Detailed flow modeling of meteor entry at low altitudes

B. Dias A. Turchi J.B. Scoggins T. Magin

Aeronautics and Aerospace Department

von KARMAN INSTITUTE FOR FLUID DYNAMICS

Meteoroids 2016

06-10 June 2016, ESTEC, Noordwijk

fnrs FREEDOM TO RESEARCH

The meteor phenomena … inspiration for space exploration

Artistic View Meteor [MidnightWatcher's]

Artistic illustration of the Apollo's re-entry (NASA)

50 -100 tonnes of meteor enter in the earth's atmosphere per day

- **Velocity** : 11.2 - 72.5 km/s
- **Composition**: FeO; MgO; Ca; SiO_2, …
- **Size**: radius 1 µm – 10 m

Meteor ablation source of inspiration for ablative heat shields

- **Velocity** : 7.9 - 14 km/s
- **Composition TPS**: C(gr), SiO_2, C_6H_5-OH
- **Size**: radius 0.5 m – 2 m

Detection of meteors by the Belgian Institute for Space Aeronomy

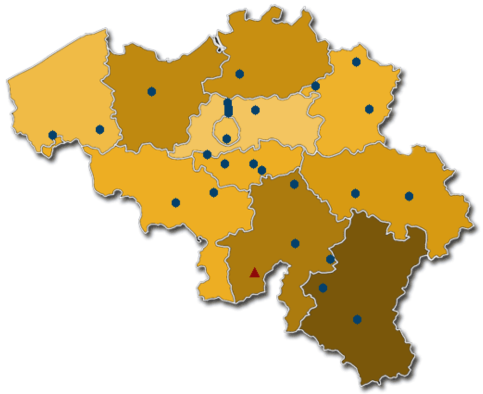
The purpose of the meteor detection:

What is the incoming meteor flux? Is it 50 or 100 tonnes per day?

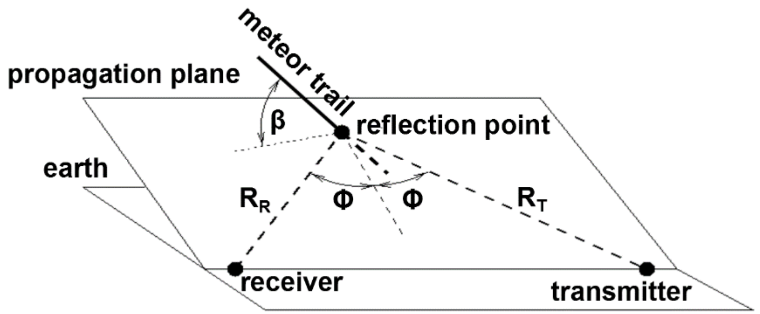
How can the ablation products influence the composition of the upper atmosphere?

Efforts made to detect meteors:

- Belgian RAdio Meteor Stations (BRAMS[1]), uses radio stations all over Belgium



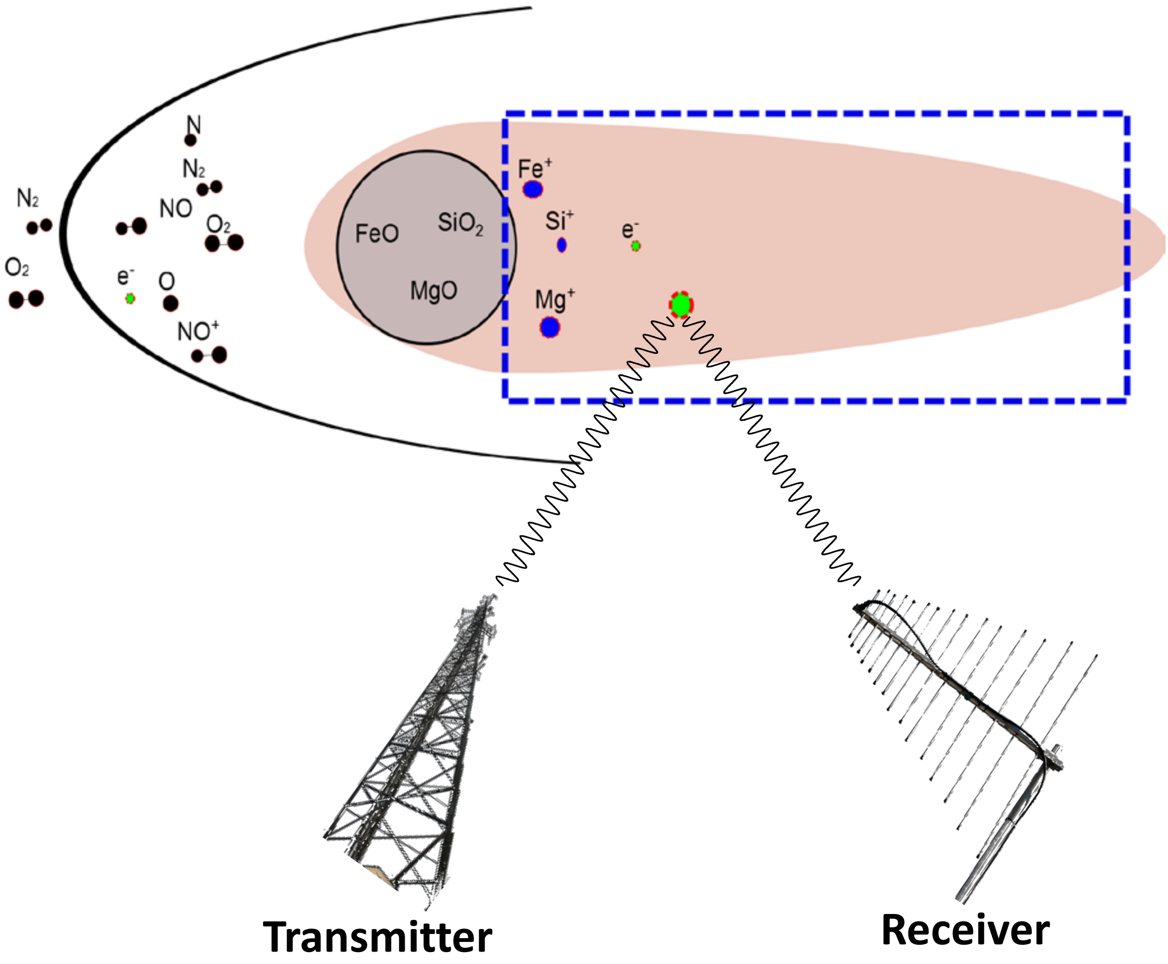
- Detect the meteor trail using radio waves (Forward Scattering technique)



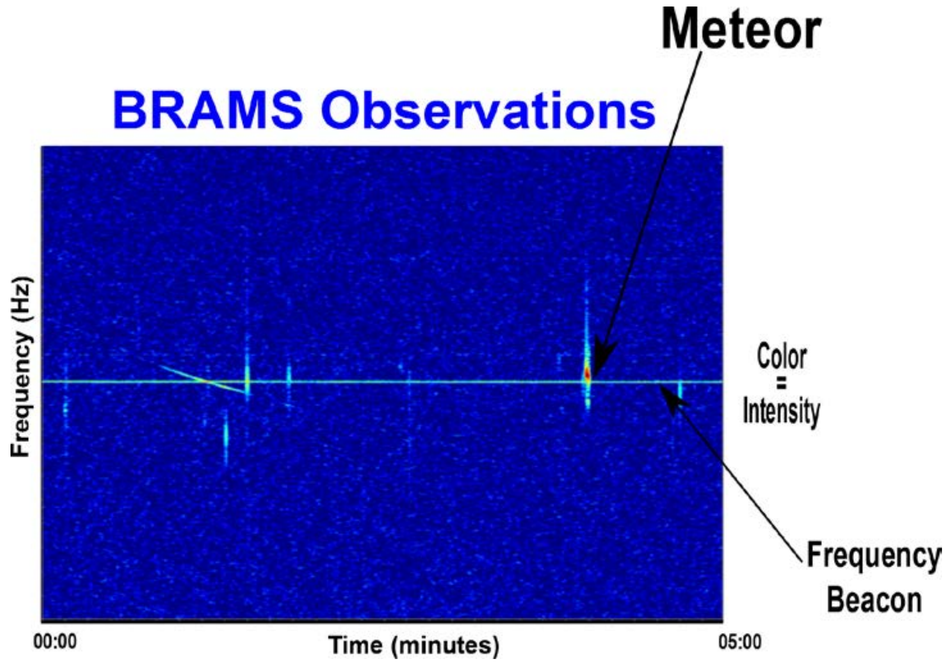
Geometry of specular radio reflections (BRAMS)

[1] http://brams.aeronomie.be/

How does BRAMS work?



Post-processing



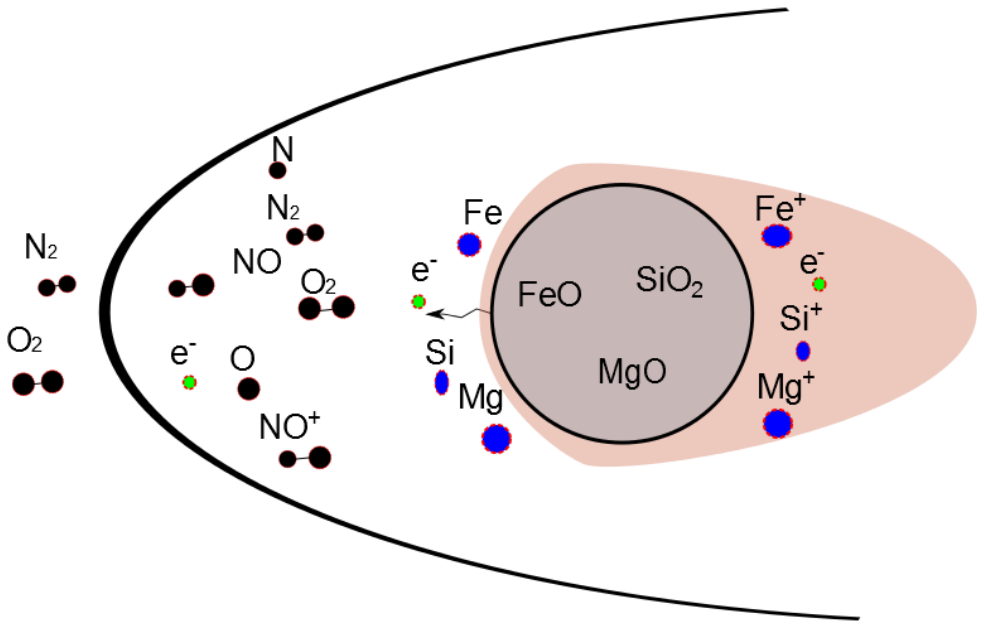
Ionized trail reflection from multiple stations:
velocity and trajectory of the meteor **but not the size!!**

Objectives

Detailed flow analysis during a meteor entry based on a aerospace engineering approach

Focus of the study:

- Continuum flow
- Single fragment meteor
- Geometry: sphere
- Forward stagnation streamline



