CFD ANALYSIS OF THE CORK-PHENOLIC HEAT SHIELD OF A REENTRY CUBESAT IN ARC-JET CONDITIONS INCLUDING ABLATION AND PYROLYSIS

15th International Planetary Probe Workshop

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Outline

- Introduction
  - QARMAN
  - Cork-phenolic TPS
    - Pyrolysis
    - Shape Change
  - SCIROCCO Case Definition
  - CFD Solver Capabilities
- Results
  - Effect of Pyrolysis
  - Effect of Recession
- Conclusions

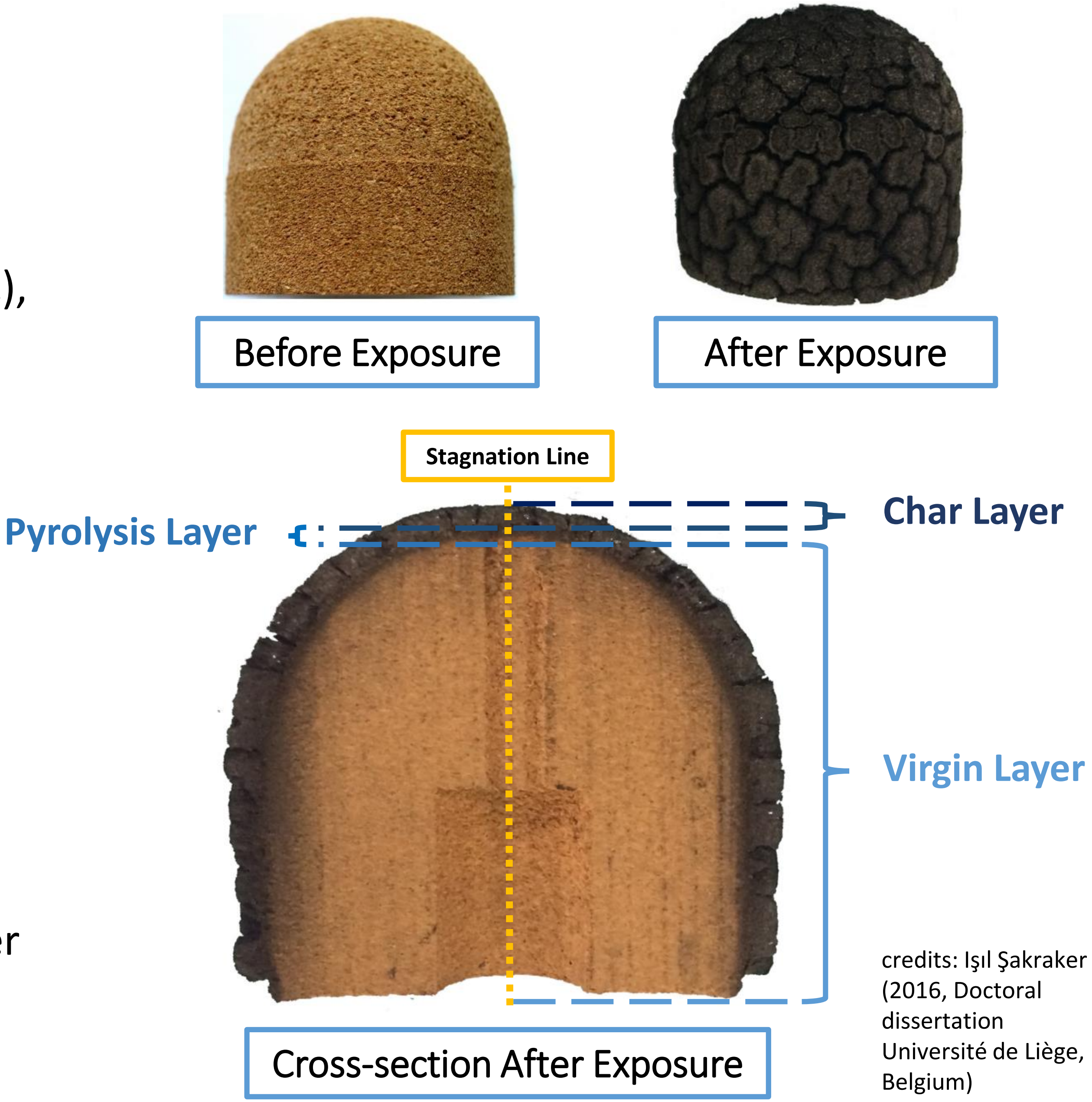
QARMAN is the "QubeSat for Aerothermodynamic Research and Measurements on AblatioN"

- Main objective is to demonstrate the viability of a CubeSat as a re-entry platform
- One of the main challenges is the thermal protection of its components
- **Thermal Protection Systems**
  - Nose: **cork-phenolic** (Amorim P50)
  - Side walls: coated titanium panels
- **Plasma Wind Tunnel testing**
  - **VKI Plasmatron** to study aerothermochemistry of cork ablation
  - **CIRA Scirocco** for a full-scale model


