fidelity framework

Objective

Quantify how carbon ablation reshapes the coupled flow–radiation environment, benchmarked against the fully-catalytic-wall reference.

Tools

- **HEGEL** – finite-volume NLTE Navier–Stokes (2D axisymmetric, implicit)
- **PLATO** – thermochemistry: thermo, finite-rate kinetics, transport, **GSI**
- **MURP / RUSSELL** – radiative transfer: QSS, ROM grouping, RTE
- **preCICE** – serial explicit CFD–radiation coupling



Coupling scheme



Fluid dynamics & thermochemistry

Park 2 temperatures (T_h , T_{ve}) nonequilibrium Navier–Stokes, conservative form:

$$\frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot (\mathbf{F}_c - \mathbf{F}_d) = \mathbf{S}, \quad \mathbf{U} = \begin{bmatrix} \rho_i \\ \rho \mathbf{u} \\ \rho E \\ \rho e_{ve} \end{bmatrix}, \quad \mathbf{S} = \begin{bmatrix} \dot{\omega}_i \\ 0 \\ \Omega_R \\ \Omega_R + \Omega_{VT}^* - p_e \nabla \cdot \mathbf{u} \end{bmatrix}$$

- 2D axisymmetric CFD simulations
- *air11* + carbon species (C, CN, CO, CO₂, C₂, C₃, ions): 20 species; PICA mixture with hydrogen species: 30 species
- Source $\mathbf{S}$: chemistry $\dot{\omega}_i$, energy exchange ($\Omega_{VT}, \Omega_{ET}, \dots$), radiation Ω_R
- **HEGEL**: finite volume, backward-Euler implicit to steady state, modified SW

Robust shock capturing

Blended reconstruction near the shock,

$$\phi = s \phi_{\text{CONST}} + (1-s) \phi_{\text{MUSCL}},$$

with shock-tailoring and near-wall mesh adaptation.



Radiative transfer

Radiative transfer equation (RTE) and its coupling back to the flow:

$$\mathbf{s} \cdot \nabla I_\lambda = J_\lambda - \kappa_\lambda I_\lambda, \quad \Omega_R = \nabla \cdot \dot{\mathbf{q}}_R = \int_0^\infty \left(4\pi J_\lambda - \kappa_\lambda \int_{4\pi} I_\lambda d\Omega \right) d\lambda$$

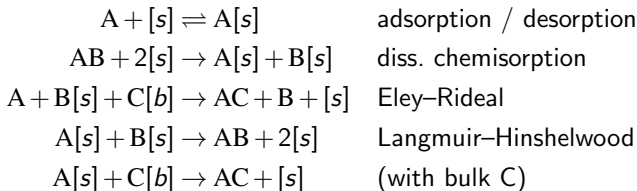
- Campaign run with **MURP**, every converged case **verified with RUSSELL**
- Same spectral database, **QSS** populations and **ROM groups** (150 groups for ablation mixtures)
- Wall flux $\dot{q}_{R,w}$ closes the surface energy balance
- Coupled to CFD via preCICE: 1 radiation solve every 5000 CFD iterations



Gas-surface interaction: ACA and sublimation

Air-Carbon Ablation (ACA) model¹

Finite-rate GSI on active sites [s] and bulk carbon [b]:



A, B = air atoms (N, O); C = bulk carbon $\Rightarrow$ AC = CO, CN.

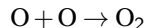
Sublimation of C, C₂, C₃²

Hertz-Knudsen flux from the carbon vapour pressure:

$$\dot{s}_i = \alpha_i (p_{sat,i} - p_{i,w}) \sqrt{\frac{M_i}{2\pi R_u T_w}}$$

$$p_{sat,i} = a_i e^{-T_{a,i}/T_w}$$

Reference: fully-catalytic wall



$\gamma = 1$: full wall recombination – ablation-free baseline for comparison.

¹ Prata *et al.*, *Air-carbon ablation model for hypersonic flight from molecular-beam data*, AIAA J., 2022.

² Park, AIAA J., 1976; Zhlukov & Abe, J. Thermophys. Heat Transfer, 1999.



Gas–surface interaction: pyrolysis and surface balances

PICA-like ablator: 0-D pyrolysis model

- Steady state: virgin (ρ_v) $\rightarrow$ char (ρ_c) + pyrolysis gas
- Constant density ratio: $\rho_v = 280$, $\rho_c = 220$ kg/m³
- $\dot{m}_c$ from the ACA + sublimation finite-rate fluxes; pyrolysis gas from the steady mass balance:

$$\phi_{ss} = \frac{\rho_v - \rho_c}{\rho_c} = 0.27, \quad \dot{m}_g = \phi_{ss} \dot{m}_c$$

- Gas composition from the virgin/char balance (pure-C char): C 0.69, H 0.26, O 0.05

$$Z_g^{(k)} = \frac{\rho_v Z_v^{(k)} - \rho_c \delta_{kC}}{\rho_v - \rho_c}$$

- Gas in chemical equilibrium at (T_w, p_w): $\dot{m}_g y_i^{eq}$

Surface balances

$$\rho_{i,w} (\mathbf{u}_w - \mathbf{V}_{i,w}) \cdot \mathbf{n} = \dot{\omega}_i^{\text{GSI}}(T_w)$$

$$\rho_w \mathbf{u}_w = (\dot{m}_c + \dot{m}_g) \mathbf{n}$$

$$\dot{q}_{C,w} + \dot{q}_{R,w} - \sum_i \dot{\omega}_i^{\text{GSI}} h_i = \varepsilon \sigma T_w^4$$