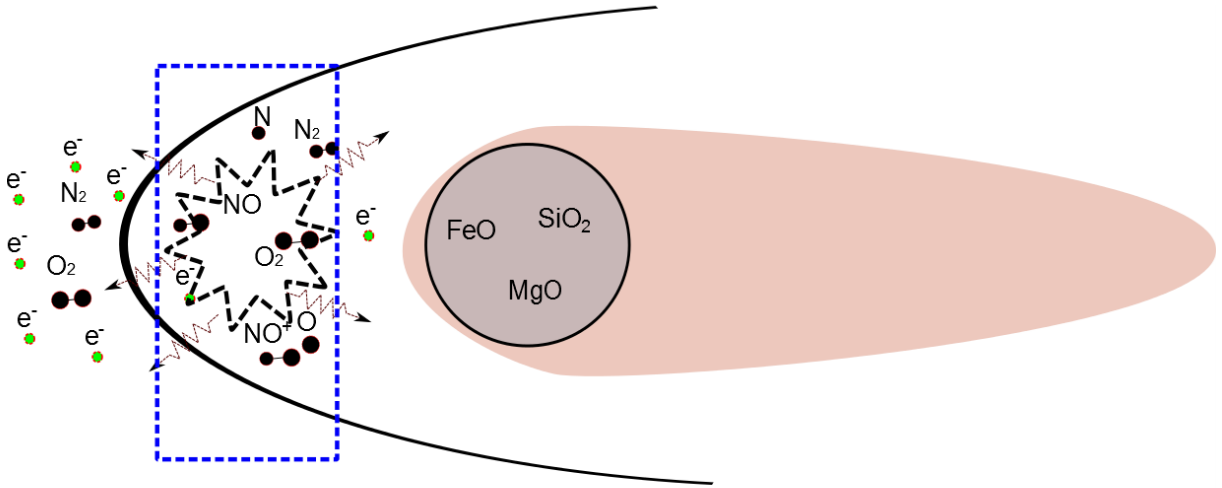
Outline

- Flow field Modeling
- Gas-surface interaction modeling for meteors
- Numerical tools & results
- Conclusion and Future Work

Outline

- **Flow field modeling**
- Gas-surface interaction modeling for meteors
- Numerical tools & results
- Conclusion and Future Work

Flow field modeling

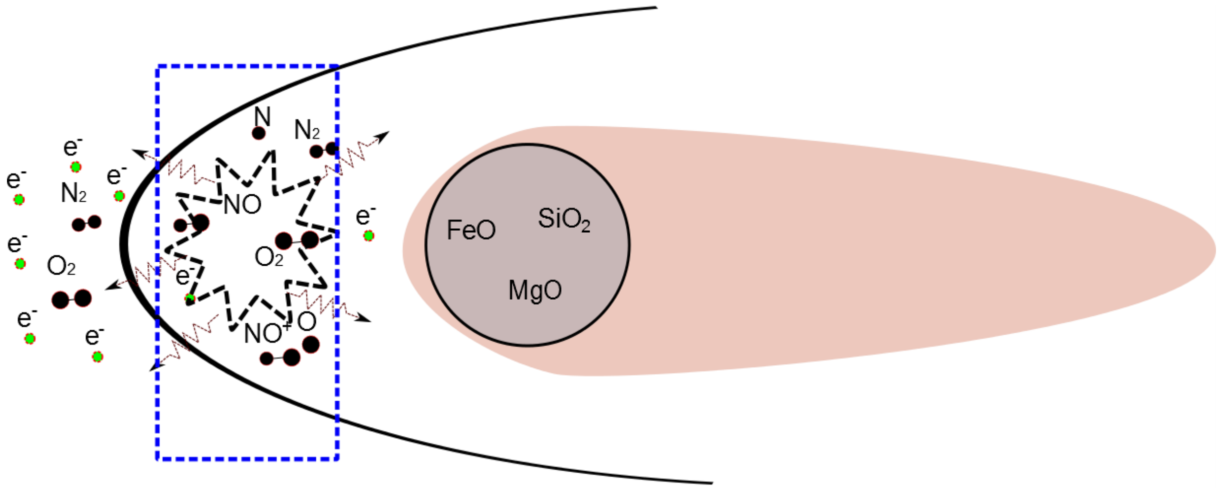


- High entry velocity (11.2 –72.5 km/s)
- High temperatures (*e.g.* 120,000 K): thermal non-equilibrium effects
- Complex chemical reactions (e.g. dissociation and ionization)
- High radiative field: computational expensive

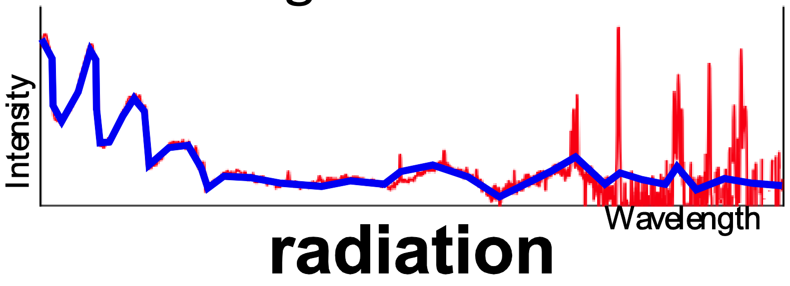
radiation

[1] Soucasse *et al*, JQSRT *(2016)*

Flow field modeling



- High entry velocity (11.2 –72.5 km/s)
- High temperatures (*e.g.* 120,000 K): complex thermodynamic properties
- Complex chemical reactions (e.g. dissociation and ionization)
- High radiative field: computational expensive

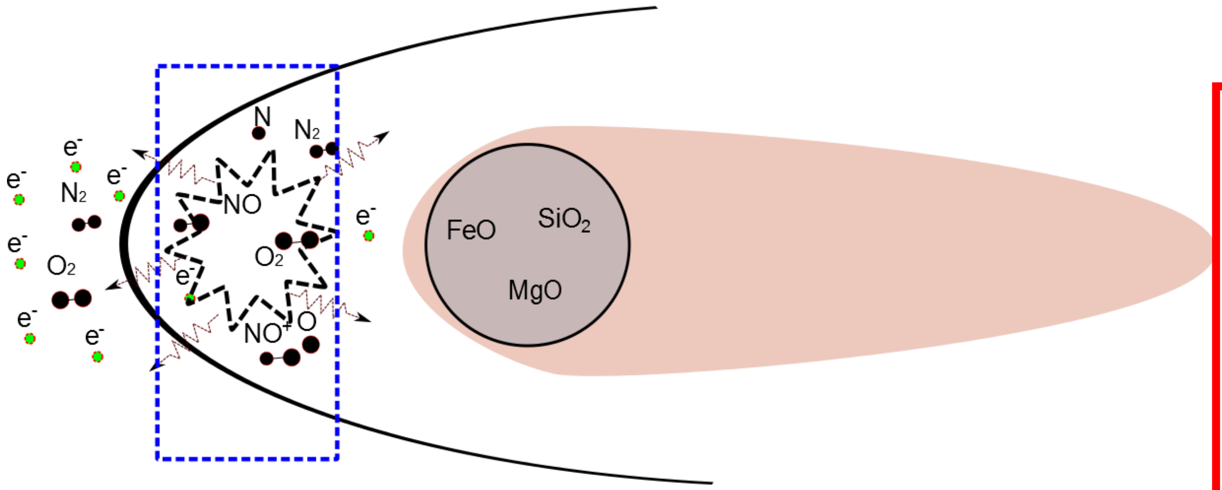


Hybrid Statistical Narrow Band (HSNB) method[1]

- Accurate description
- Low CPU cost for coupling
- Atomic line treated by Line-by-Line method

[1] Soucasse *et al,* JQSRT *(2016)*

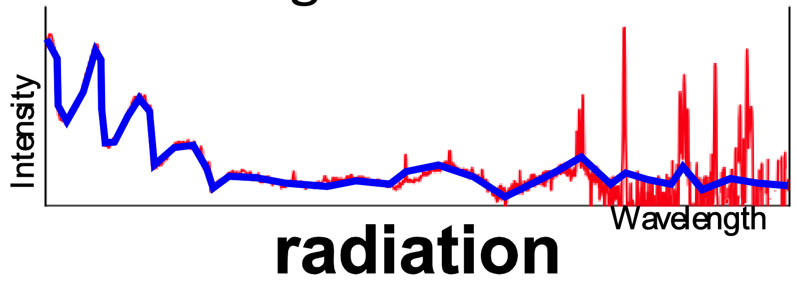
Flow field modeling



Assumptions:

- Atmospheric Gas reactions: non equilibrium
- Ablations products: frozen
- Only air radiation mechanisms considered

- High entry velocity (11.2 –72.5 km/s)
- High temperatures (*e.g.* 120,000 K): complex thermodynamic properties
- Complex chemical reactions (e.g. dissociation and ionization)
- High radiative field: computational expensive



Hybrid Statistical Narrow Band (HSNB) method[1]

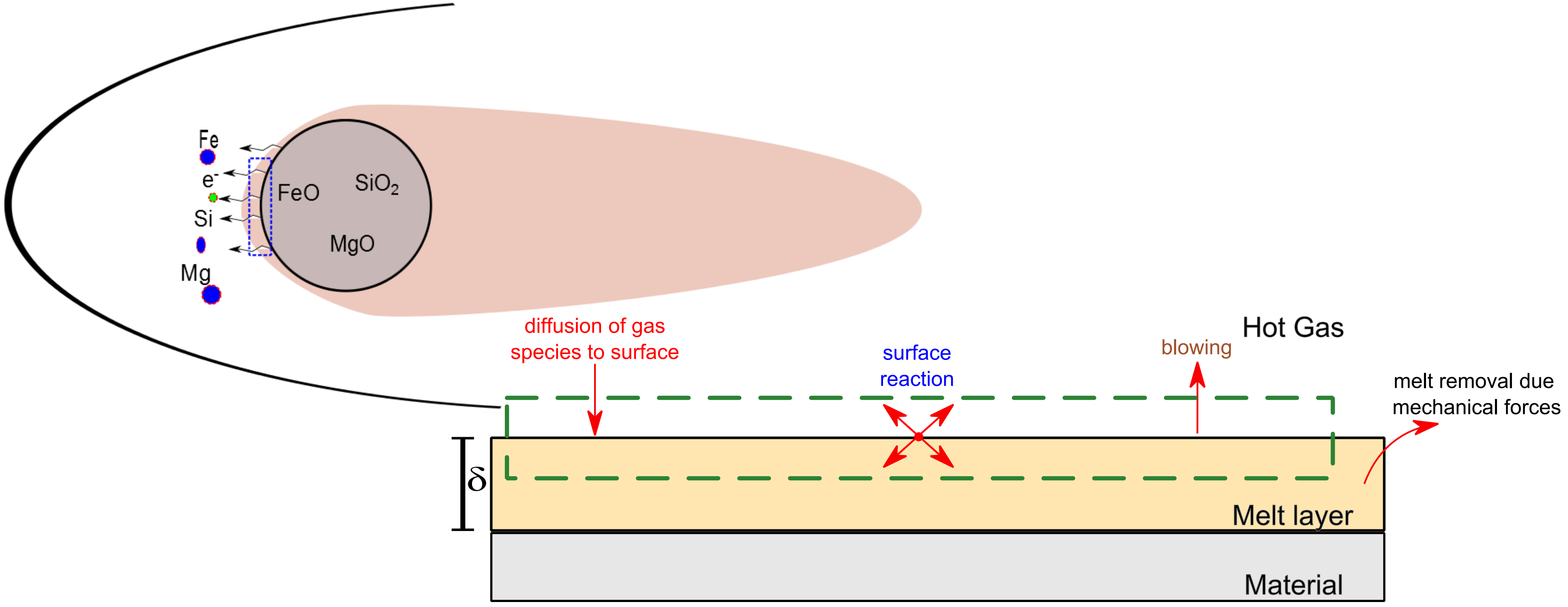
- Accurate description
- Low CPU cost for coupling
- Atomic line treated by Line-by-Line method