credits: VKI

Pyrolysis gas elemental composition
is found from experimental results

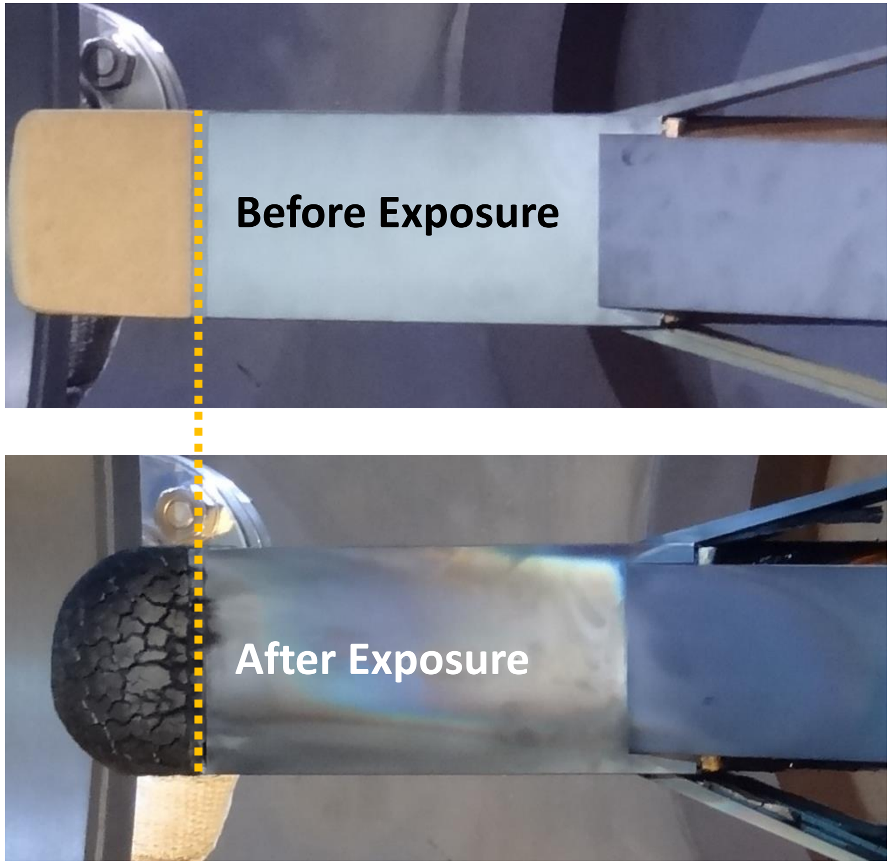
- Unlike more common ablators (carbon-phenolic), **cork itself pyrolyzes in addition to the resin** when exposed to heat
- Analyzing the **cooling effect** due to pyrolysis requires the knowledge of the elemental compositions of
  - **Cork**
  - **Phenol**
  - **Resultant pyrolysis gas**
- Layered structure of the **cork samples** tested in the **VKI Plasmatron** are examined
- Mass balance between states of before and after heat exposure is established



credits: Işıl Şakraker (2016, Doctoral dissertation Université de Liège, Belgium)

Mass loss due to ablation and pyrolysis is inherently accompanied by shape change in the form of surface recession

- Ideal approach:
  - **Fully coupled** flow and material phenomena
  - Requires accurate modelling of **internal decomposition** and knowledge of detailed **material properties**
  - Rigorous implementation
- Selected approach:
  - **Steady-state CFD** with **gas-surface interactions**
  - **Recession speeds** are found from CFD by extracting the **mass blowing rates** from an initial solution
  - Points along the **ablative wall** are **recessed in the surface normal direction** in **iterative** steps
  - New mesh is computed and CFD is reran