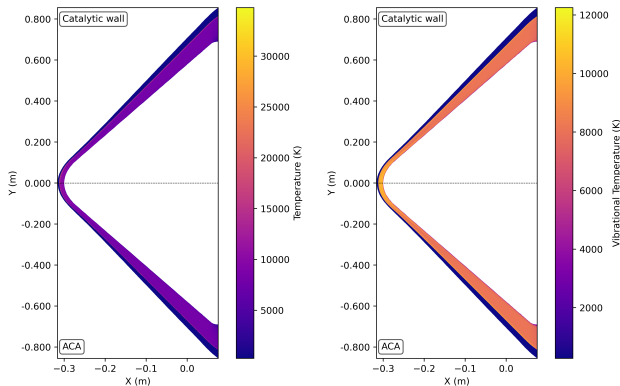
T_w computed iteratively from energy balance with under relaxation



Test case

60° sphere-cone capsule, Earth entry

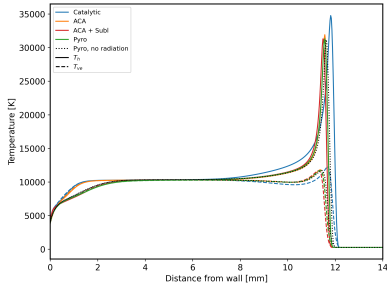
- Nose radius 22 cm
- Freestream: $U_\infty = 10, 15$ km/s, $T_\infty = 270$ K, $p_\infty = 80$ Pa
- Composition: 79% N₂ / 21% O₂
- air11 (10 km/s) and air17 (15 km/s)
- Wall: **radiative equilibrium** ($\varepsilon = 0.9$) at 10 km/s; **isothermal** ($T_w = 3000$ K) at 15 km/s
- Surface chemistry: **fully-catalytic, wACA + sublimation + pyrolysis**
- These are high pressure, high velocities cases to validate the framework at more extreme coupling conditions.



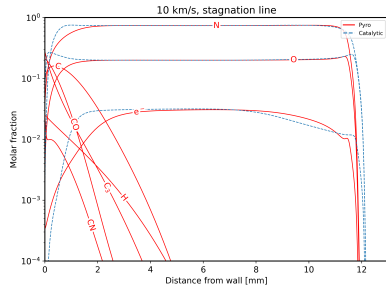
T_h (left), T_{ve} (right); catalytic (top) vs. ACA (bottom), 10 km/s.



10 km/s: Stagnation line

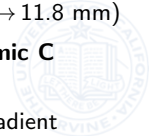


T_h and T_{ve} along the stagnation line.

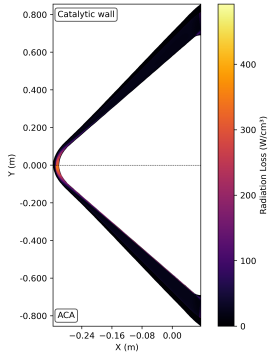


Species molar fractions (log scale).

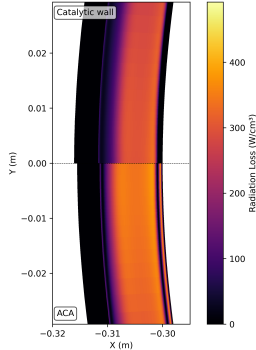
- Ablation **lowers** the nonequilibrium peaks and relaxes faster; stand-off contracts $\sim 2\%$ (12.0 $\rightarrow$ 11.8 mm)
- **CO** and **C₃** dominate at the surface ($X \simeq 0.2$ and 0.3) but dissociate within ~ 1 mm $\Rightarrow$ **atomic C** dominates the boundary layer
- Sublimation blowing **thickens the boundary layer** and reduces the near-wall temperature gradient



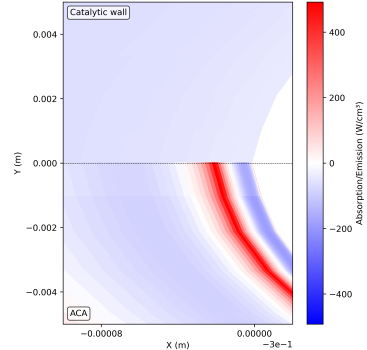
10 km/s: Radiation field



Radiation field



Zoom: stagnation line

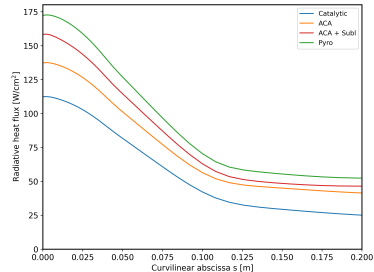
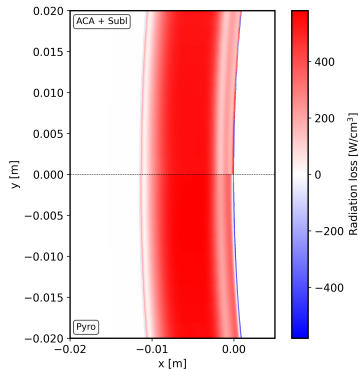
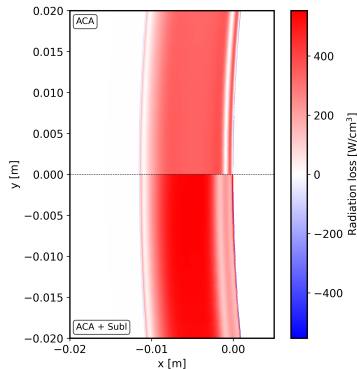


Zoom: boundary layer

Catalytic (top) vs. ACA (bottom): the ACA products add a distinct **atomic-C / CN emission band** in the boundary layer, while the catalytic wall shows only weak absorption.