[1] Soucasse *et al*, JQSRT *(2016)*

Outline

- Flow field modeling
- **Gas-surface interaction modeling for meteors**
- Numerical tools & results
- Conclusion and Future Work

Ablation Model Surface Mass Balance (SMB)



Mass removal due to evaporation :

- Species i mass balance (O_2, N_2, …, FeO, Fe, SiO_2, MgO, …):

$$J_{i,w} + \sum_{r=1}^{N_r} \omega_i^r = (\rho v)_w y_{i,w} \quad i=1,\dots,N_s \qquad (1)$$

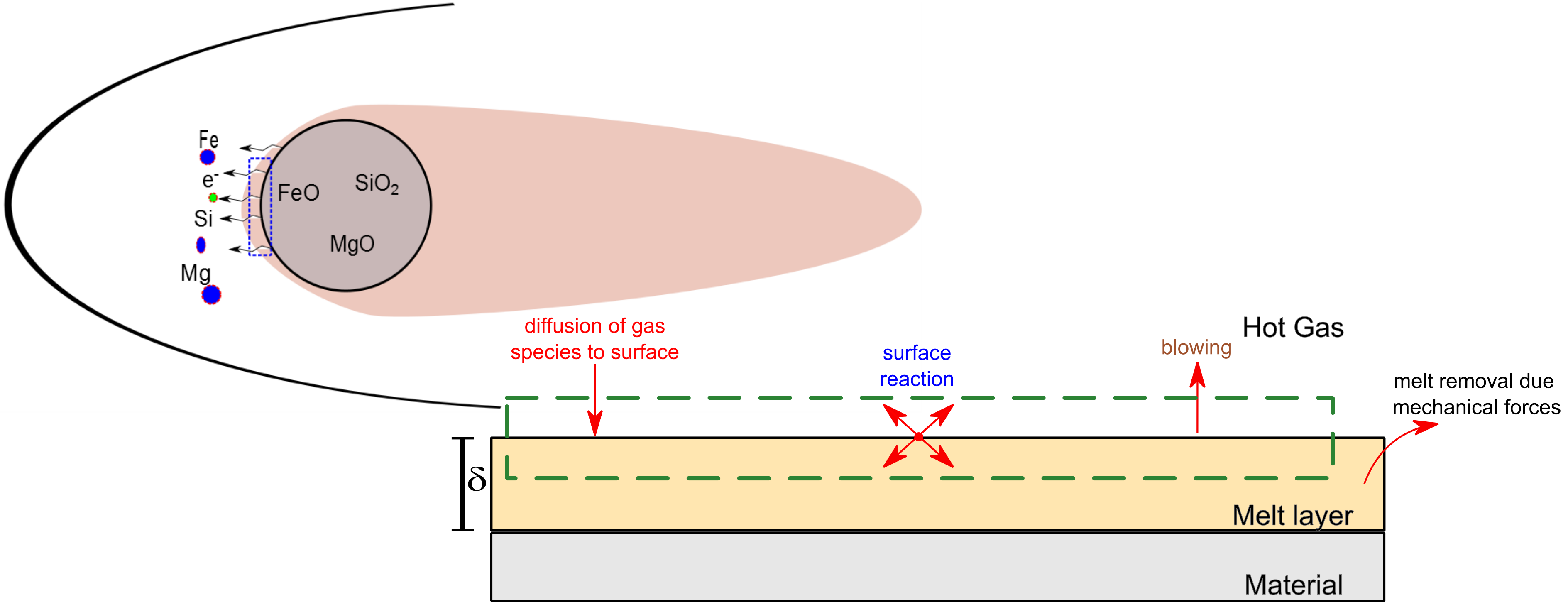
Mass removal due to mechanical forces :

- Tangential velocity[1]:

$$u = \tau_{flow/melt} \int_0^{\delta} \frac{dr}{\mu(T)} + \frac{\partial P}{\partial \theta}_{flow/melt} \int_0^{\delta} \frac{r}{\mu(T)} dr$$

[1] *Bethe et al,* Journal of the Aerospace Sciences Vol.26, No.6 (1959)

Ablation Model Surface Mass Balance (SMB)



Mass removal due to evaporation :

- Elements k mass balance (O, N, …, Fe, Si, Mg, …):

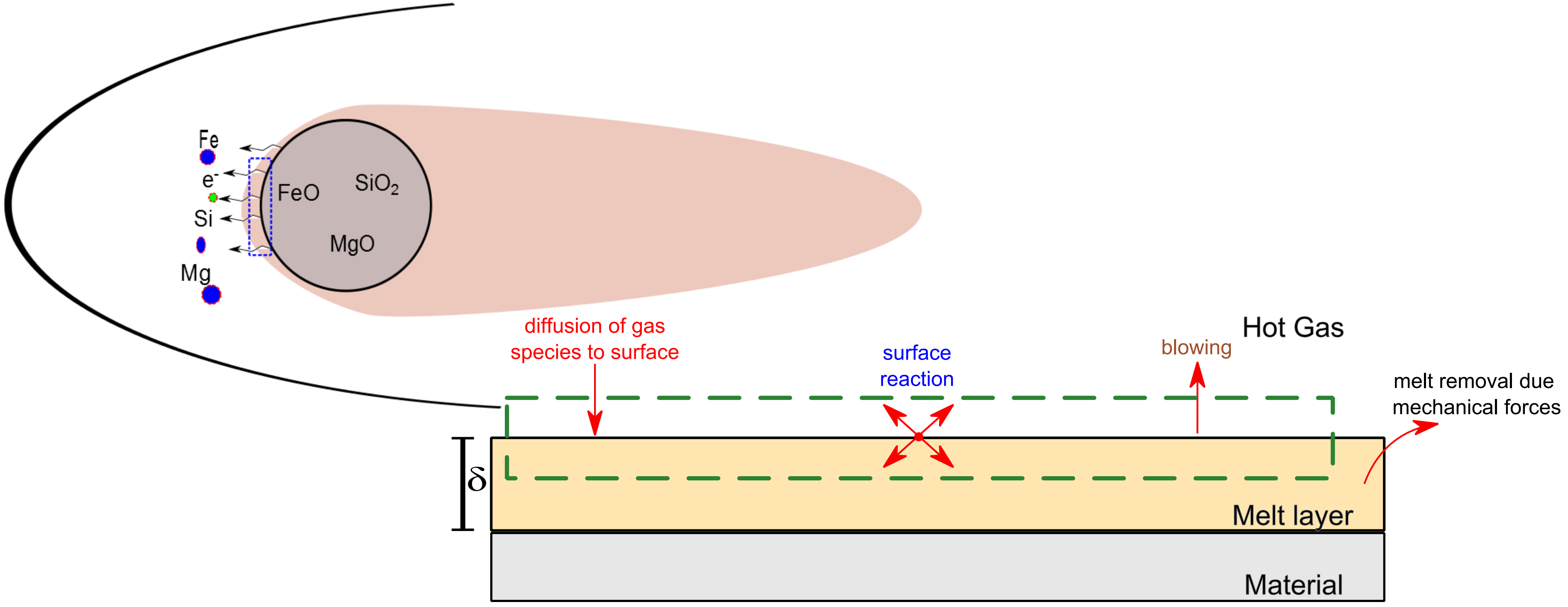
$$\sum_{i=1}^{Ns} \sigma_{i,k} \frac{M_k}{M_i}(1) \Rightarrow J_{i,k} + \dot{m}_{evap}\ y_{k,s} = (\rho v)_w\ y_{k,w} \qquad \mathrm{k}=1,\ldots,\epsilon$$

Mass removal due to mechanical forces :

- Tangential velocity:

$$u = \tau_{flow/melt} \int_0^{\delta} \frac{dr}{\mu(T)} + \frac{\partial P}{\partial \theta}_{flow/melt} \int_0^{\delta} \frac{r}{\mu(T)} dr$$

Ablation Model Surface Mass Balance (SMB)



Total mass removal

Mass removal due to evaporation :

- evaporation mass blowing rate, $\dot{m}$:

$$\dot{m}_{evap} = \frac{J_{i,k}}{(y_{k,w} - y_{k,s})}$$

- $y_{k,w}$: gaseous mixture at the wall computed by chemical equilibrium
- $J_{i,k}$: elemental mass diffusion computed by CFD

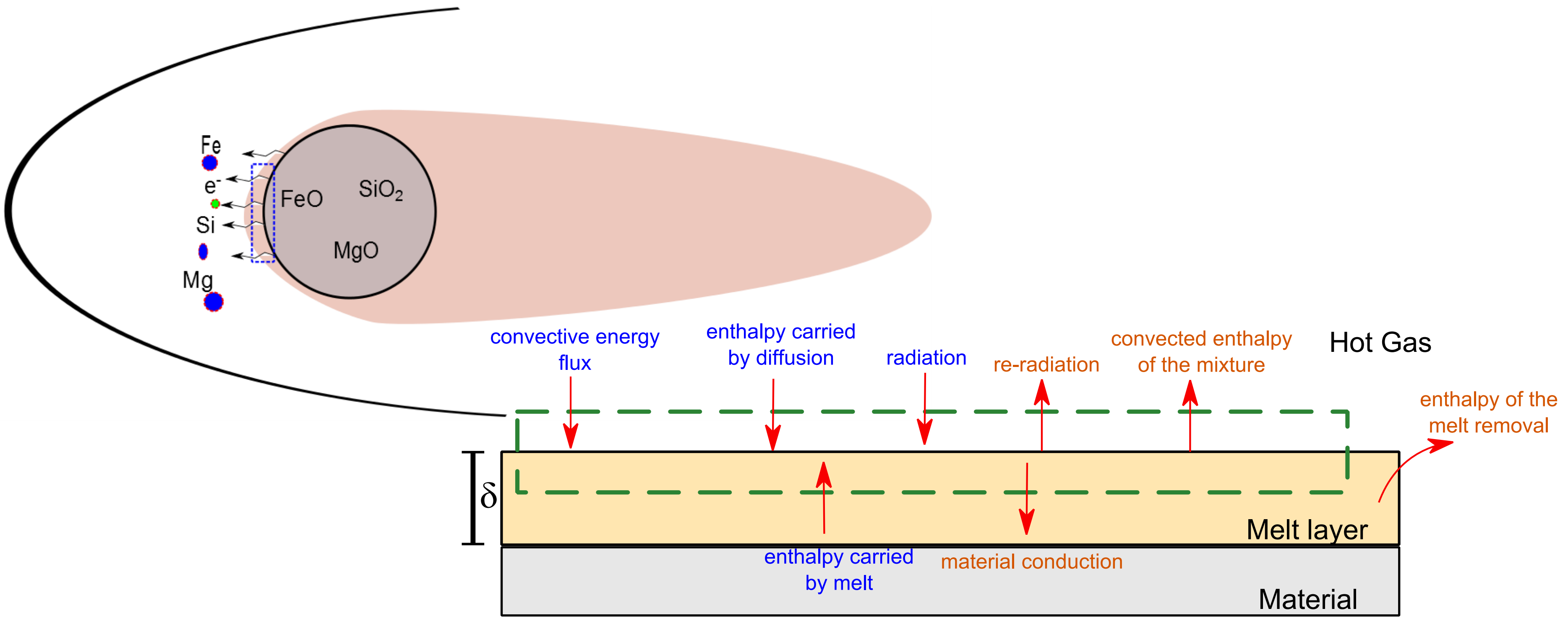
+

Mass removal due to mechanical forces :

