Simulations of Electron Transpiration Cooling with Eilmer4

Nick N. Gibbons,
The University of Queensland, Brisbane, Queensland 4072, Australia

May 13, 2021

Space News: Perseverence Rover

- Sister rover to Curiosity with new and improved components
- Landed in Jezero crater on Mars, 18th February 2020

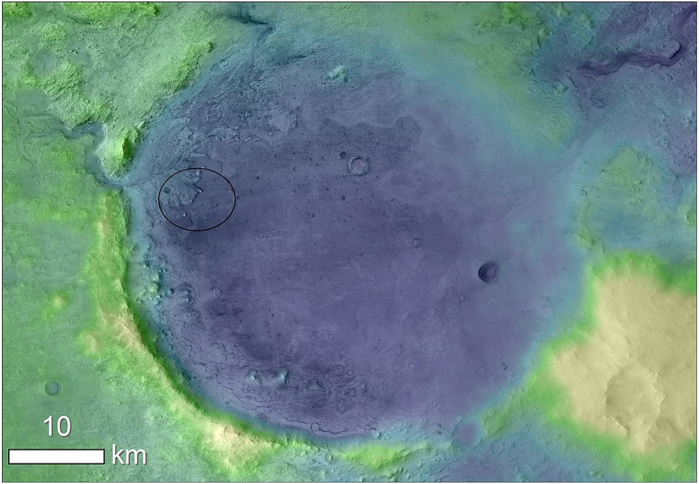

Figure 1: False colour altimeter image of Jezero Crater, Mars.[1]

[1] photojournal.jpl.nasa.gov/jpeg/PIA23511.jpg

Space News: Perseverence

- Autonomous landing using Terrain Relative Navigation (TRN)

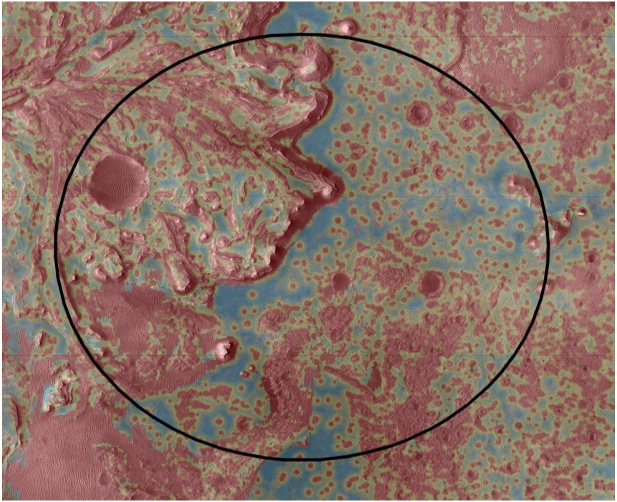

Figure 2: False colour hazard map of Jezero Crater, Mars. [2]

[2] www.jpl.nasa.gov/images/jezeros-hazard-map

Space News: Perseverence

- Autonomous landing using Terrain Relative Navigation (TRN)

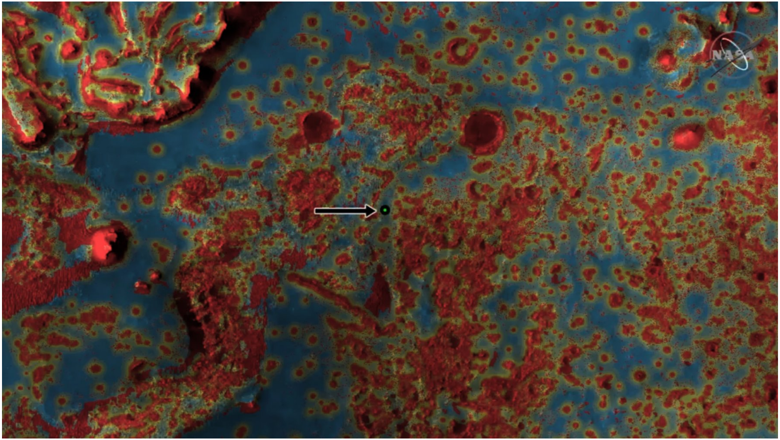

Figure 3: Perseverence rover landing site. [3]

[3] @ThePlanetaryGuy

Space News: Chang'e 5

- China's Chang'e 5 rover returns 2kg of moon rocks from Oceanus Procellarum
- Rocks are 1.2 billion years old (much younger than the Apollo or Luna missions)
- Launch date 24th November 2020, Lander returned 16th December