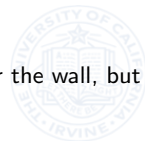


10 km/s: Near-wall radiation with sublimation and pyrolysis

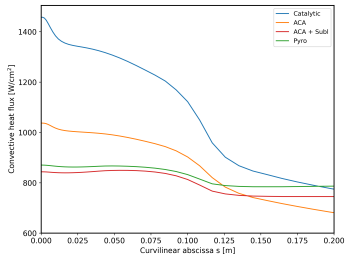


Radiative heat flux to the wall.

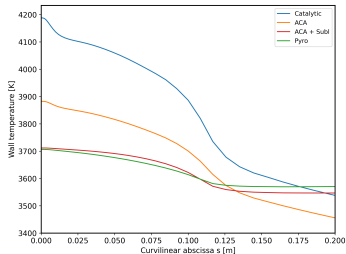
Subl adds additional **C emission** in a larger boundary layer; Pyro adds a thin **absorption film** near the wall, but increases the emission of the rest of the BL.



10 km/s: Heat flux & wall temperature



Convective heat flux

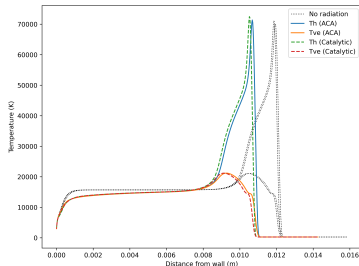


Radiative-equilibrium wall temperature.

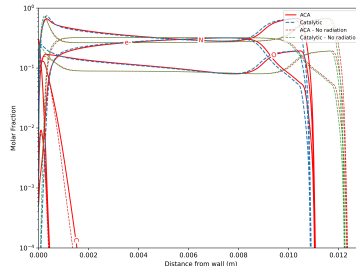
Stagnation point	$\dot{q}_{conv}$ [W/cm ²]	$\dot{q}_{rad,w}$ [W/cm ²]	T_w [K]	$\dot{m}$ [kg/m ² /s]
Catalytic	1458	112	4190	—
ACA	1037	137	3880	0.06
ACA + Subl	844	158	3710	0.23
Pyro	870	172	3710	0.18



15 km/s: Stagnation line

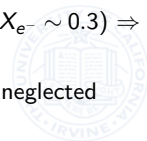


T_h , T_{ve} along the stagnation line; with vs. without radiation.

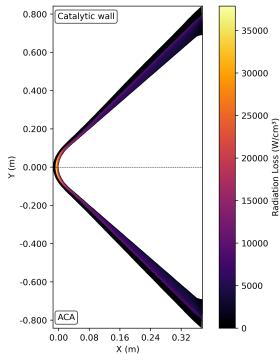


Species molar fractions (log scale).

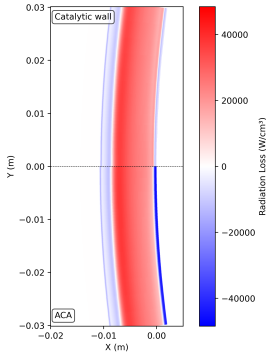
- Isothermal wall ($T_w = 3000$ K), catalytic vs. ACA. Peak $T_h \sim 71,000$ K, **strong ionization** ($X_{e^-} \sim 0.3$) $\Rightarrow$ atomic-line and continuum radiation dominate
- **Radiative cooling** now visibly contracts the shock layer: two-way coupling can no longer be neglected



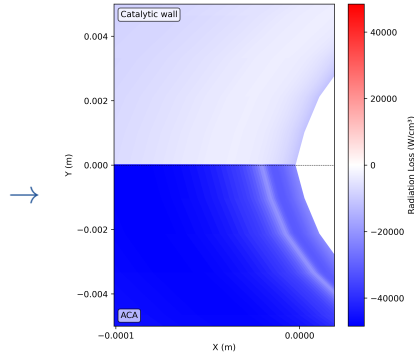
15 km/s: Radiation field



Radiation field

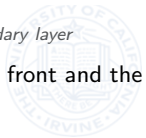


Zoom: stagnation line

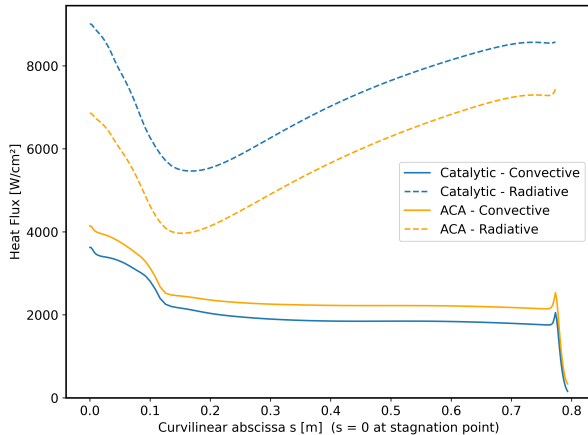


Zoom: boundary layer

- Peak **emission** (red) now sits in the **equilibrium core** behind the shock, while **both** the shock front and the boundary layer **absorb** energy (blue).