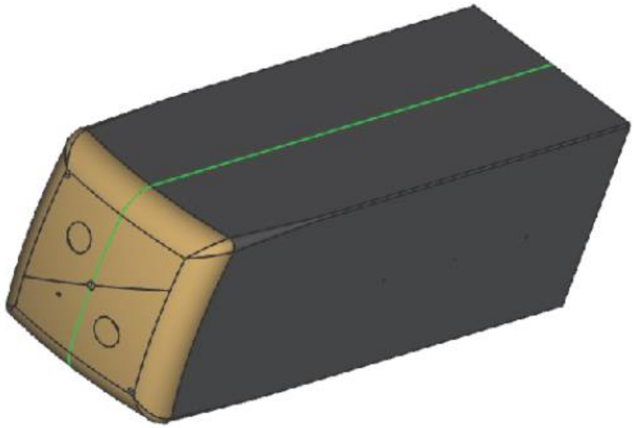


QARMAN model in SCIROCCO

Credits: Davide Masutti

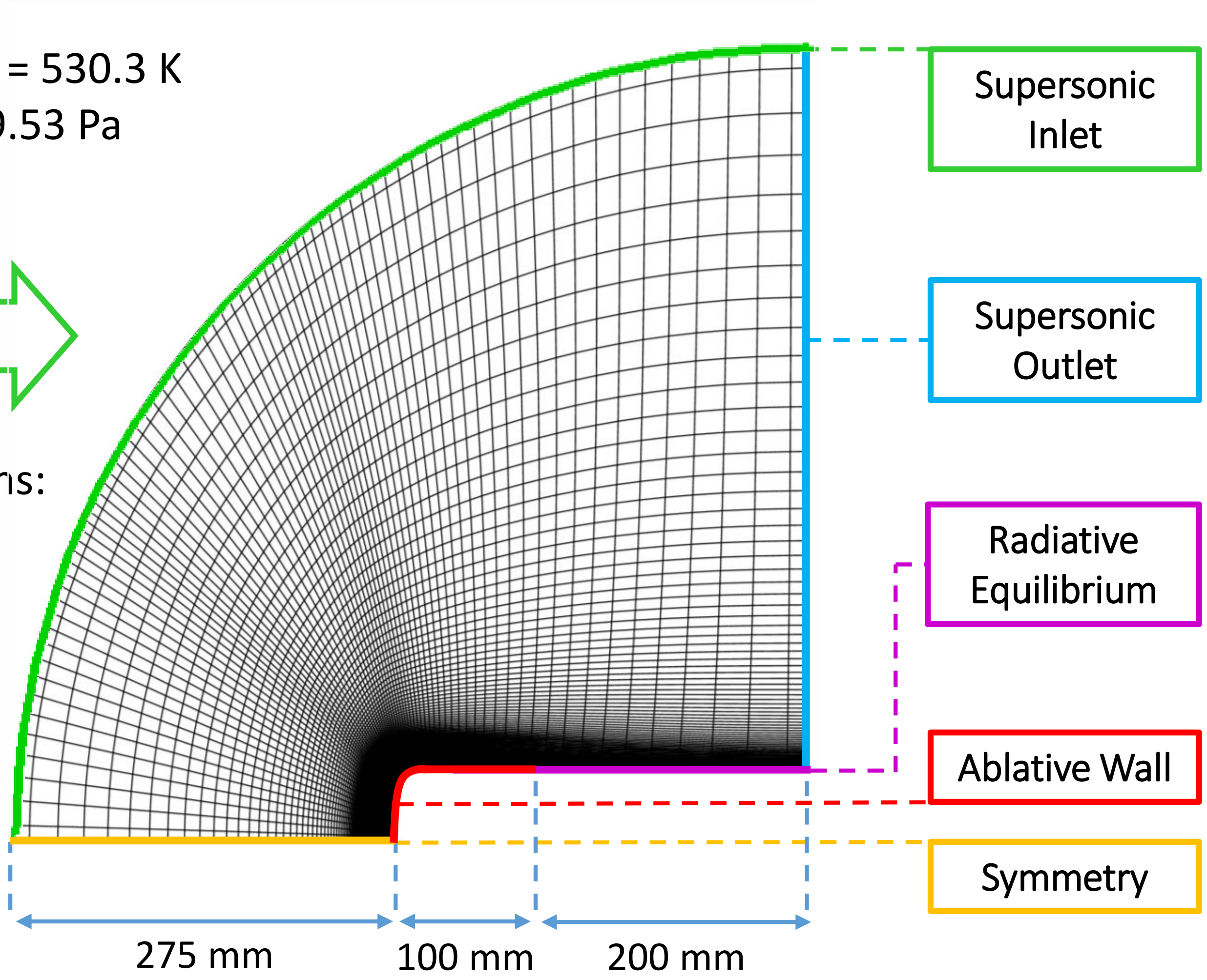
QARMAN model in SCIROCCO conditions

- Simplified 2D geometry without panels
- Half of the perpendicular cross-section
- Single block structured grid with 11925 cells in Gambit



Temperature = 530.3 K
Pressure = 39.53 Pa
Mach = 8.46

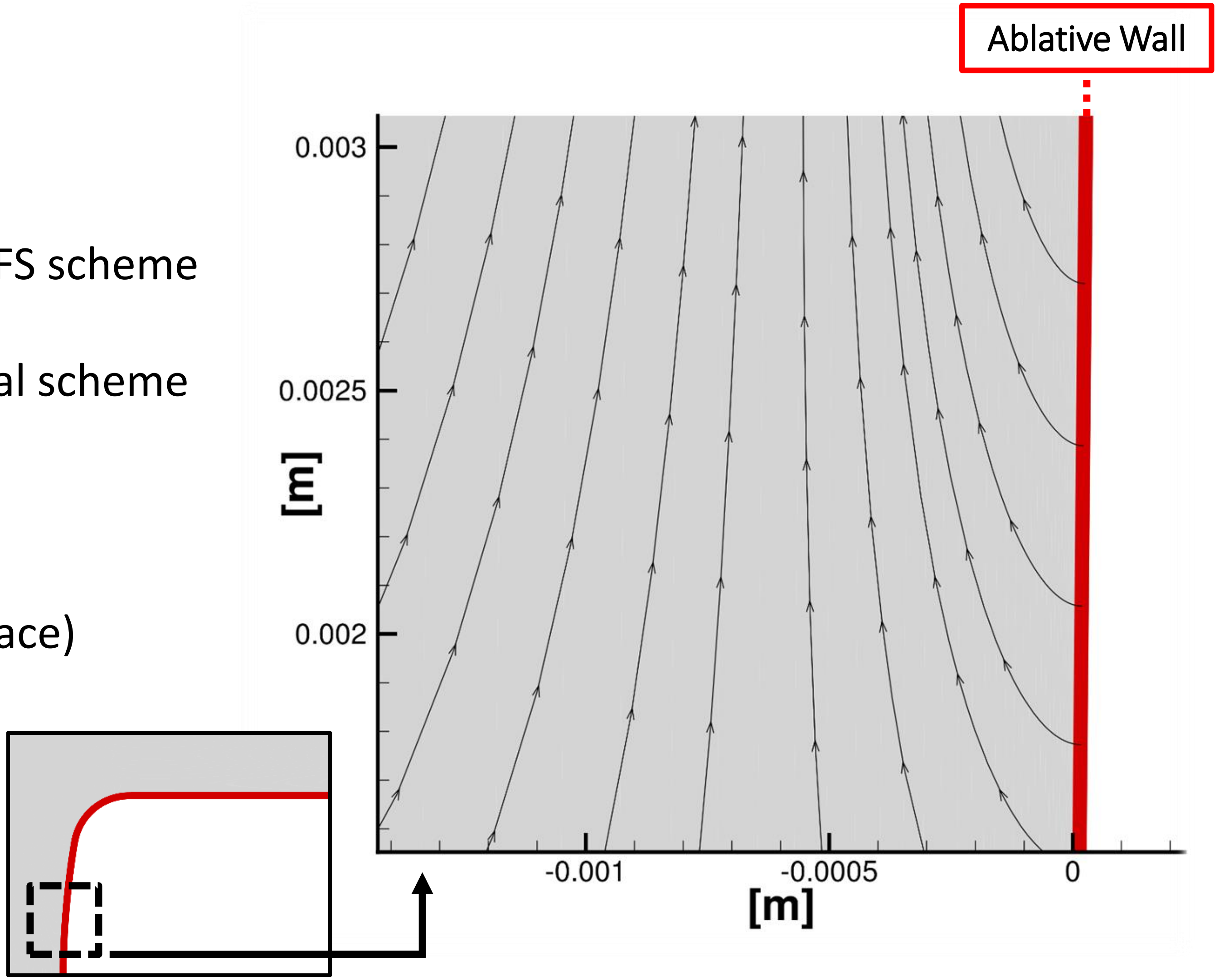
Mass Fractions:
N_2 = 0.667
O = 0.233
N = 0.1
NO = 0
O_2 = 0