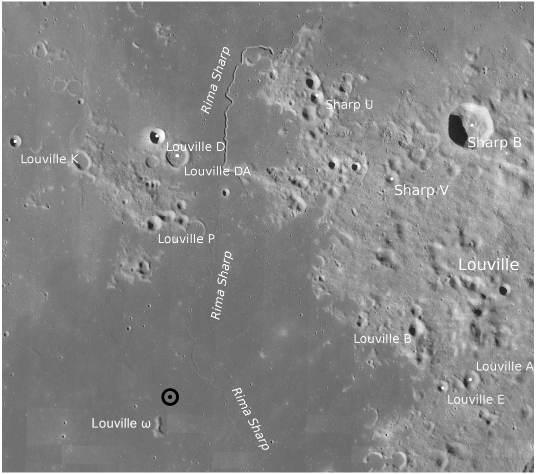

Figure 4: Chang'e 5 landing site. [4]

[4] en.wikipedia.org/wiki/Chang%27e_5#/media/File:Landepunkt_Chang%E2%80%99e_5.jpg

Space News: Hayabusa 2

- Ion-engine powered sample return mission to 162173 Ryugu
- "Rubble Pile", Type Cb asteroid, relatively young, formed from asteroid collisions
- Two samples taken and returned to Woomera Test Range on 5th of December

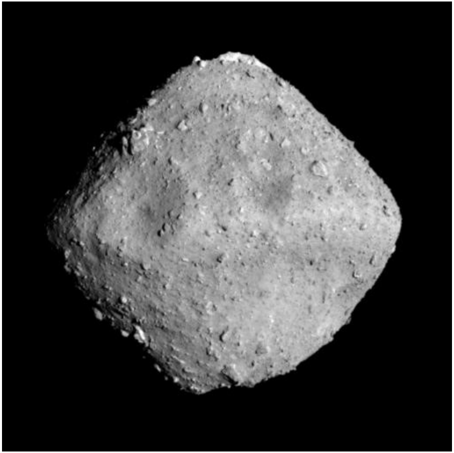

Figure 5: Asteroid 162173 Ryugu [5]

[5] global.jaxa.jp/press/2018/06/images/20180627_hayabusa2_01.jpg

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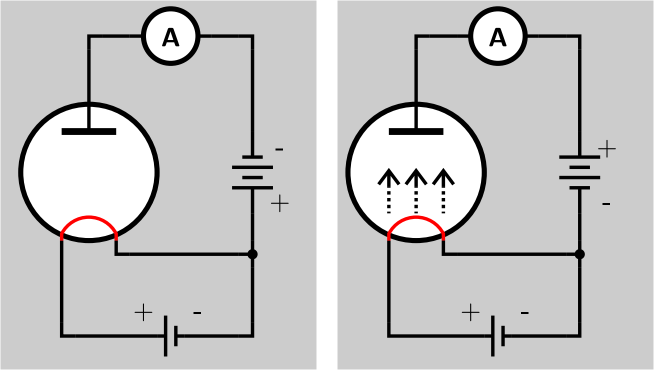
Background: Electron Transpiration Cooling

- Thermionic emission discovered by many physicists in the 1800's
- Electrons not even known about until 1897
- First proper treatment by Owen Richardson in 1900s, (1928 Nobel Prize)



No current **Electron flow**

Figure 6: The "Edison Effect": en.wikipedia.org/wiki/File:EdisonEffect.svg

Background: Electron Transpiration Cooling

- Interest in thermionic emission for hypersonics in 1960's Touryan, 1965
- No mention of cooling, mostly concerned with power generation (?)
- Plasma wind-tunnel experiments at Mach 2.5, enthalpy of 32 MJ/kg