15 km/s: Heat flux



Convective (solid) & radiative (dashed) flux; isothermal $T_w = 3000$ K.

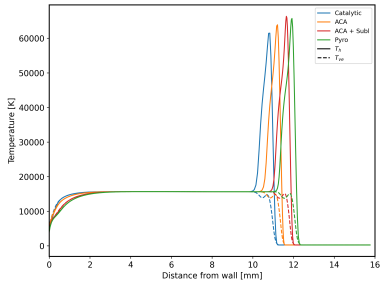
The trend reverses

At 10 km/s the carbon products **raise** the radiative flux (+27% ACA, +54% full PICA model); at 15 km/s ACA **lowers** it (−24%).

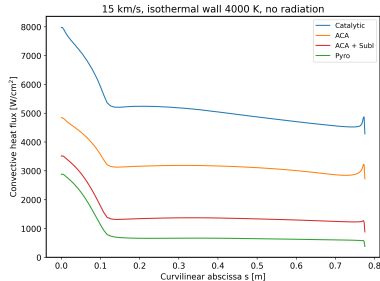
- **Radiation dominates:** $\sim 50\times$ the 10 km/s radiative flux
- BL absorption by carbon species reduces the radiative flux at the wall, but slightly increases the convective flux



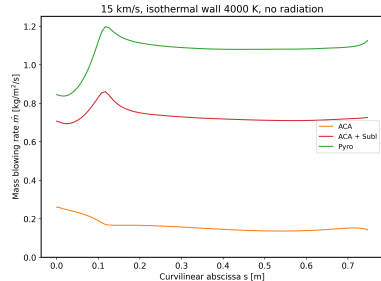
15 km/s: Surface models at $T_w = 4000$ K (uncoupled)



Convective heat flux.



Stagnation-line temperatures.



Mass blowing rate.

Higher blowing $\Rightarrow$ lower convective heating: $\dot{q}_{conv}$ $8.0 \rightarrow 4.8 \rightarrow 3.5 \rightarrow 2.9$ kW/cm² as $\dot{m}$ grows to 0.85 kg/m²/s.



Conclusions & future work

Conclusions

- **RUSSELL**: MURP spectral library + ROM grouping, **conservative DG sweep**, one source for CPU and GPU
- Verified vs. MURP in 1D, 2D-axi, 3D; **1–2 orders of magnitude** faster on one GPU
- **GSI models reshape the wall state**: lower T_w and $\dot{q}_{conv}$, higher recession and radiative flux; sublimation drives the blowing
- **Ablation products** have a **non-monotonic** effect: emission at 10 km/s (+54% $\dot{q}_{rad}$), absorption at 15 km/s (–24% $\dot{q}_{rad}$, higher $\dot{q}_{conv}$)
- All converged cases **re-solved with RUSSELL**

Future work

- **Coupled high-speed campaign**: 15 km/s, sublimation + pyrolysis, radiative-equilibrium wall
- **Higher velocities**: 20, 30, 50 km/s (meteor entry)
- **Material response**: HUME (conduction, transient pyrolysis, recession)
- **3D coupled flow–radiation with RUSSELL**

Thank You

Questions?

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Backup – Spectral model: QSS and line-by-line coefficients

Line by line

- Atoms N, O, C, H; diatomics N_2 , N_2^+ , O_2 , NO, CN, CO, C_2
- Voigt profiles: Doppler, natural, Stark, van der Waals, resonance
- Air ≈ 3 M lines, air + carbon ≈ 6 M; grids up to 10^6 points
- Bound-free and free-free continua

Non-Boltzmann populations

- Atomic electronic QSS: PLATO kinetics, escape factors, dense LU per cell
- Diatomic QSS master equation, 3-T rovibronic populations
- Batched across cells on the GPU



Backup – Angular discretization: control-angle finite volume

$M = n_\theta \times n_\varphi$ solid-angle bins (default 8×16), I piecewise constant in angle; the exact face integral collapses to one vector per bin:

$$d_{f,m} = \int_{\Delta\Omega_m} (\mathbf{s} \cdot \mathbf{n}_f) d\Omega = \left(\int_{\Delta\Omega_m} \mathbf{s} d\Omega \right) \cdot \mathbf{n}_f \equiv \boxed{\boldsymbol{\Omega}_m \cdot \mathbf{n}_f}$$

$$\begin{aligned} \Omega_m^x &= \left[\frac{\theta_2 - \theta_1}{2} - \frac{\sin 2\theta_2 - \sin 2\theta_1}{4} \right] (\sin \varphi_2 - \sin \varphi_1), & w_m &= (\varphi_2 - \varphi_1)(\cos \theta_1 - \cos \theta_2) \\ \Omega_m^y &= \left[\frac{\theta_2 - \theta_1}{2} - \frac{\sin 2\theta_2 - \sin 2\theta_1}{4} \right] (\cos \varphi_1 - \cos \varphi_2), & \Omega_m^z &= \frac{1}{2} (\sin^2 \theta_2 - \sin^2 \theta_1) (\varphi_2 - \varphi_1) \end{aligned}$$

$$a_{f,m} = (\boldsymbol{\Omega}_m \cdot \mathbf{n}_f) A_f, \quad a_{f,m}^+ = \max(a_{f,m}, 0), \quad a_{f,m}^- = \max(-a_{f,m}, 0)$$