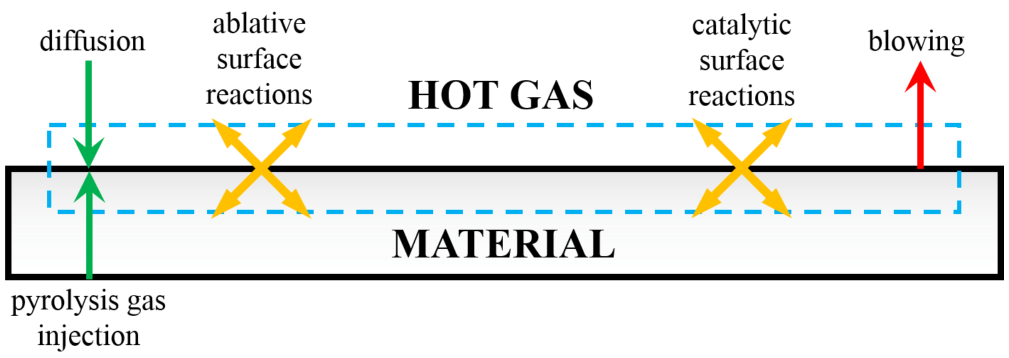
COSMIC in-house finite volume code is coupled with the **Mutation++** library to compute ablation

- **COSMIC**
  - Second order in space and time
  - Convective flux discretization with AUFS scheme with Van Albada limiter
  - Diffusive flux discretization with central scheme

- **Mutation++**
  - **Gas Surface Interaction module** (mass and energy balances at the surface)
  - Homogeneous chemistry
  - Thermodynamic properties
  - Transport properties



Species surface mass balance

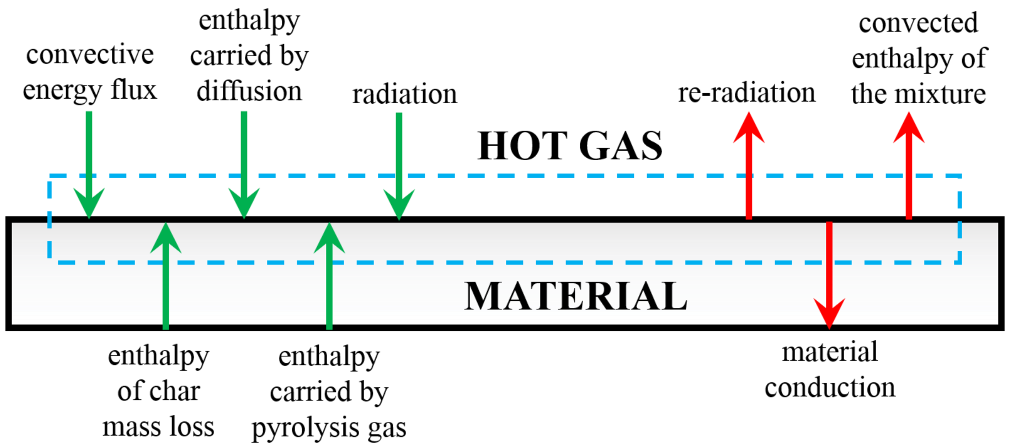


- **Finite-rate ablation** model to calculate mass fluxes
- ***v* ≠ 0**, due to blowing
- Blowing rates are computed directly, no need for further corrections on heat fluxes

$$(\rho_i v)_w + \left(\rho_i v_i^d\right)_w = \dot{\omega}_{i_w} + \dot{m}_g y_{i_g} \qquad (\rho v)_w = \dot{m}_c + \dot{m}_g = \dot{m}_{total}$$

$$\dot{m}_c = \sum_i^N \dot{\omega}_{i_w} \qquad \phi = \frac{\dot{m}_g}{\dot{m}_c} = \left(\frac{\rho_v}{\rho_c} - 1\right) \qquad \dot{s} = \frac{\dot{m}_c}{\rho_c}$$

Species surface energy balance



- **Steady-state conduction** at the surface
- Constant speed recession
- Time-independent temperature profile within material

$$\lambda_w \frac{\partial T}{\partial r}\bigg|_w - \sum_i^N \left(h_i \rho_i v_i^d\right)_w + \dot{m}_g h_g + \dot{m}_c h_c = (h\rho v)_w + \dot{q}_{cond,s}^{ss}$$

$$\dot{q}_{cond,s}^{ss} = \lambda_{s_w} \frac{\partial T}{\partial r}\bigg|_s = \dot{s}\left(\rho_{c_w} h_{c_w} - \rho_{v_{in}} h_{v_{in}}\right) + \dot{m}_g h_g$$

Roadmap for the analysis

Radiative Wall → Ablative Wall → Including Pyrolysis + Shape Change

Radiative Wall

- $\epsilon = 0.9$
- Air with 5 species (O, O_2, N, N_2, NO)

Ablative Wall

- Oxidation at the wall
- Air with 11 species (… C, C_2, C_3, CN, CO, CO_2)