- mass removal :

$$\dot{m}_{melt} = \rho_{melt} u \delta$$

Ablation Model Surface Energy Balance (SEB)



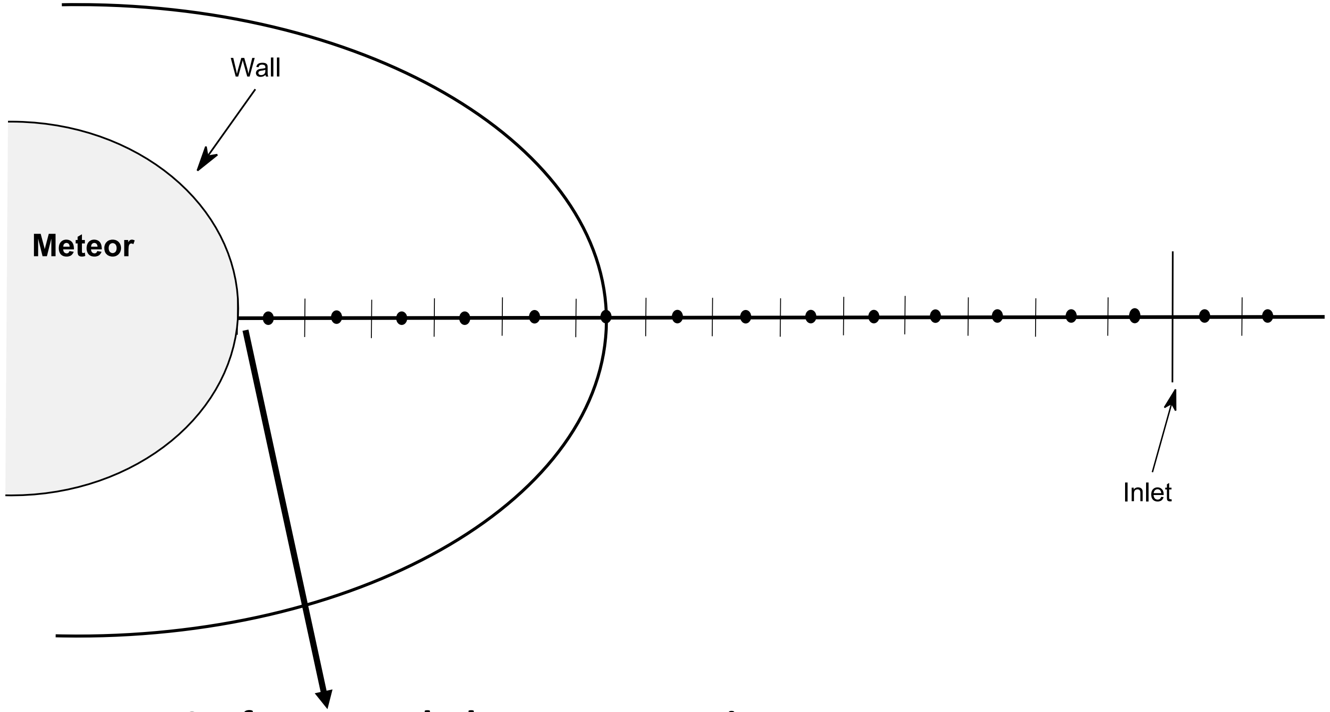
- Energy Balance:

$$\lambda \nabla T_w + \sum_{i=1}^{N_s} h_i \rho_i V_i + (\dot{m}_{evap} + \dot{m}_{melt}) h_c + q_{rad,in} = q_{rad,out} + \dot{m}_{evap} h_w + k \frac{\partial T}{\partial r} + \dot{m}_{melt} h_c$$

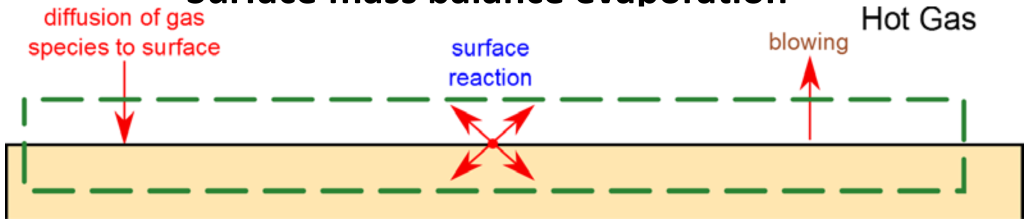
Outline

- Flow field Modeling
- Gas-surface interaction modeling for meteors
- **Numerical tools & results**
- Conclusion and Future Work

Meteor ablation flow solver



Surface mass balance evaporation



Stagnation-Line Code CFD Solver [1]

- 1D Stagnation-Line solver in spherical coordinates
- Cell-centered finite volume
- Roe's Riemann solver
- Fully implicit time-integration

$$\frac{\partial}{\partial t}\mathbf{U} + \frac{\partial}{\partial r}\mathbf{F}^{\mathbf{inv}} + \frac{\partial}{\partial r}\mathbf{F}^{\mathbf{vis}} + \frac{\mathbf{G}^{\mathbf{inv}} + \mathbf{G}^{\mathbf{vis}}}{r} = \mathbf{S}$$

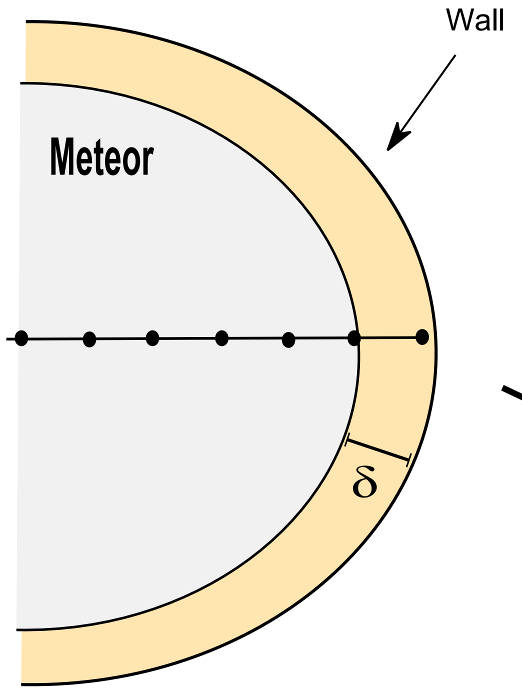
coupled

Mutation^{++} library [2]

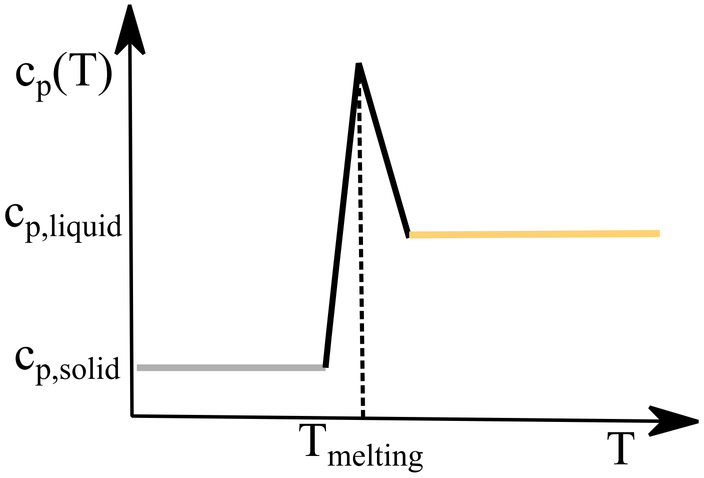
- Thermodynamic properties
- Transport properties
- Air chemistry
- Multiphase Equilibrium Solver[3]

[1] *Munafò et al*, Phys. Fluids 26, 097102 (2014)
[2] *Scoggins et al,* AIAA 2014-2966 (2014)
[3] *Scoggins et al, Combust. Flame* 162(12):4514-4522 (2015)

Meteor ablation material solver



Variable thermodynamic properties:

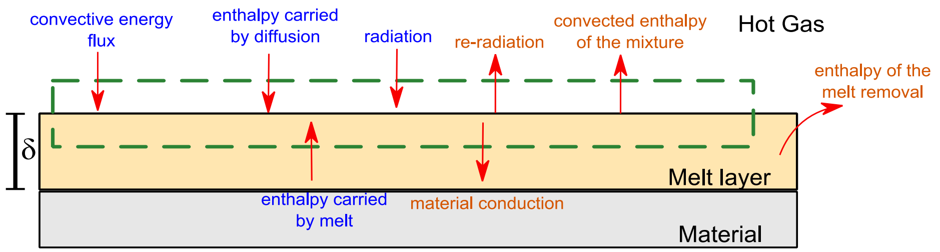


Melting material solver

- 1D in spherical coordinates
- Finite difference method
- Unsteady solver
- Expicit time integration

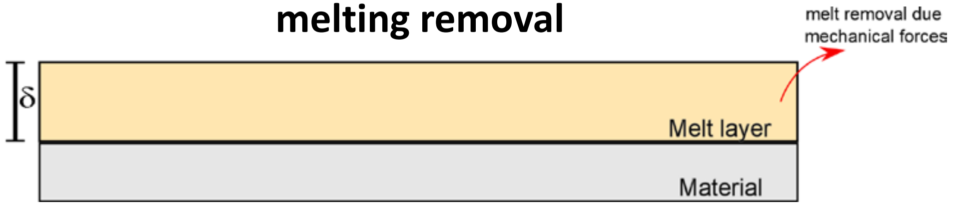
$$\rho c_p(\mathrm{T}) \frac{\partial T}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r}\left(r^2 k \frac{\partial T}{\partial r} \right)$$