Backup – The cell-local system; $p = 0$ is the finite-volume update

$$[S_m]_{\alpha\beta} = - \int_K b_\beta (\mathbf{s}_m \cdot \nabla b_\alpha) dV$$

$$[M]_{\alpha\beta} = \int_K b_\beta b_\alpha dV$$

$$[F_m^+]_{\alpha\beta} = \sum_{f: a_{f,m} > 0} \int_f (\mathbf{s}_m \cdot \mathbf{n}_f) b_\beta b_\alpha dS$$

$$[\mathbf{g}_m^-]_\alpha = \sum_{f: a_{f,m} < 0} \int_f |\mathbf{s}_m \cdot \mathbf{n}_f| I_m^{\text{up}} b_\alpha dS$$

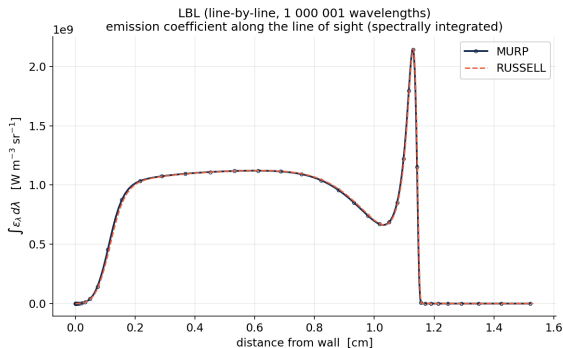
Direction enters linearly: $S_m = \sum_{c=1}^d \Omega_m^c S^{(c)}$.

$p = 0$: the DG system collapses to the donor-cell FV update of MURP

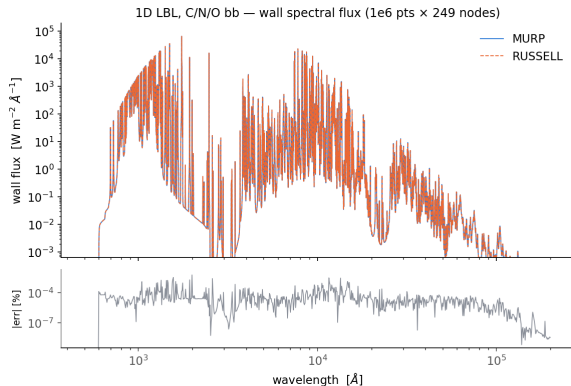
$$b \equiv 1 \Rightarrow S_m \equiv 0 \Rightarrow \bar{I}_{m,K} = \frac{j_K V_K w_m + \sum_f a_{f,m}^- \bar{I}_{m,K'(f)}}{\sum_f a_{f,m}^+ + \kappa_K V_K w_m}$$



Backup – 1D line by line: coefficient and wall-spectrum matching

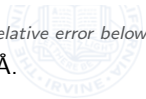


Spectrally integrated emission coefficient along the line.

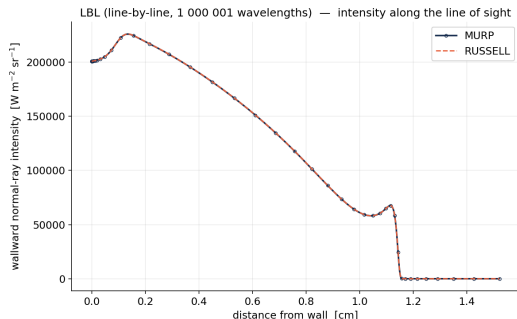


Wall spectral flux, 10^6 wavelengths $\times$ 249 nodes; relative error below.

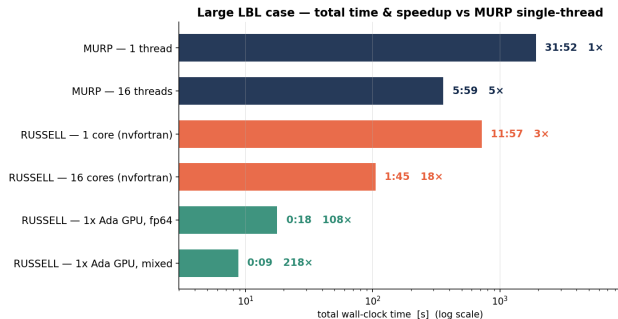
10 km/s stagnation line with ablation products (C, N, O bound-bound), 3333 lines, 500–200 000 $\text{\AA}$.



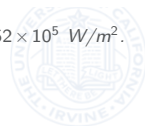
Backup – 1D line by line: intensity and speed-up



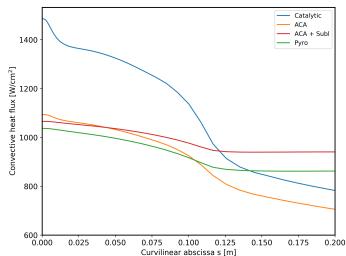
Intensity along the line.



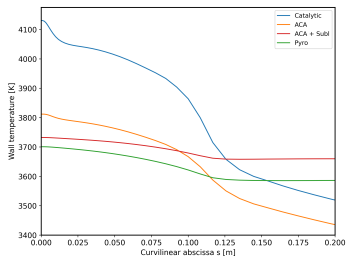
Total wall time, same case; all legs give $q_{\text{wall}} = 9.1552 \times 10^5 \text{ W/m}^2$.