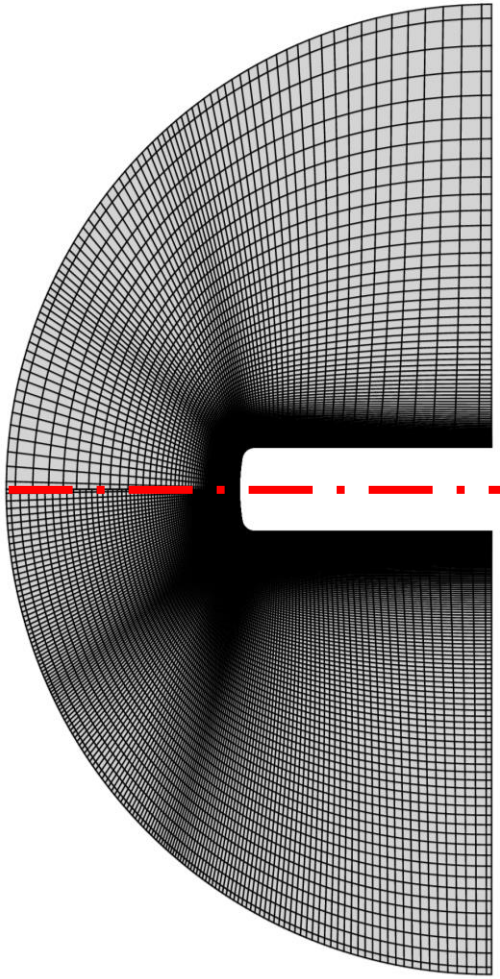
Including Pyrolysis

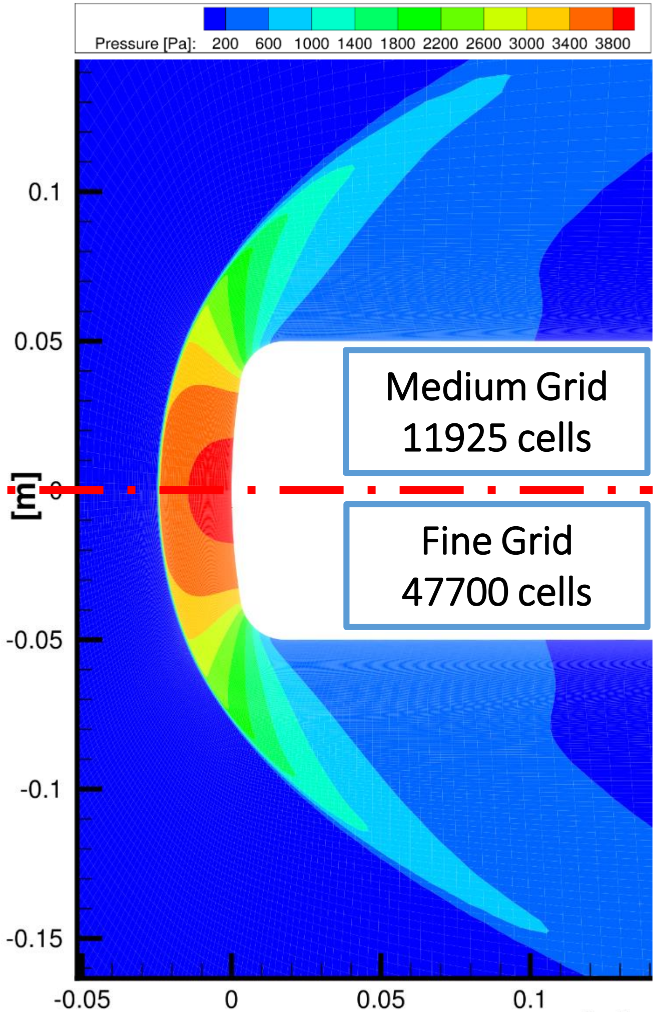
- Include pyrolysis gas
- Air with 14 species (… H, H_2, C_2H)