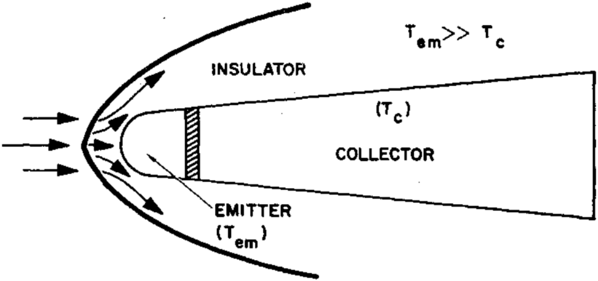
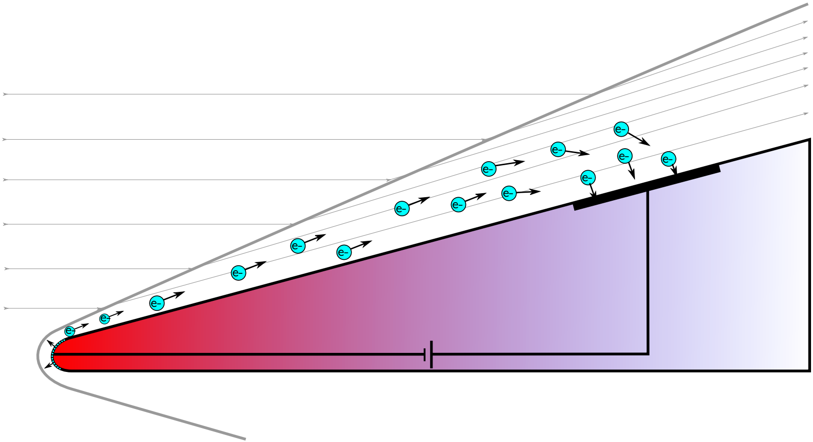


Figure 7: Plasma generator schematic from Touryan, 1965, figure 2

Background: Electron Transpiration Cooling

- Electrons take energy away from the surface and cool the emission point
- Surfaces can be sharp, compared to internal active cooling
- Need temperature/oxidation resistant material with low work function Φ



Background: Electron Transpiration Cooling

- Sharp leading edges are hot because of $1/\sqrt{R}$, but good for lower drag
- Low drag valuable to lifting hypersonic vehicles Lewis, 1999
- Sharp really means "sharp" $R \approx 1cm$

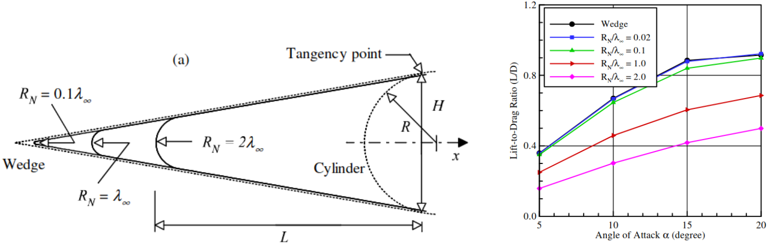


Figure 8: Figures 1 (left) and 13 (right) from Santos, 2007

Current Work: ETC Linkage Project

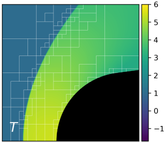
- Lockheed Martin's research division producing new electride materials
- Linkage Project with UQ started in 2020 to explore uses in hypersonics
- Brad Wheatley is our liason with Lockheed Martin Australia

Experiments in X2:

- Oliver Paxton
- Hadas Porat (DST)
- Ingo Jahn
- Richard Morgan

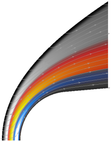
Two Fluid Plasma Modelling:

- Shazeb Imran
- Daryl Bond
- Vince Wheatley



CFD Modelling in Eilmer:

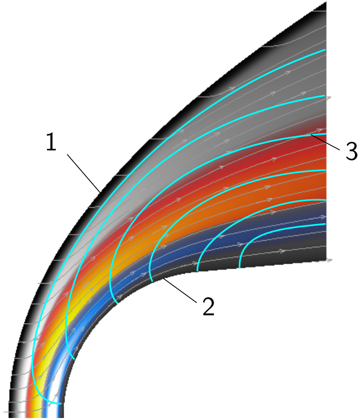
- Kyle Damm
- Rowan Gollan
- Peter Jacobs
- Myself



Current Work: ETC Modelling in Eilmer

Electron Transpiration Cooling in CFD:

1. High-temperature compressible flow simulation code
2. Thermionic/Radiative equilibrium wall boundary condition
3. Electric field solver and fluid coupling



Current Work: 1. High-temperature flow simulation

As of July 2020, major improvements to Eilmer4 to handle:

1. A: Multicomponent species diffusion including ionised species
1. B: Vibrational/electronic energy exchange source terms
1. C: Catalytic wall boundary conditions