Backup – 10 km/s: Heat flux & wall temperature, no radiation



Convective heat flux, no radiation.

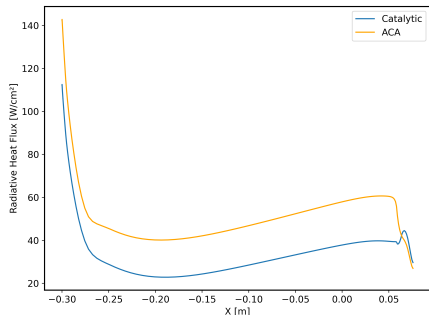


Radiative-equilibrium wall temperature, no radiation.

Stagnation point	$\dot{q}_{conv}$ [W/cm ²]	T_w [K]	$\dot{m}$ [kg/m ² /s]
Catalytic	1486	4130	—
ACA	1094	3810	0.07
ACA + Subl	1066	3730	0.13
Pyro	1037	3700	0.17

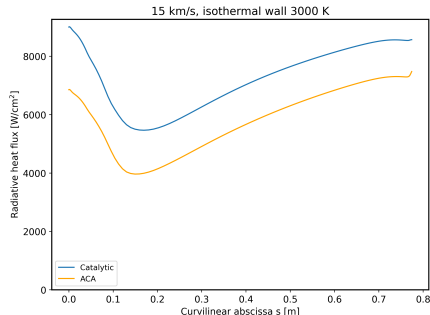


Backup – Radiative heat flux: 10 vs. 15 km/s (isothermal wall)

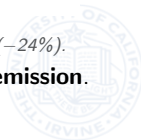


10 km/s: ACA raises the radiative flux (+27%).

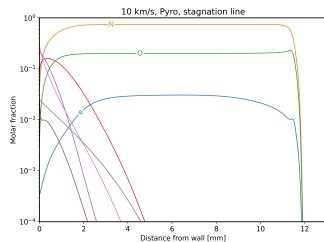
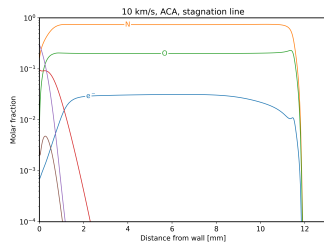
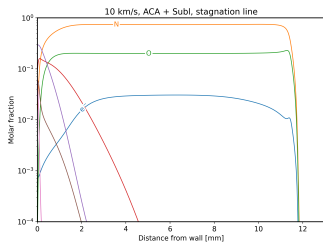
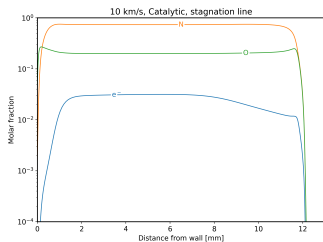
The ACA effect **reverses** with speed: at 15 km/s boundary-layer **absorption** outweighs atomic-C **emission**.



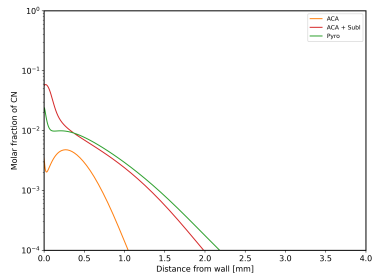
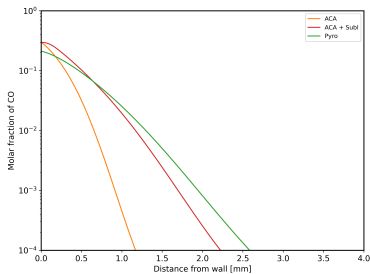
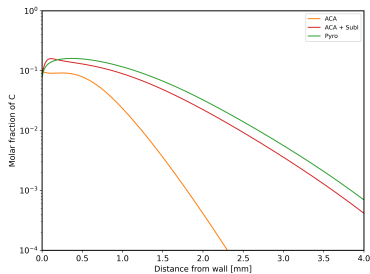
15 km/s: ACA lowers the radiative flux (−24%).



Backup – 10 km/s stagnation line, species per surface model



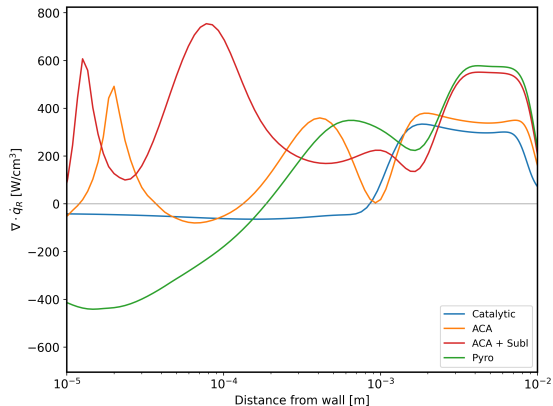
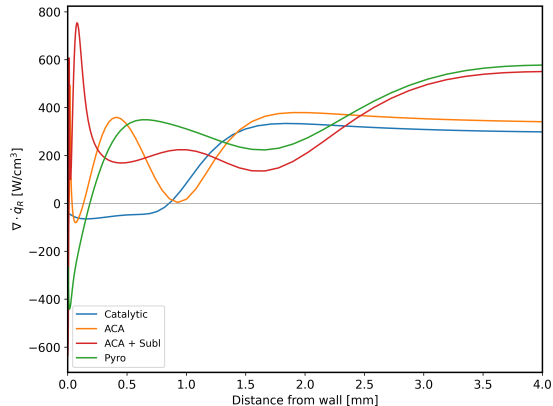
Backup – 10 km/s: C, CO and CN across the surface models



Molar fractions along the stagnation line, first 4 mm from the wall.