Surface energy balance



+

melting removal

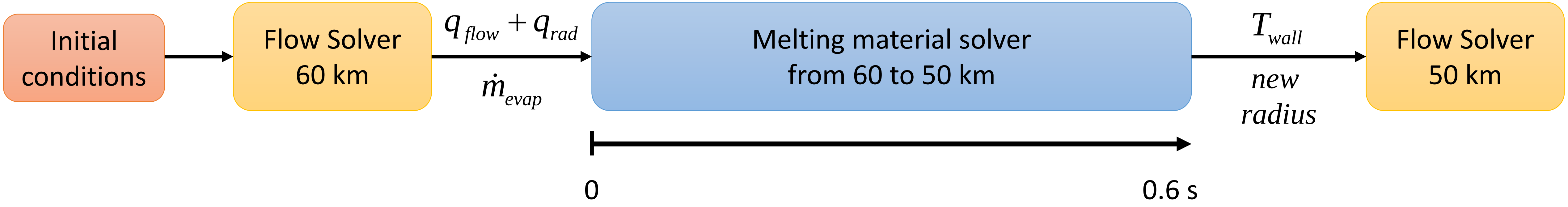


Flow/ material solver coupling strategy

Simulation conditions:

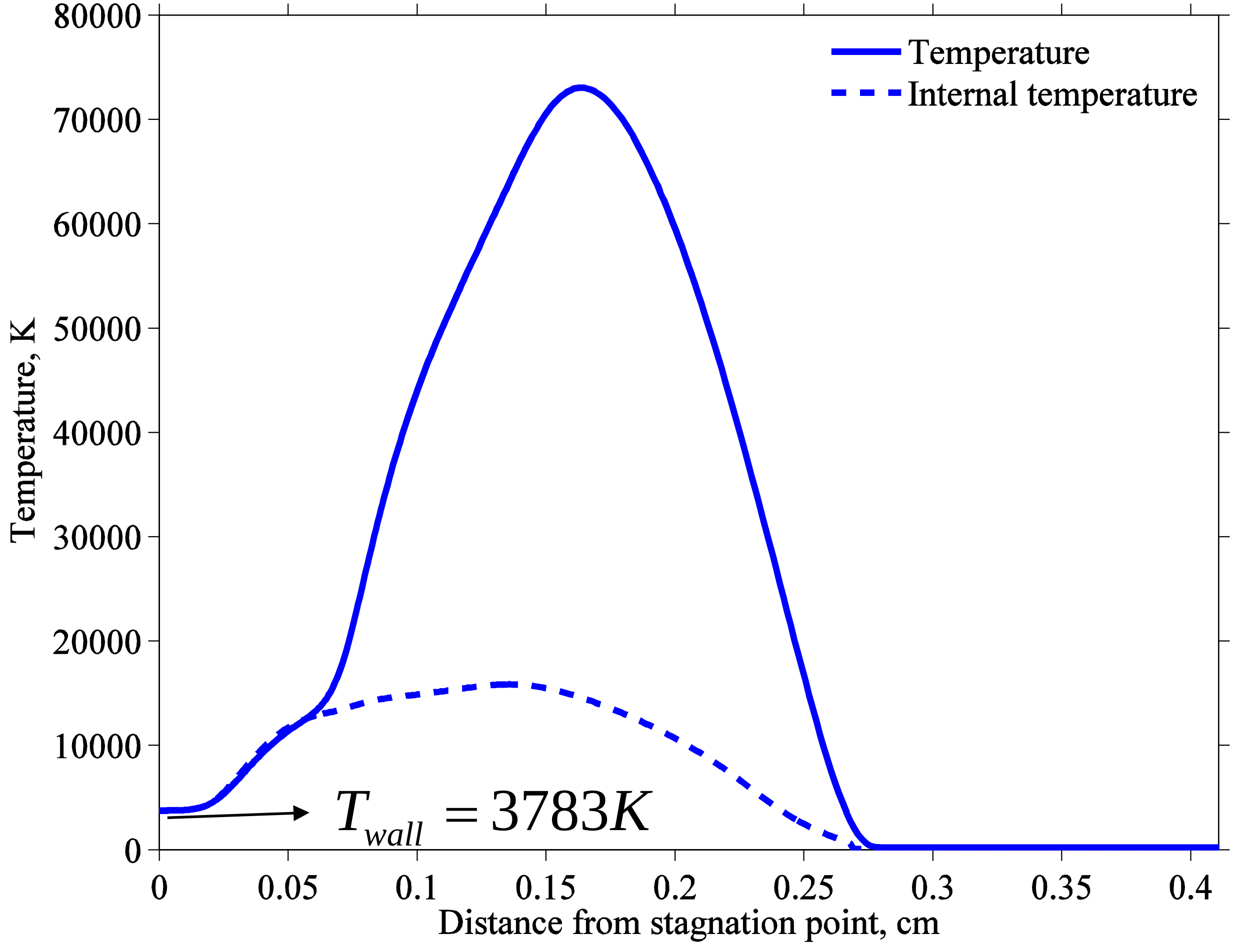
- Meteor composition in the atmosphere:
  - Simplify Ordinary Chondrite (SiO_2: 0.65, MgO: 0.35) meteor, 1 cm radius
- Entry velocity: 15 km/s
- Altitude: 60 to 50 km

Explicit coupling approach:

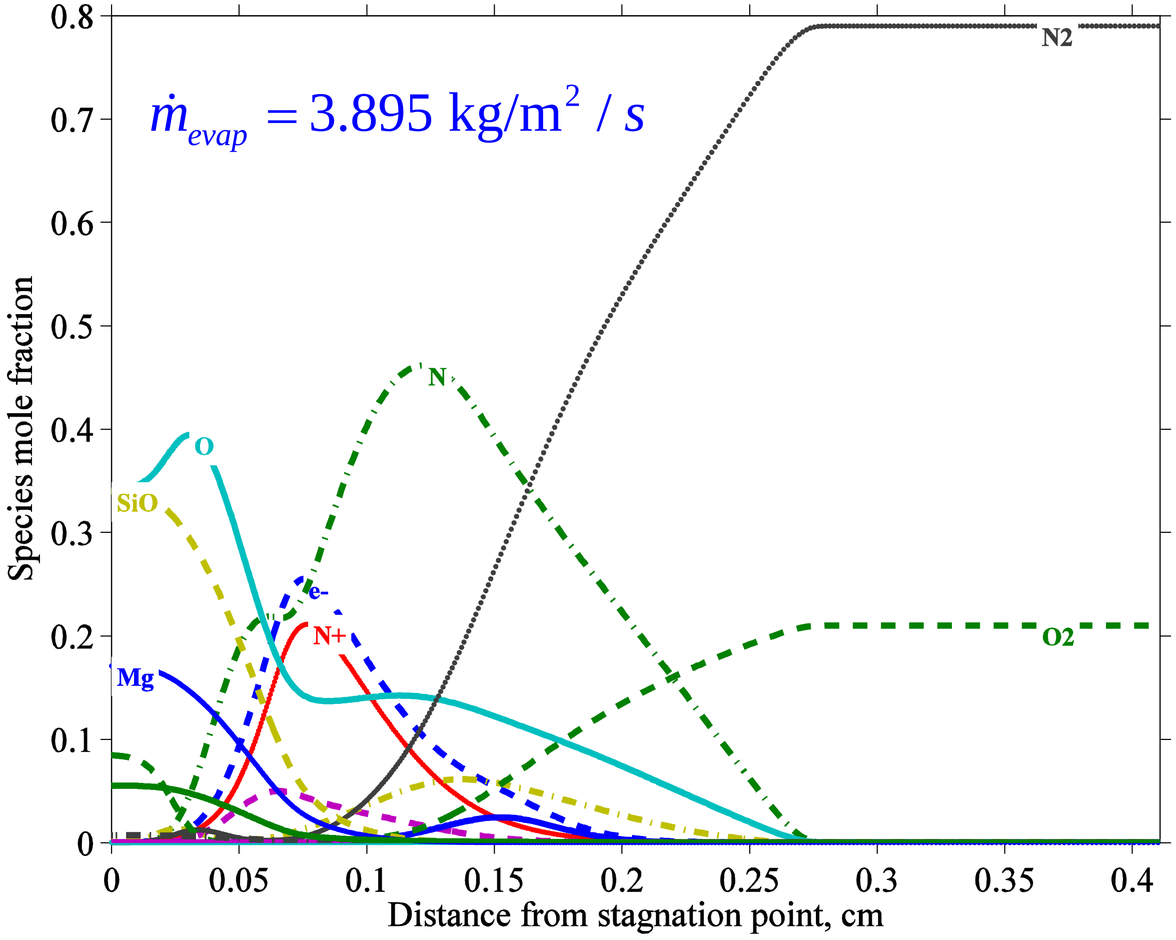


Flow field at 60 km

Temperature along stagnation streamline



Species diffusion along stagnation streamline

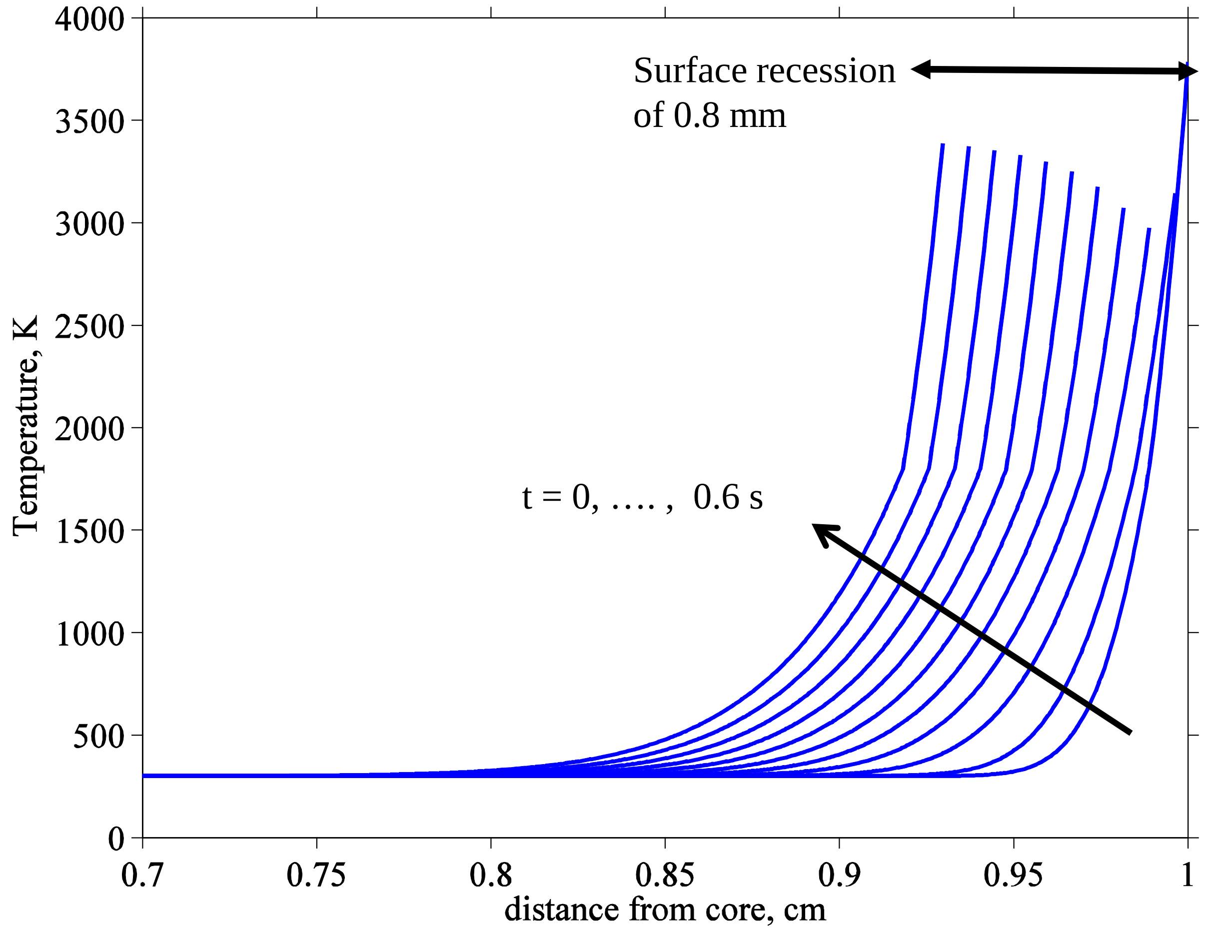


Total heat flux

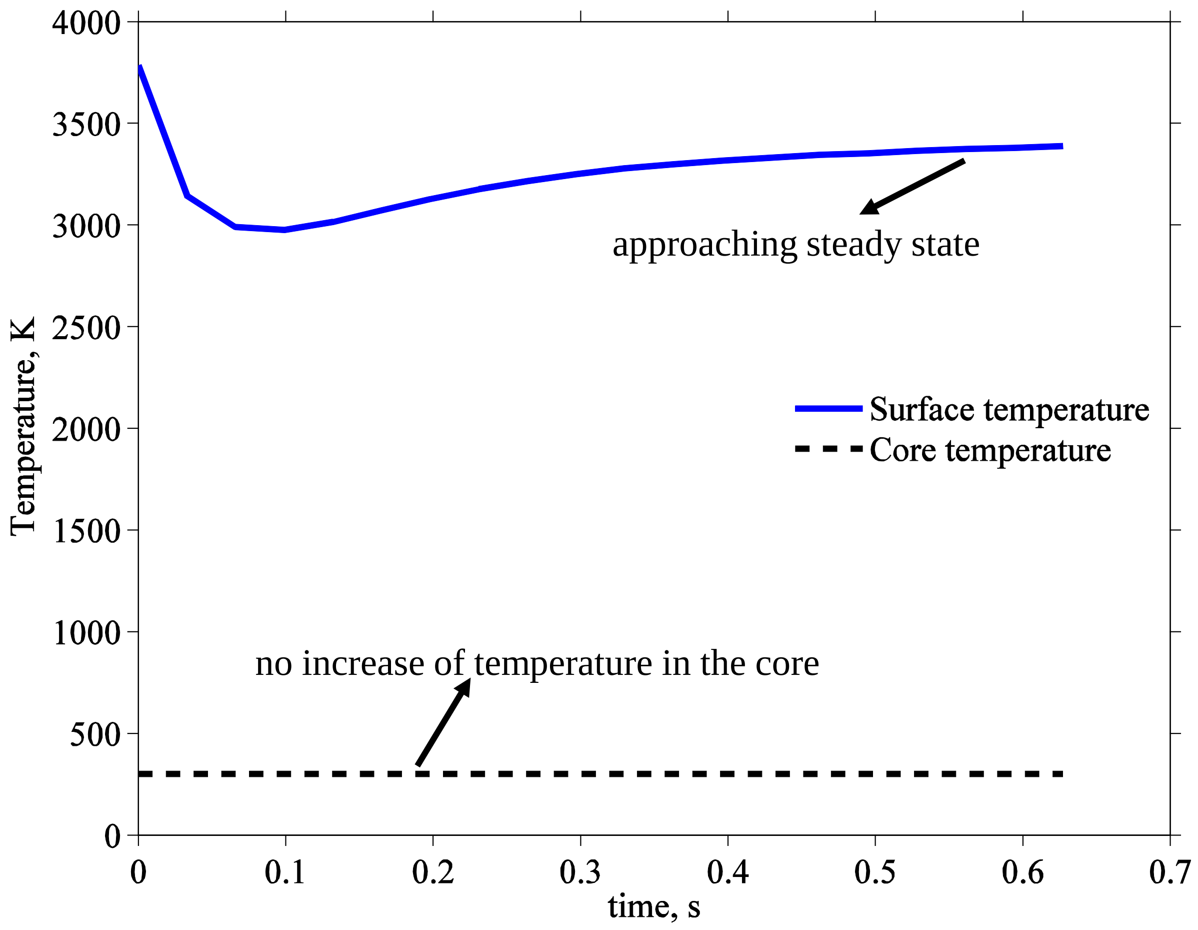
$$q_{flow} = 0.108\ MW / m^2 \quad + \quad q_{rad} = 8.527\ MW / m^2$$

Material response from 60 to 50 km (temperature)

Temperature distribution along the material

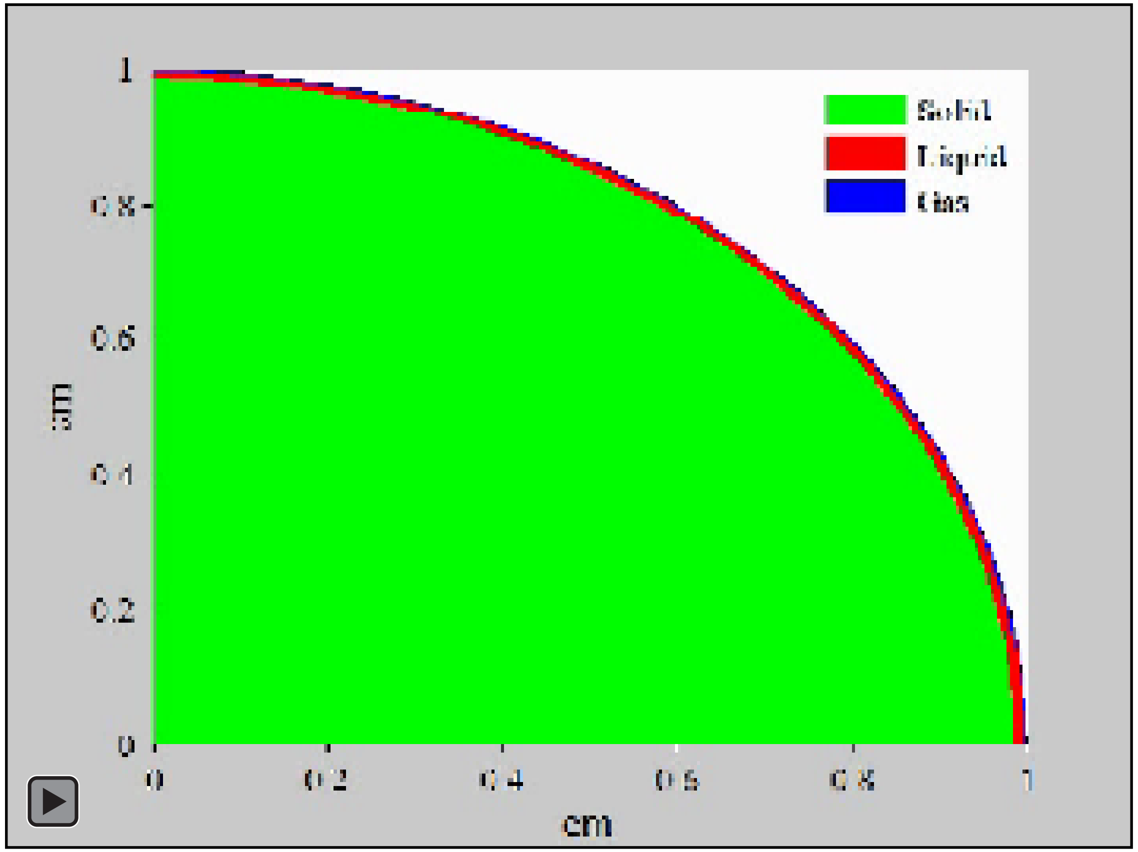


Temperature at the surface and at the core

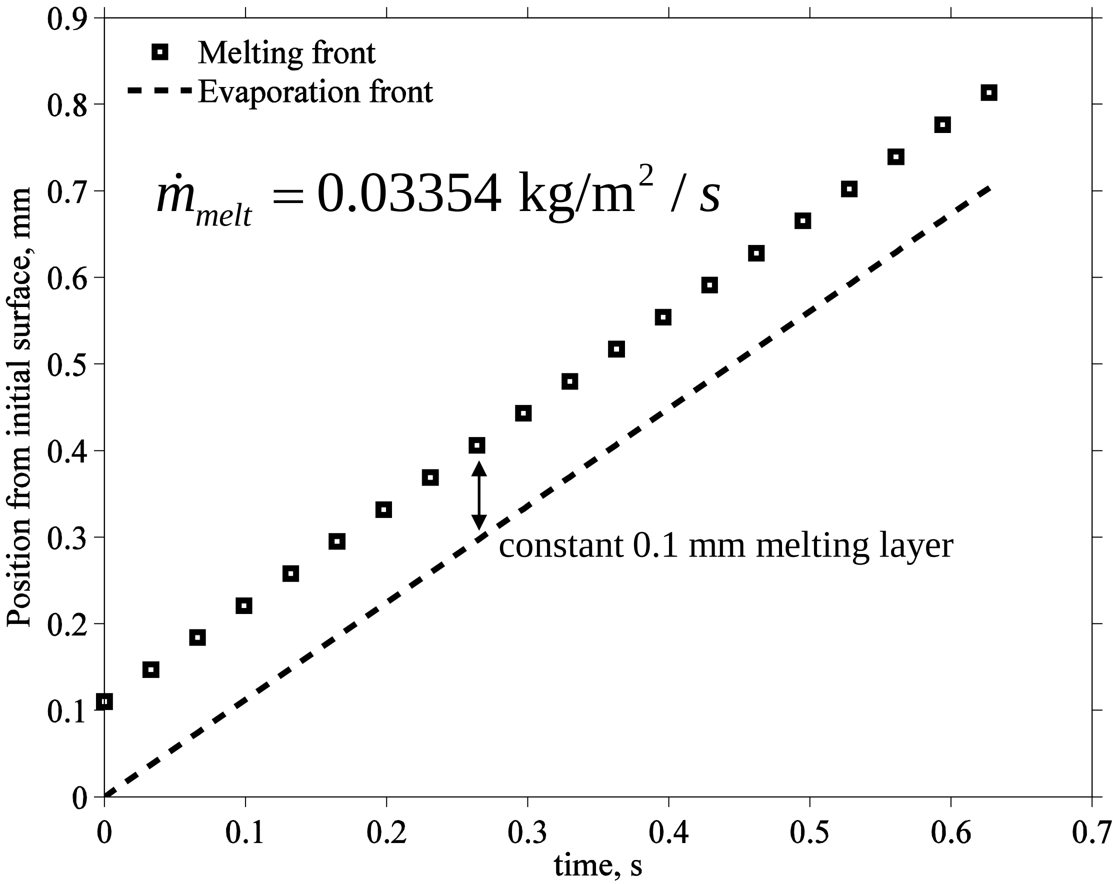


Material response from 60 to 50 km (evaporation and melting front)