1. A: Multicomponent Species Diffusion

$$\frac{\partial \rho_s}{\partial t} + \frac{\partial}{\partial x_j}(\rho_s u_j) + \frac{\partial}{\partial x_j} D_s \frac{\partial Y_s}{\partial x_j} = \dot{\omega}_s \quad (1)$$

- Diffusion coefficients calculated using collision integrals from Gupta et al., 1990
- Charged particle D_s are modified to enforce ambipolar diffusion:

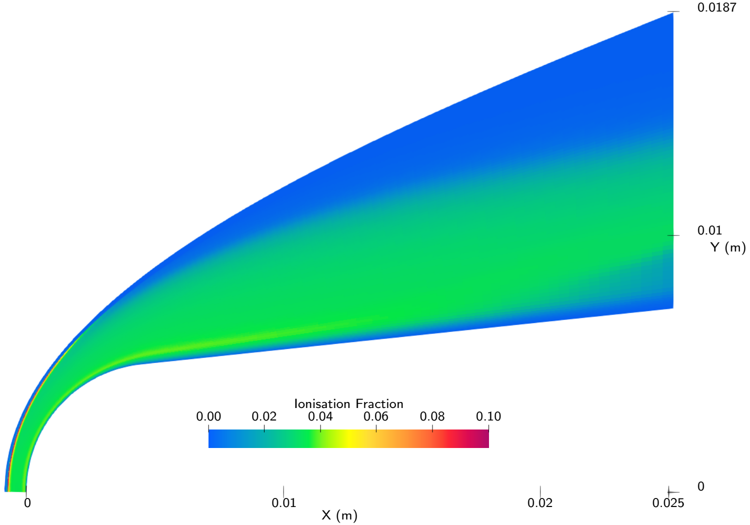
$$D_a = \frac{\sum_i^{ions} D_i Z_i \left(1 + \frac{T_e}{T}\right)}{\sum_i^{ions} \frac{D_i Z_i}{D_e} \frac{T_e}{T} + 1} \quad (2)$$

- Enabled with:

```
config.mass_diffusion_model = "ficks_first_law"
config.diffusion_coefficient_type = "binary_diffusion"
```

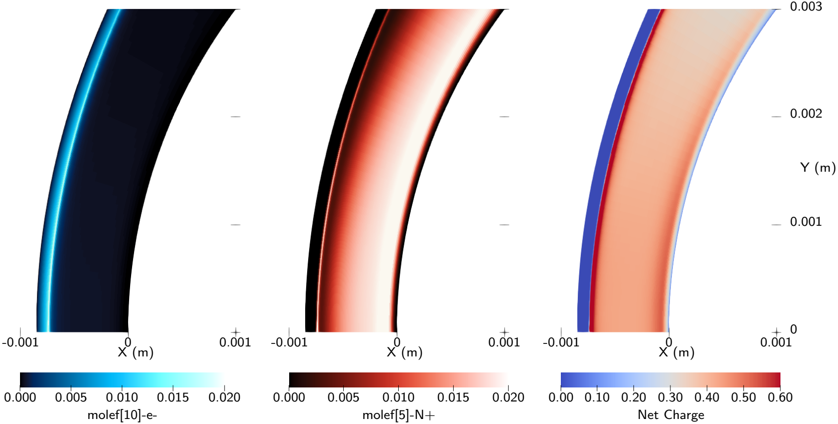
1. A: Multicomponent Species Diffusion

- Two-temperature simulations of Oliver Paxton's proposed experiments:



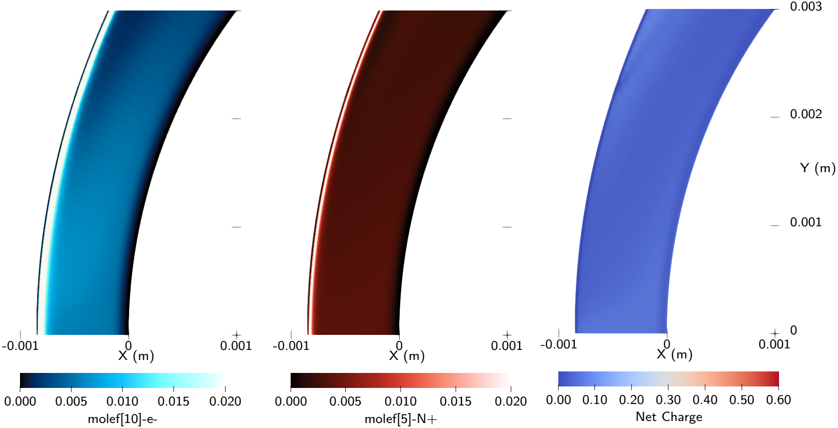
1. A: Multicomponent Species Diffusion

- Without ambipolar diffusion



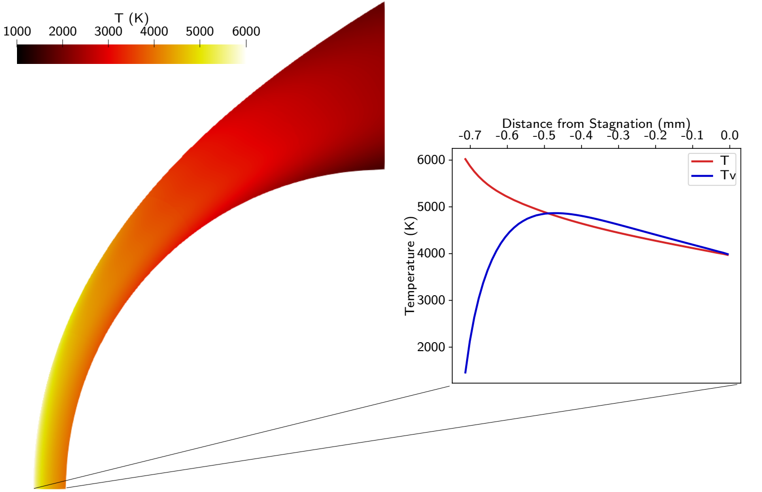
1. A: Multicomponent Species Diffusion

- With ambipolar diffusion:



1. B: Vibrational/Electronic Energy Exchange

- In the two-temperature model, the temperatures relax via molecular collisions:



1. B: Vibrational/Electronic Energy Exchange

- The relaxation time τ_{ms} depends on the molecular m and collider s
- Electron energy exchange requires collision cross section data σ_{es}

$$\frac{\partial \rho e_v}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_j e_v) = \rho \sum_{m}^{mol} \sum_{s} X_s \frac{e_{vm}(T) - e_{vm}(T_v)}{\tau_{ms}} + \sum_{s} \bar{v} n_e n_s \sigma_{es} k_b (T - T_v) \tag{3}$$

1. B: Vibrational/Electronic Energy Exchange

```
model = "TwoTemperatureAir"
```

- Single hardcoded model implementing Gupta et al., 1990 and Gnoffo, Gupta, and Shinn, 1989
- Includes relaxation rates and chemical rate equations

```
model = "TwoTemperatureGas"
```

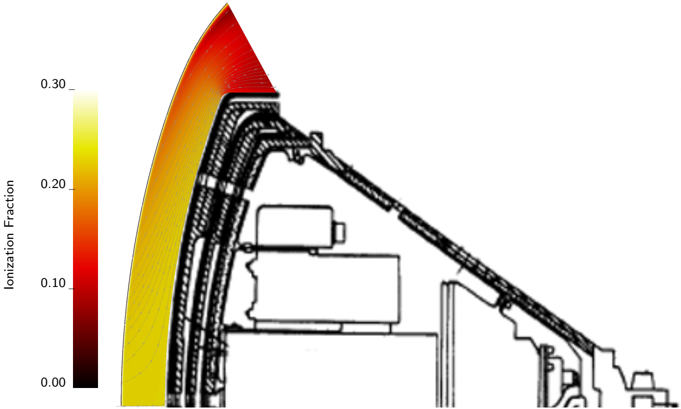
- Composite gas model with interchangeable components

```
$ cat air-11sp-energy-exchange.inp

Mechanism{
   "(*molcs) ~~ (*heavy)",
   type = "V-T",
   rate = "Landau-Teller",
   relaxation_time = {"ParkHTC", submodel={"Millikan-White"}}
}
```

1. B: Vibrational/Electronic Energy Exchange

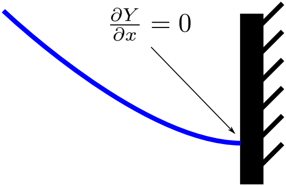
- Simulations of the Project FIRE flight tests (Lewis and Scallion, 1966)
- Multiple different relaxation schemes in `examples/eilmer/2D/fireII`:
  - A copy of the legacy model (Gnoffo/Gupta Nasa TRs, 1989)
  - The classic Park model (Chul Park, JHTH, 1993)
  - Brand new model based on QCC calculations (Kim and Jo, IJHMT, 2021)