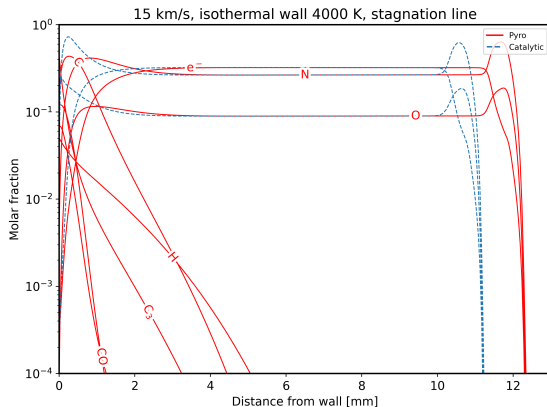
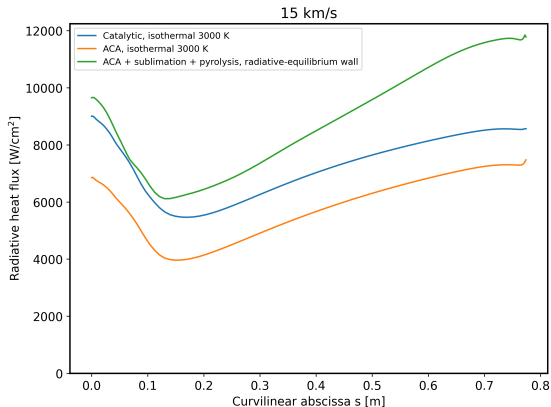
Backup – 10 km/s: radiative source along the stagnation line



$\nabla \cdot \dot{q}_R$, linear (left) and logarithmic (right) distance from the wall.



Backup – 15 km/s: radiative wall flux with the full PICA model

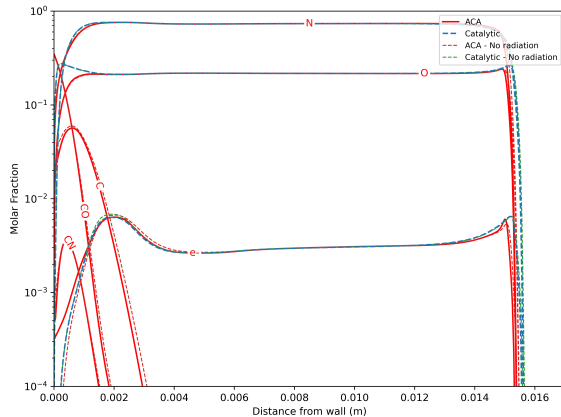
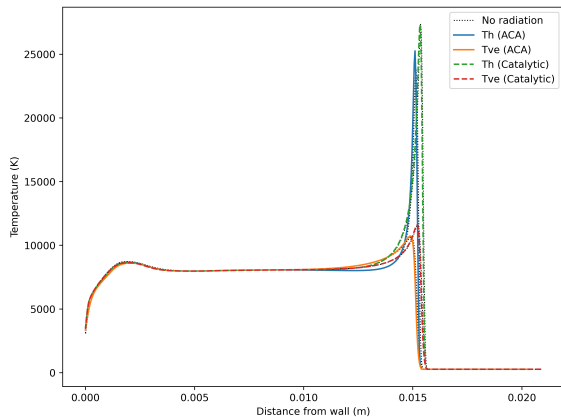


Left: MURP wall flux, catalytic and ACA (isothermal, coupled) vs. full PICA model (radiative-equilibrium wall, one-way radiation solve).

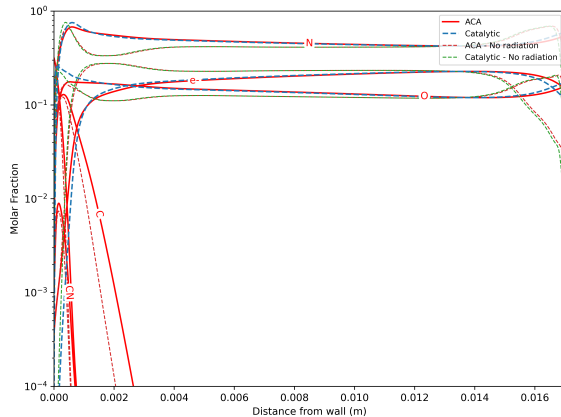
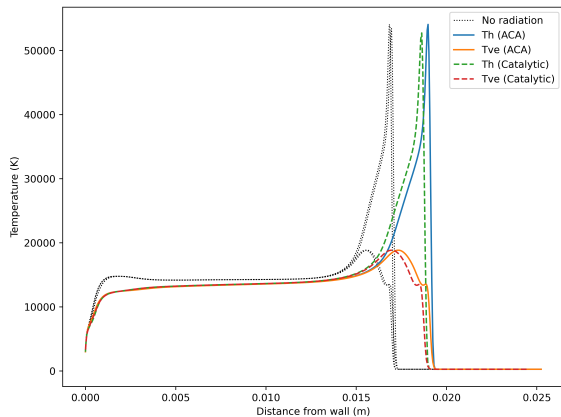
Right: stagnation-line species at $T_w = 4000$ K.