Shape Change

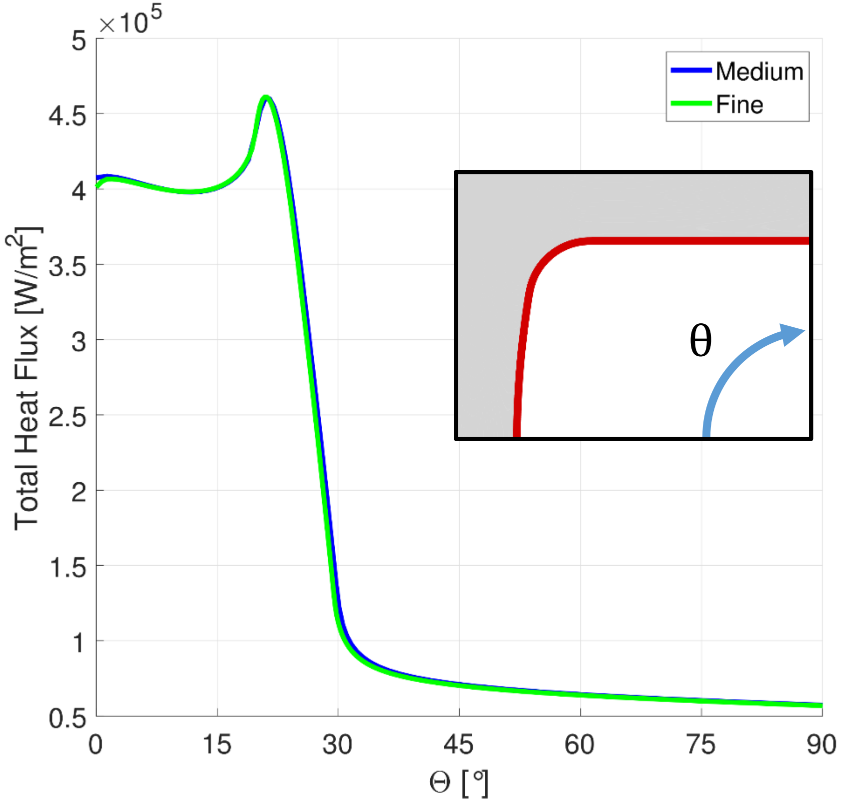
- Scaled geometry
- Evolved geometry

Grid independence for radiative equilibrium wall



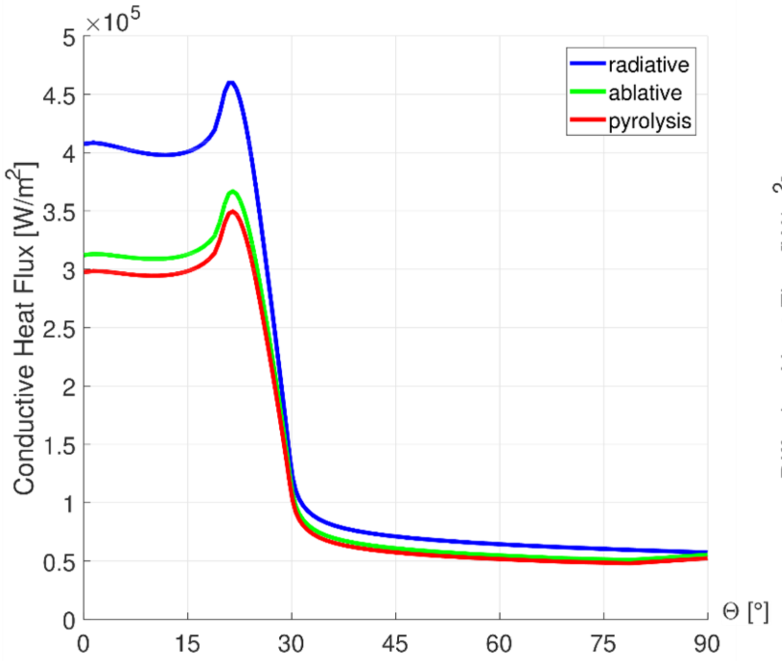


Pressure

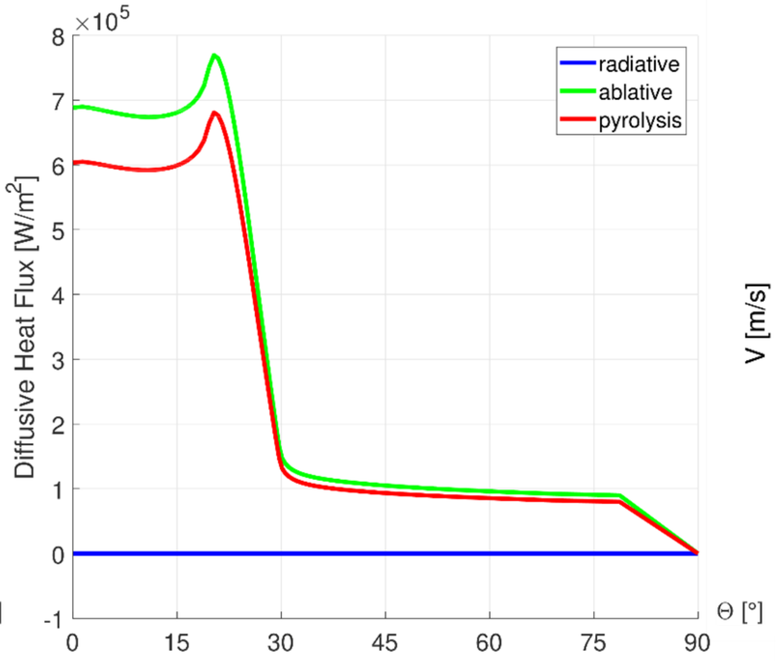


Wall Heat flux

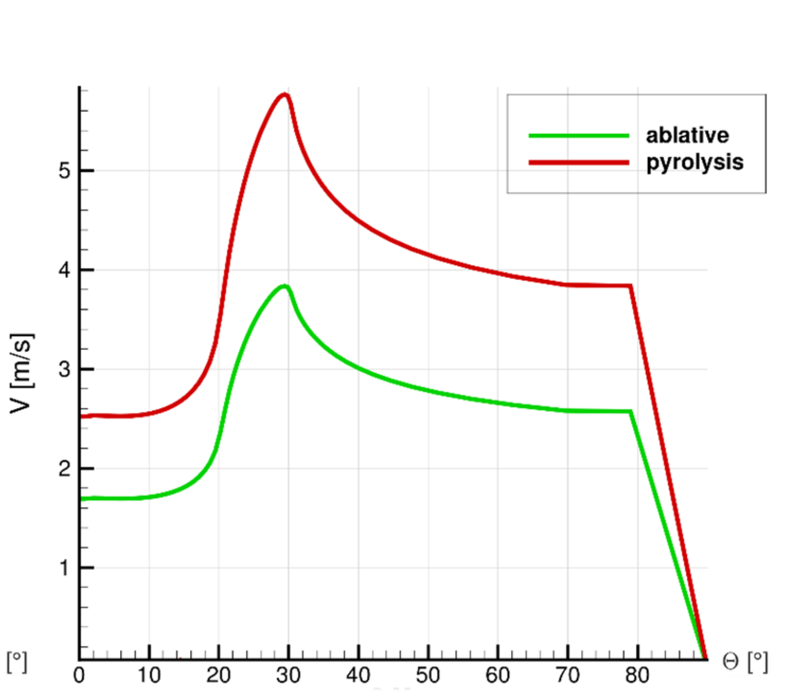
Radiative, **ablative** and **pyrolysis** gas included cases