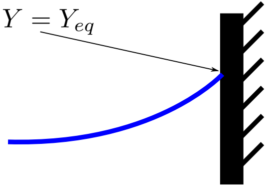
1. C: Catalytic Wall Boundary Conditions

- Real walls can cause accelerated chemistry and significant flow changes:

Non-catalytic:

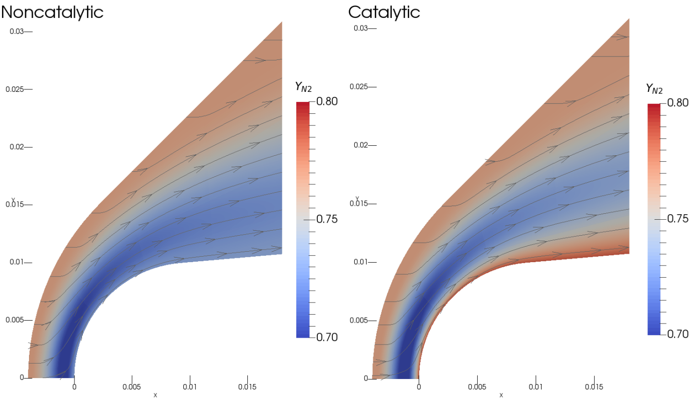


Fully catalytic:



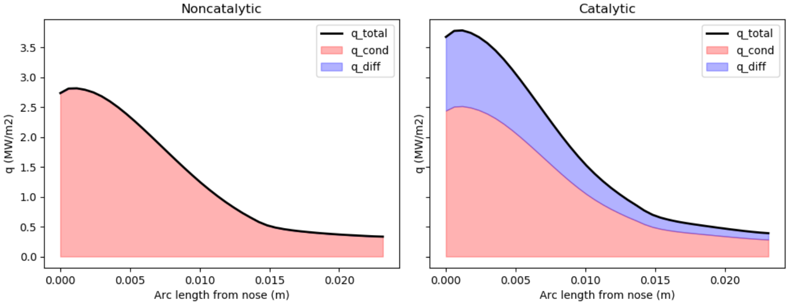
1. C: Catalytic Wall Boundary Conditions

- Extra options for `WallBC_NoSlip_FixedT`:
  - `catalytic_type="equilibrium"`
  - `catalytic_type="fixed_composition"`
- See example in `examples/eilmer/2d/wall-catalysis`:



1. C: Catalytic Wall Boundary Conditions

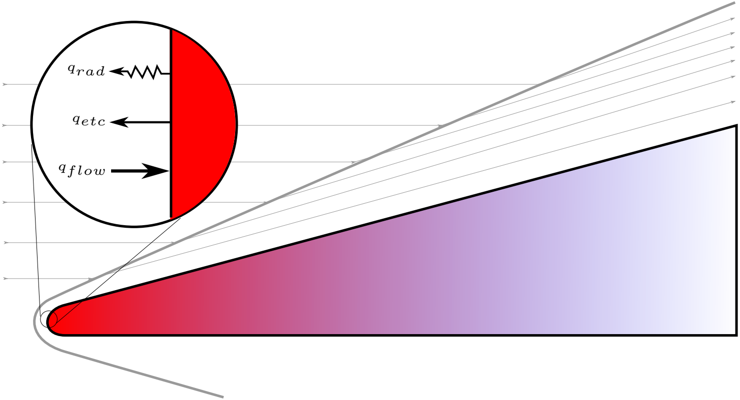
- Chemistry at the wall can significantly increase heat transfer:



2. Thermionic/Radiative Equilibrium Boundary Condition

- Energy from the flow q_{flow} heats the edges of a hypersonic vehicle
- Meanwhile, the surface is cooled by radiation q_{rad} and possibly ETC q_{etc}
- Final temperature can be estimated with a steady state energy balance:

$$0 = q_{flow} - q_{rad} - q_{etc} \tag{4}$$



2. Thermionic/Radiative Equilibrium Boundary Condition

- Eilmer BC `WallBC_ThermionicEmission` solves these equations for T
- This gives a varying steady-state wall temperature along the boundary

$$0 = q_{flow} - q_{rad} - q_{etc} \tag{5}$$

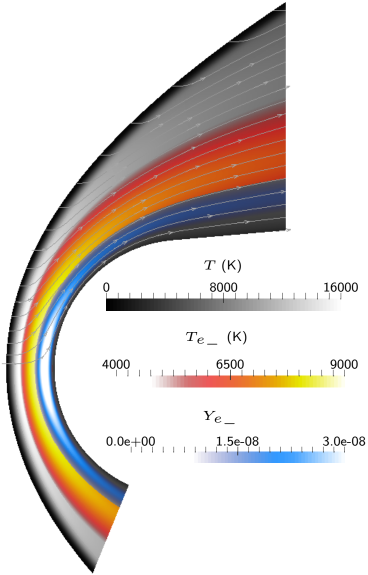
$$q_{flow} = \kappa \frac{\partial T}{\partial x} - \sum_s h_s D_s \frac{\partial Y_s}{\partial x} \tag{6}$$

$$q_{rad} = \epsilon \sigma_{SB} T^4 \tag{7}$$

$$q_{etc} = \frac{A_r T^2 exp\left(\frac{-\Phi}{k_B T}\right)}{Q_e} (\Phi + 2k_B T) \tag{8}$$

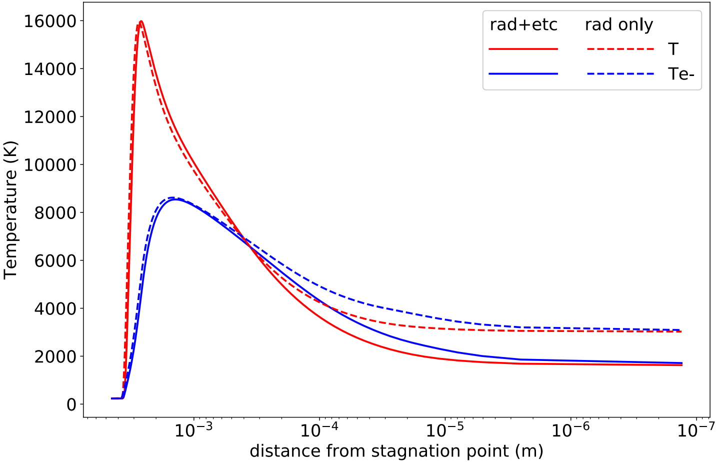
Application: Blunt Wedge from (Alkandry, 2014)

- "Conceptual Analysis of Electron Transpiration Cooling for the Leading Edges of Hypersonic Vehicles", AIAA 2014-2674
- $v = 6km/s$, $\rho = 2.3 \times 10^{-4}$, $T = 238K$ flow
- 11 species, two temperature air model with ionisation
- Electron emission according to Richardson's law



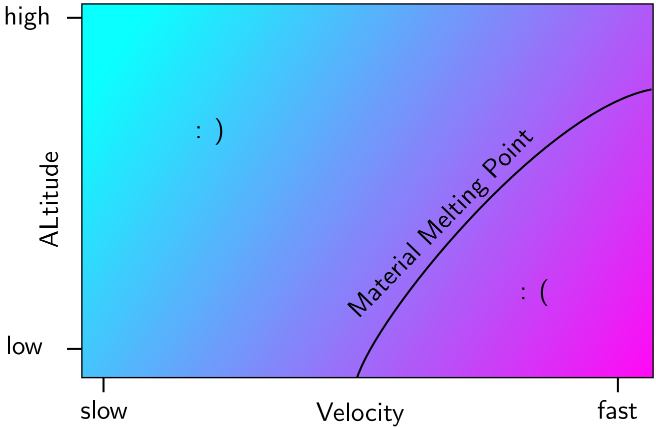
Application: Blunt Wedge from Alkandry, 2014

- Stagnation line temperature data
- ETC+Radiation vs. Radiation only



Application: What does it mean?