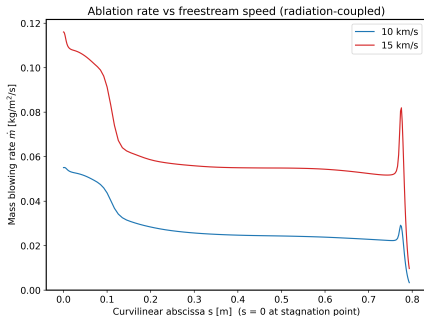
Backup – 60° line of sight, 10 km/s



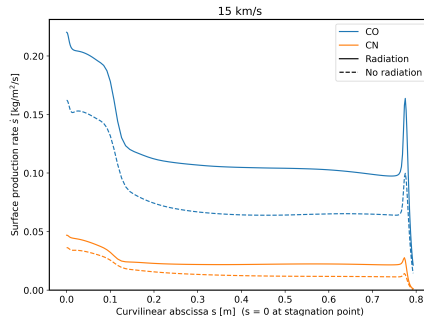
Backup – 60° line of sight, 15 km/s



Backup: ACA response scales with speed (isothermal wall)

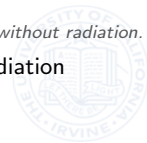


Mass blowing rate along the wall, 10 vs. 15 km/s.

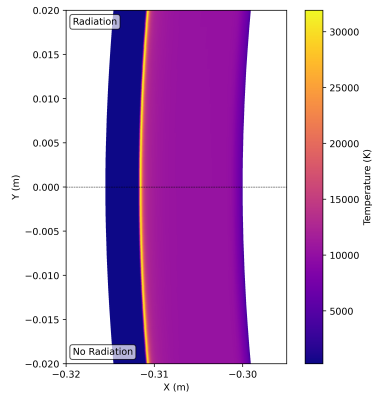
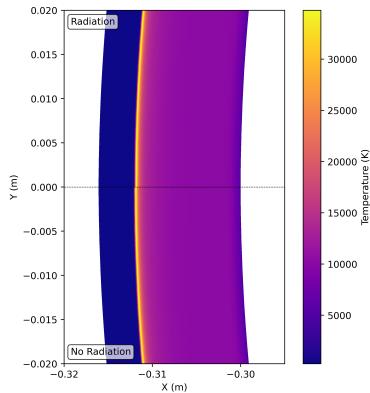


CO / CN surface production, 15 km/s; with vs. without radiation.

The ACA recession roughly **doubles** ($\sim 0.055 \rightarrow \sim 0.116 \text{ kg/m}^2/\text{s}$ at the stagnation point), and radiation coupling **increases** surface CO/CN production – the two-way coupling intensifies with speed.



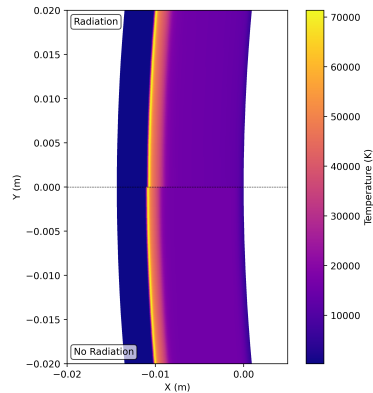
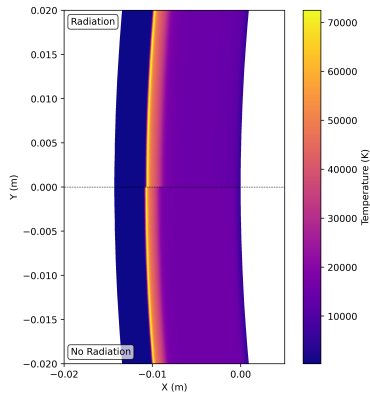
Backup – Radiation displaces the shock, 10 km/s



Catalytic (left), ACA (right).



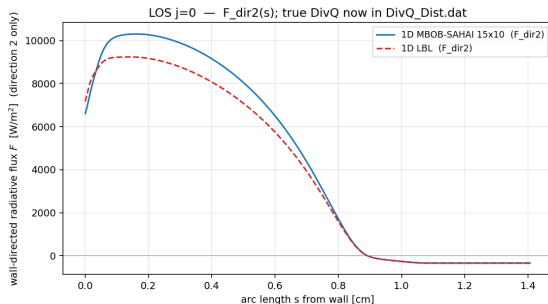
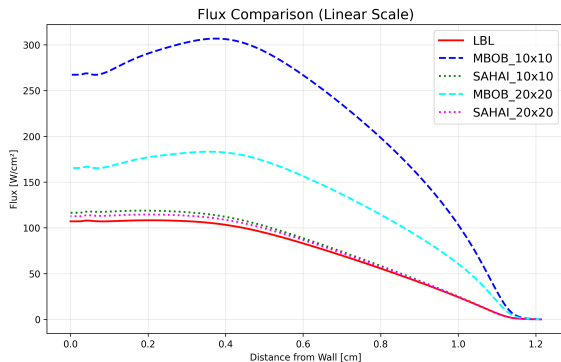
Backup – Radiation displaces the shock, 15 km/s



Catalytic (left), ACA (right).



Backup – 1D radiative flux: ROM grouping vs. LBL



Backup – 1D radiative source $\nabla \cdot \mathbf{q}_{\text{rad}}$ along the LOS