Conductive heat flux



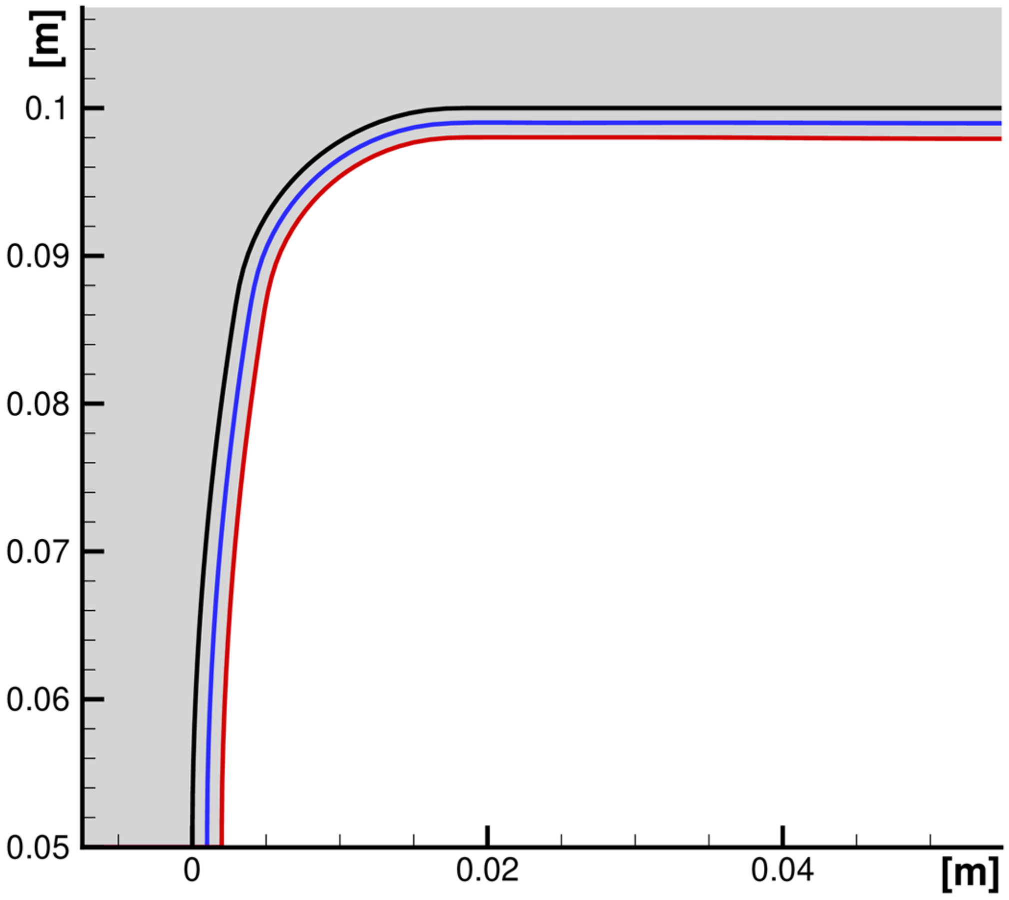
Diffusive heat flux



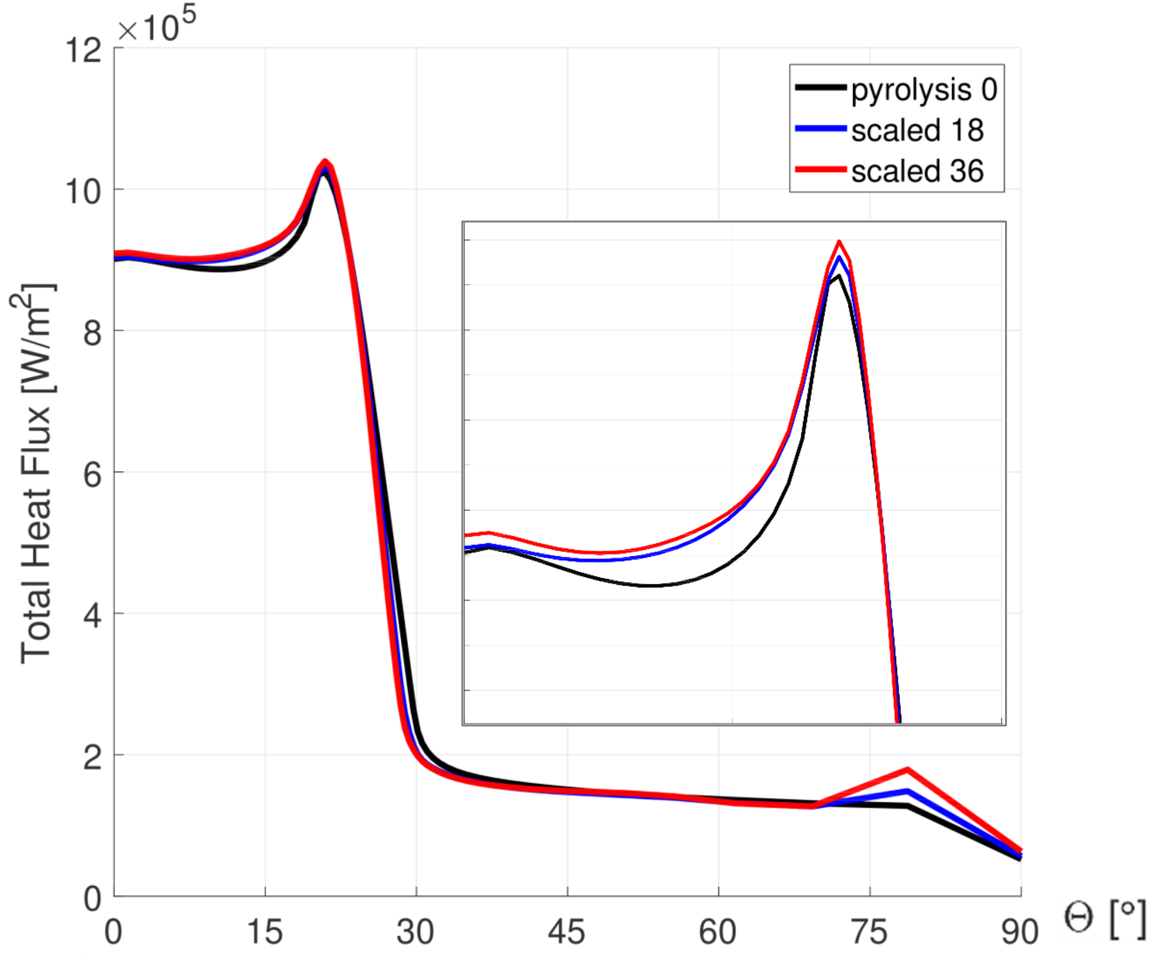
Velocity magnitude along the wall

Stagnation point values	**Radiative**	**Ablative**	**Pyrolysis**
Temperature [K]	1681	1882	1789
Recession Speed [mm/s]	-	0.0366	0.0550