Animation of moving fronts

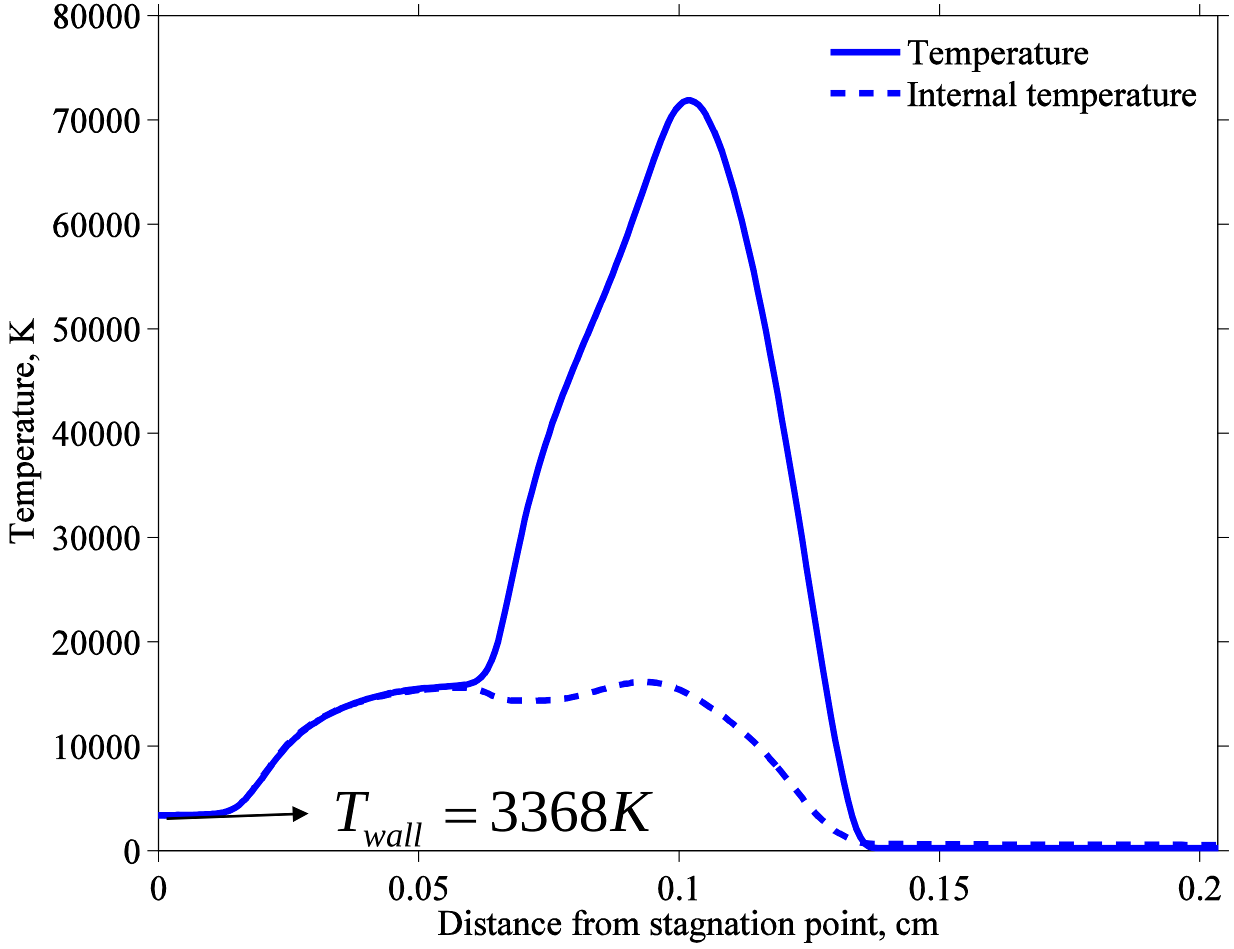


Melt and evaporation fronts

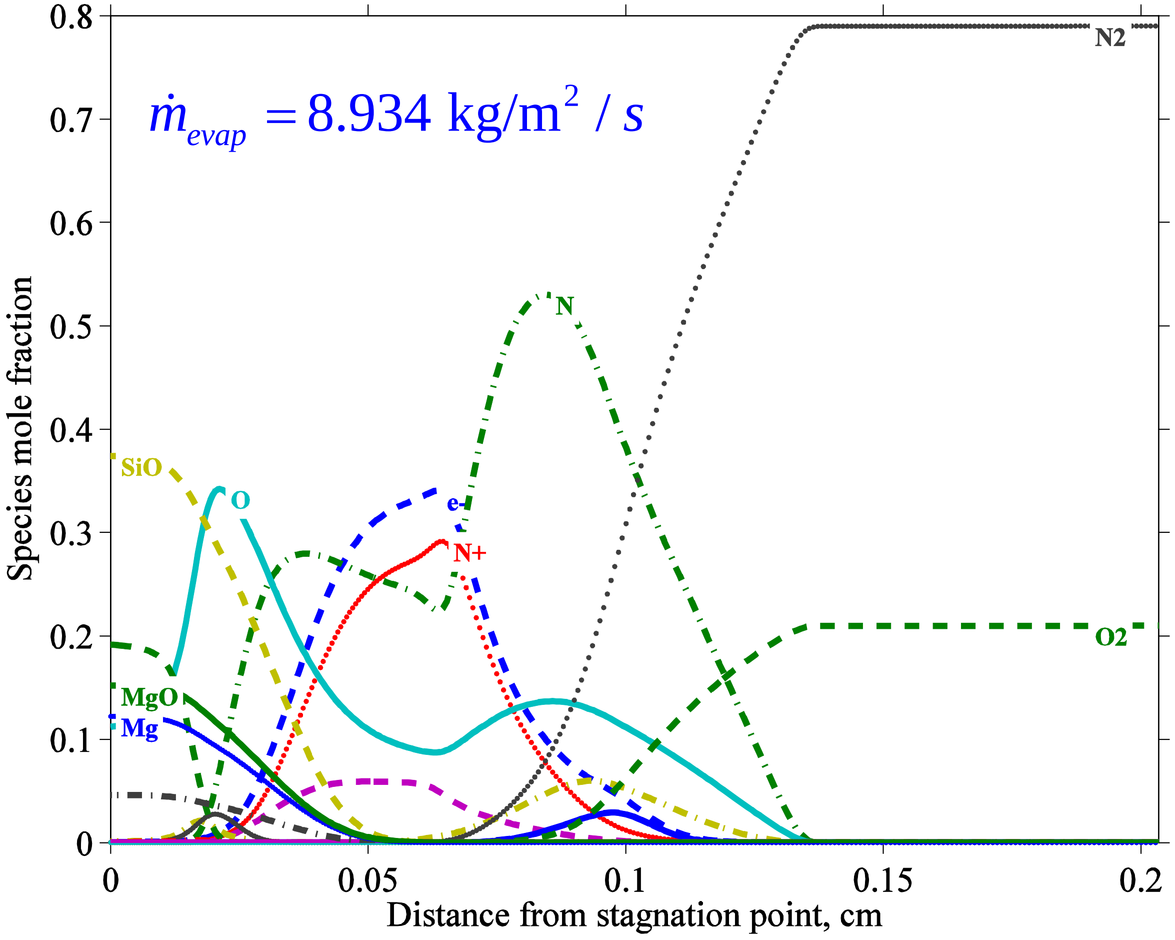


Flow field at 50 km

Temperature along stagnation streamline



Species diffusion along stagnation streamline



Total heat flux

$$q_{flow} = 0.262 MW / m^2 \quad + \quad q_{rad} = 2.415\ MW / m^2$$

Outline

- Gas-surface interaction modeling for meteors
- Flow field Modeling
- Numerical tools & results
- **Conclusion and Future Work**

Conclusion

- Tools developed at VKI for spacecraft entries have been adapted and applied to meteor entry applications:

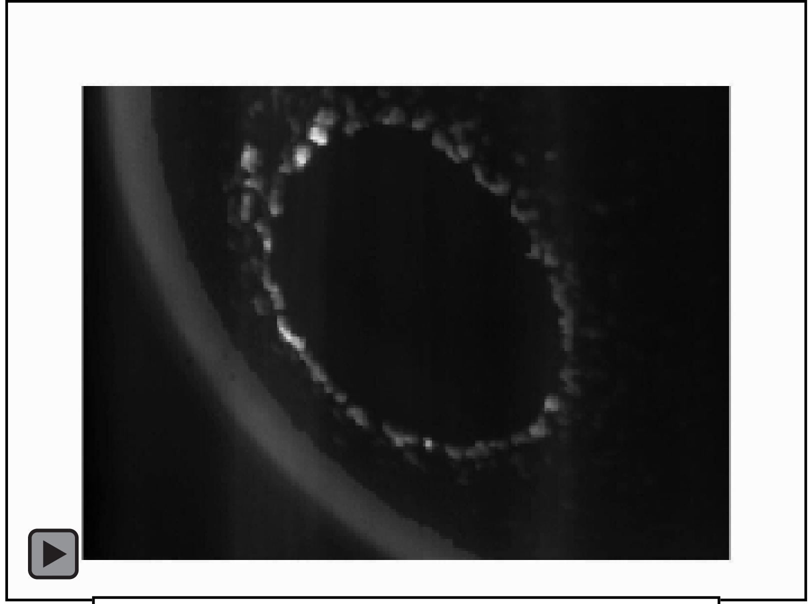
    - The study of radiation has been made with the HSNB method
    - The ablative boundary condition was developed with an approach similar to re-entry vehicles
    - The material and flow solver were coupled through an explicit procedure

- Important results have been obtained using engineering tools:

    - The initial conditions for the flow solver are very important
    - More trajectory points are needed between 60 and 50 km for the solver coupling
    - The melting layer remains very thin leading to a small mass removal
    - The major source of mass lost is through evaporation
    - During intensive evaporation the major source of heat flux is coming from the radiation

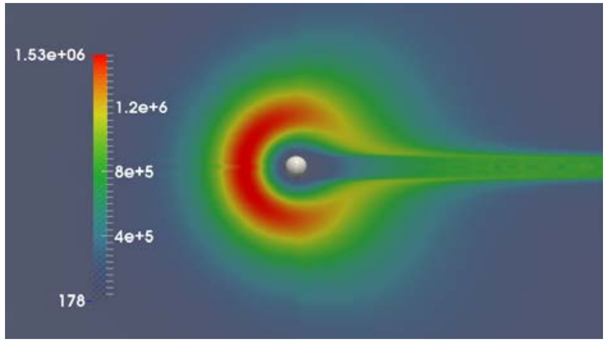
On-going work

- Experimental studies of real meteors in the Plasmatron[1]



- Study of the meteor ablation in the Argo solver[2] and comparison with experimental results

- Development of DSMC tools for higher altitudes (rarefied regimes)



[1] Zavalan, VKI RM (2016)
[2] Schrooyen, PhD thesis (2016)