- Why does this ETC stuff matter anyway?
- CFD model gives $T_{wall} = f(v, \rho, R)$
- Doing a sweep of altitude/velocity tells us where we can fly



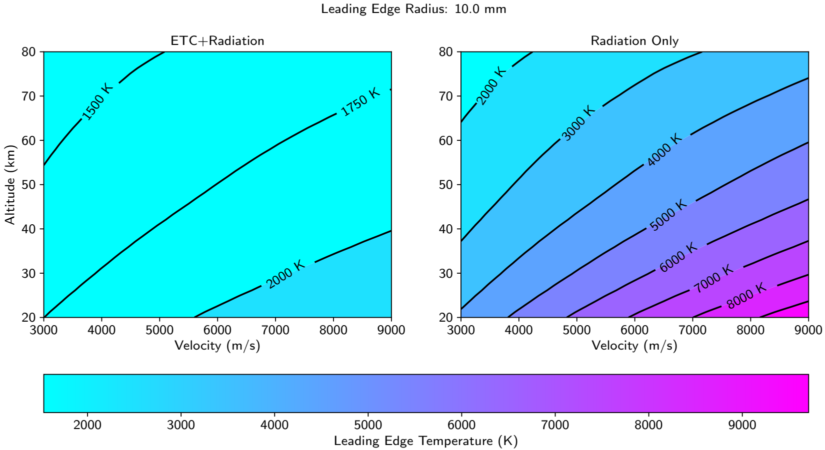
Application: What does it mean?

- I've submitted an abstract to 2021 Spaceplanes conference to try this
- 200 (?) simulations, need steady-state solver
- In the meantime let's try a simple model for q_{flow}:

$$q_{flow} = 7.455 \times 10^{-5} \; \frac{\rho^{0.4705} \; v^{3.089}}{R^{0.52}} \tag{9}$$

- Correlation for convective heating from Brandis and Johnston, 2014
- Computed from a large number of LAURA simulations Gnoffo, 1990

Application: What does it mean?



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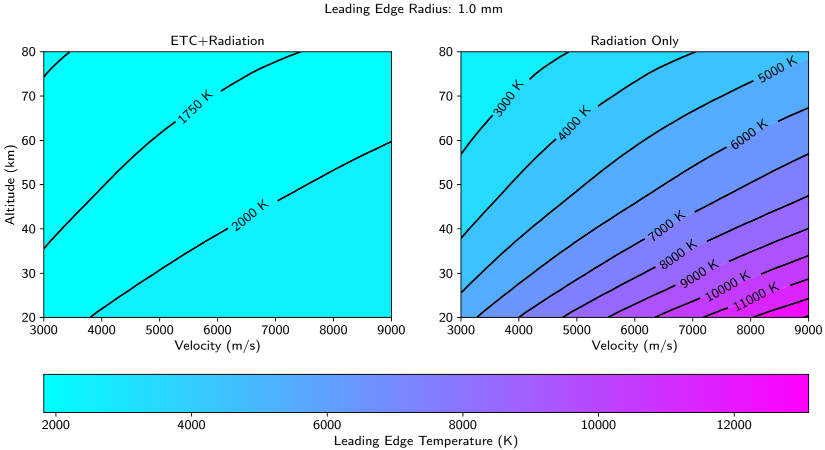
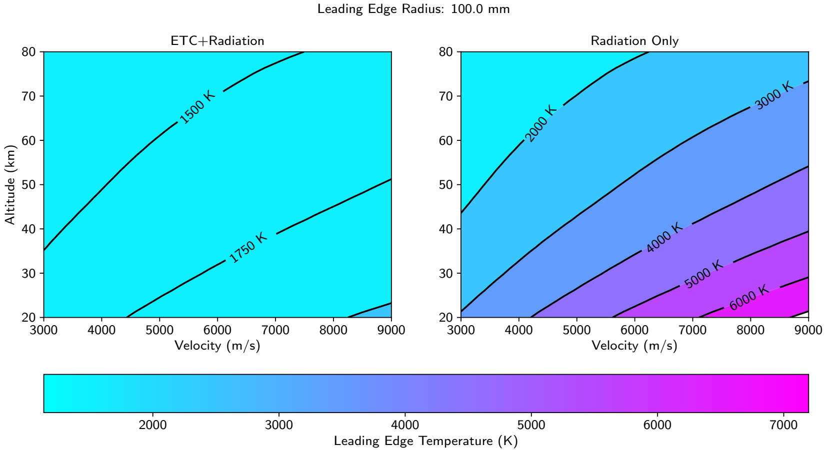


Application: What does it mean?



Conclusion: The Future of Eilmer4

- Official Eilmer4 paper in the works
- Version 4.0 Release
- Updated Website Coming Soon

WE NEED YOU!

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