Surface and heat flux variation: **Scaled geometry**

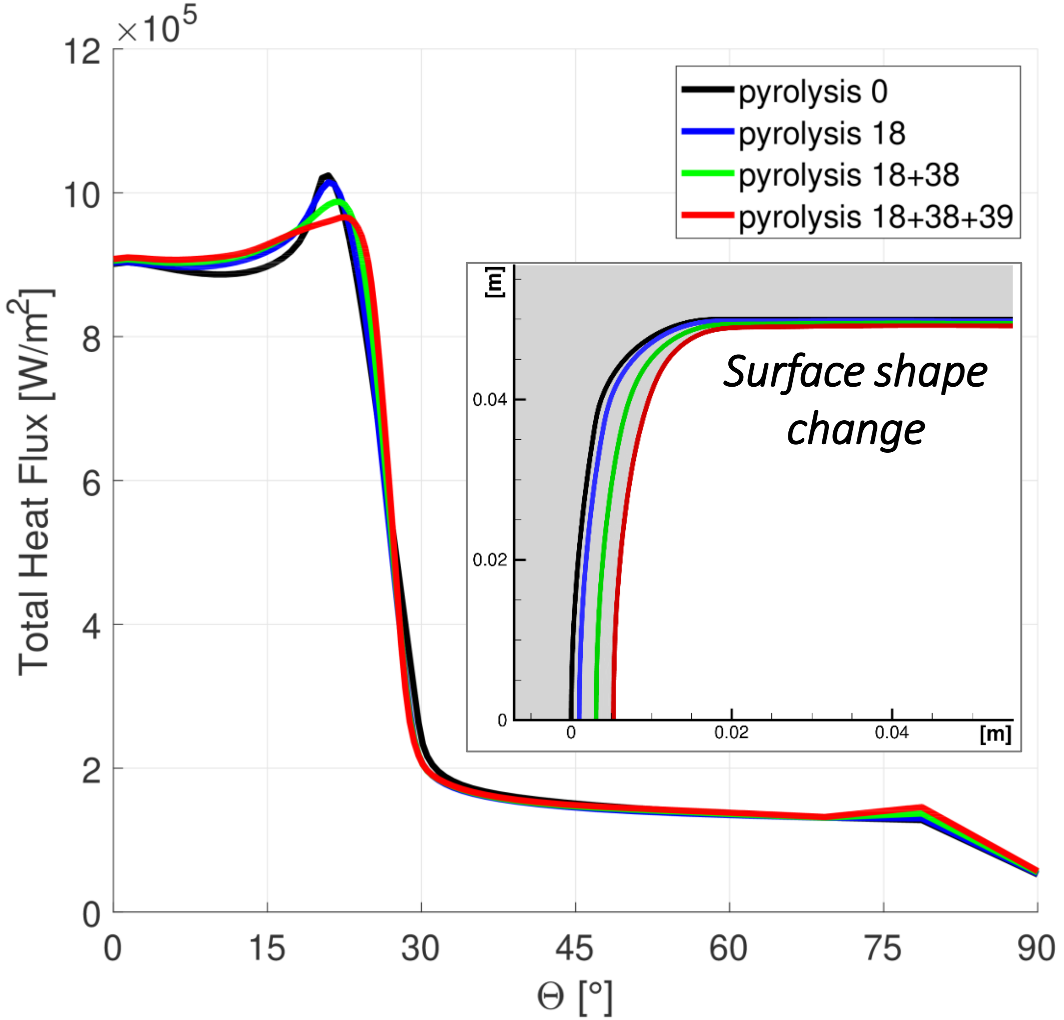


Scaled surface shapes

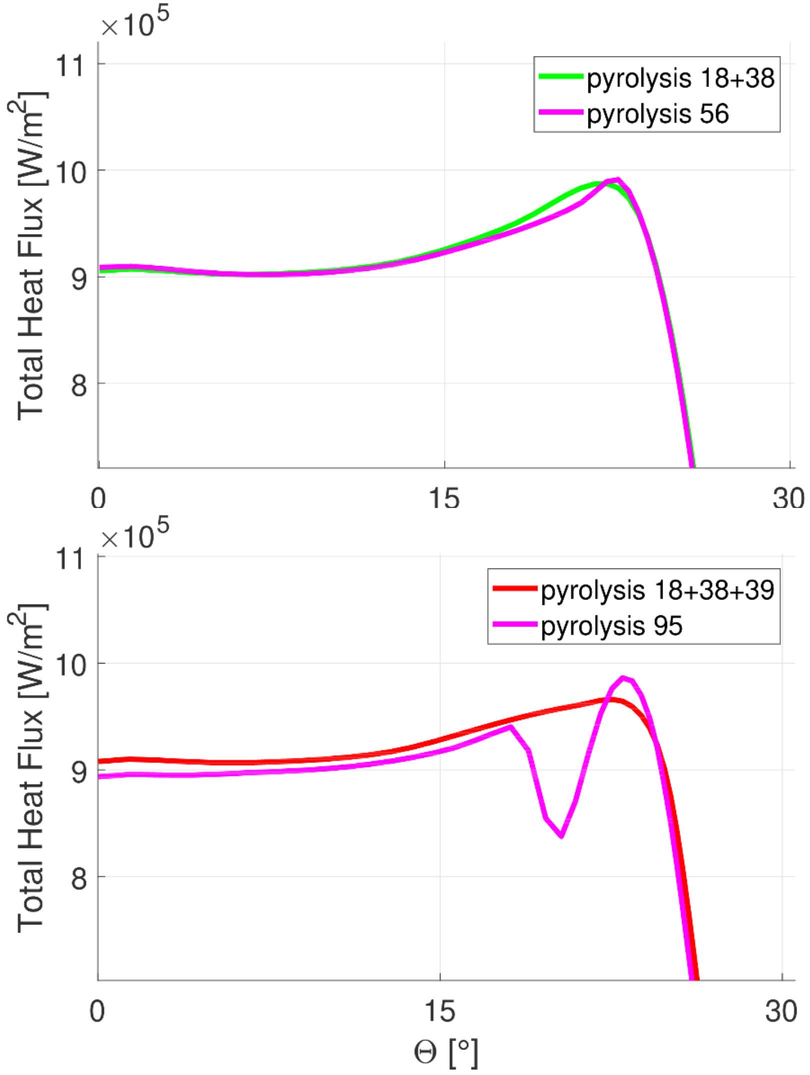


Heat flux distributions along the wall

Surface and heat flux variation: **Evolved geometry**



Heat flux distributions along the wall



Conclusions

- Cork-phenolic TPS elemental composition successfully identified based on literature and test data
- First coupled flow-ablation-pyrolysis simulation of the QARMAN re-entry CubeSat performed using the GSI module of the VKI Mutation++ Library and Cosmic CFD solver
- Findings:
  - Cork-phenolic pyrolysis effectively cools the surface
  - Heat flux evolution governed by shape change rather than radius of curvature variation
  - Recessing QARMAN TPS for long periods based on initial solution fails to capture the correct evolution of the shape and deteriorates the heat flux
  - Iterative steps are required to adapt to changes in recession speeds

Thank you for your attention.

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