Detailed flow modeling of meteor entry at low altitudes

B. Dias A. Turchi J.B. Scoggins T. Magin

Aeronautics and Aerospace Department

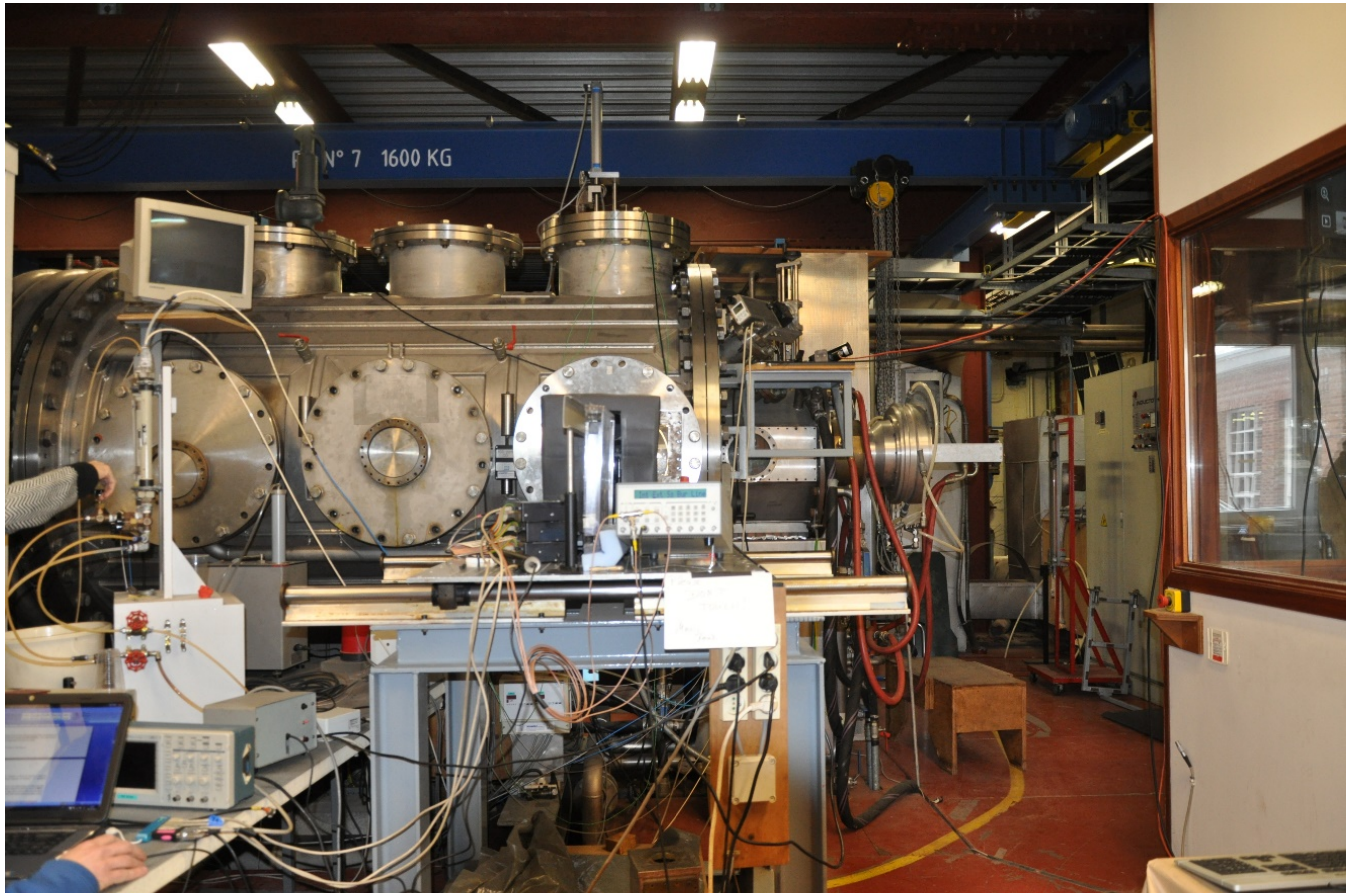
von KARMAN INSTITUTE
FOR FLUID DYNAMICS

Acknowledgment:

- Federico Bariselli
- Aldo Frezzotti
- Florentina Luiza Zavalan
- the *Belgian Research Action through Interdisciplinary Networks* (BRAIN) for the METRO: *Meteor TRajectories and Origins* project

fnrs FREEDOM TO RESEARCH

VKI Plasmatron Facility



Plasmatron Facility

Gases: Air, N_2, CO_2, Ar

Power: 1.2 MW

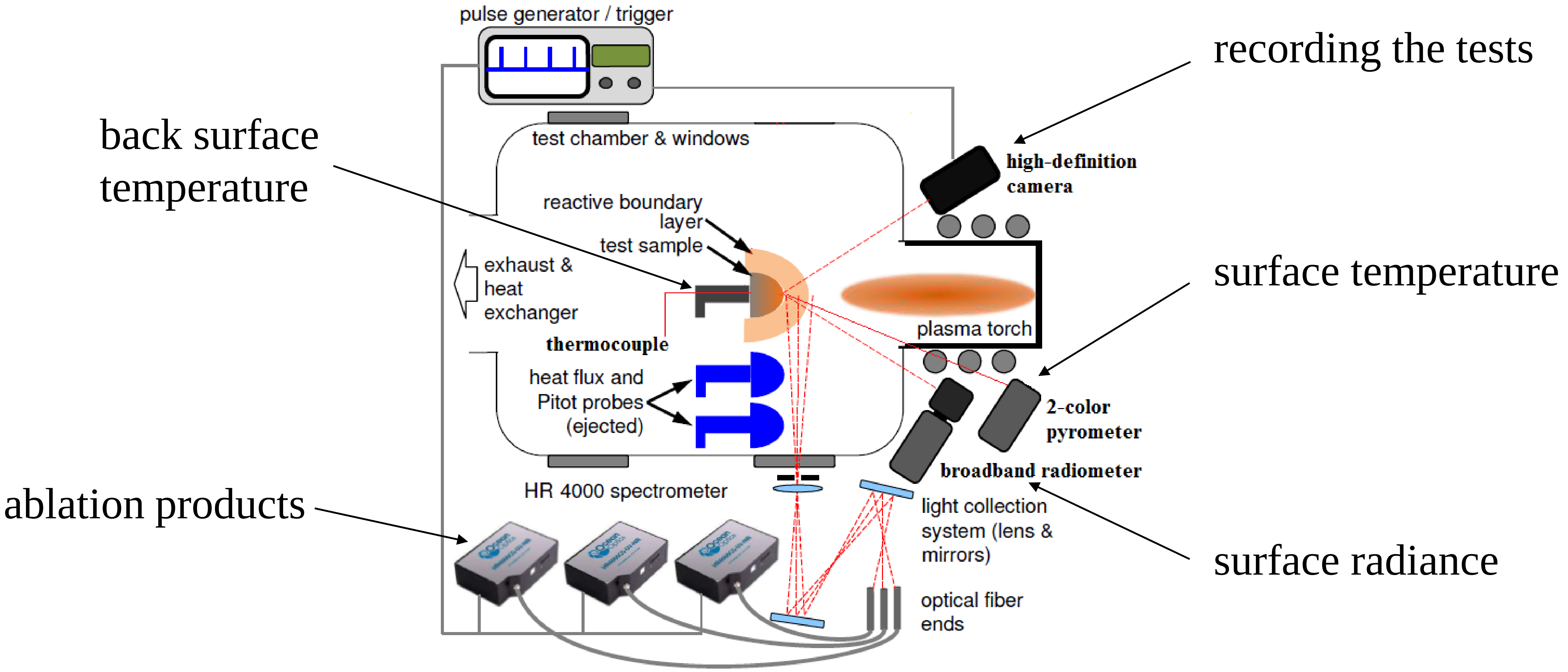
Temperature: up to 10000 K

Heat-flux:

- **Standard configuration**
  90 kW/m² – 3 MW/m²
- **Subsonic accelerated nozzle**
  up to ~ 8 MW/m²
- **Supersonic nozzle**
  up to ~ 16 MW/m²

Pressure: 1000 Pa – 22000 Pa

Experimental setup for testing meteorites



Experimental setup (B. Helber)

Description of the sample holders

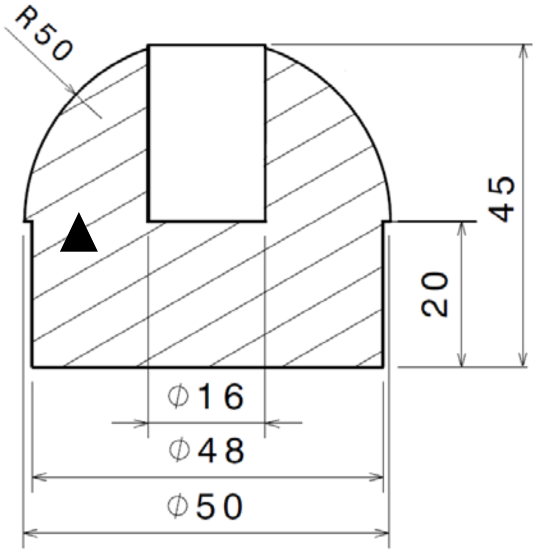
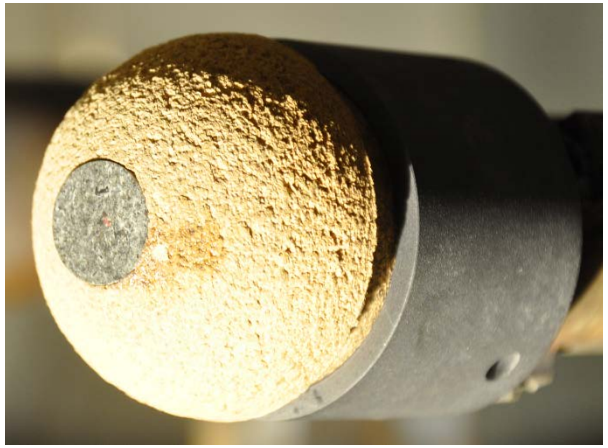
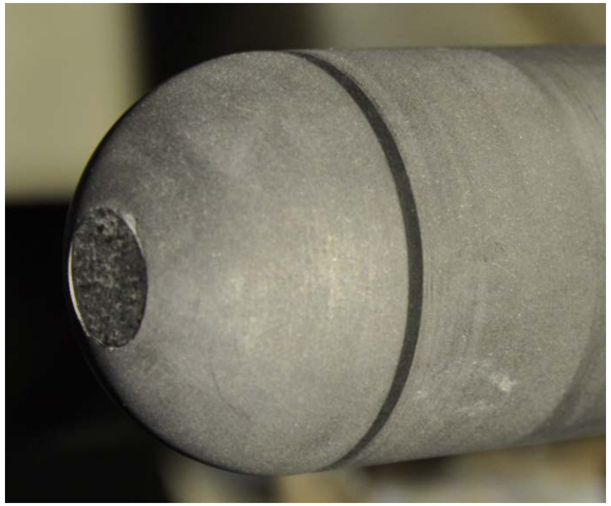


Figure 6. Hemispheric holder configuration

▲	+	–
Cork	good insulator	pollution
Graphite	less pollution	conductor



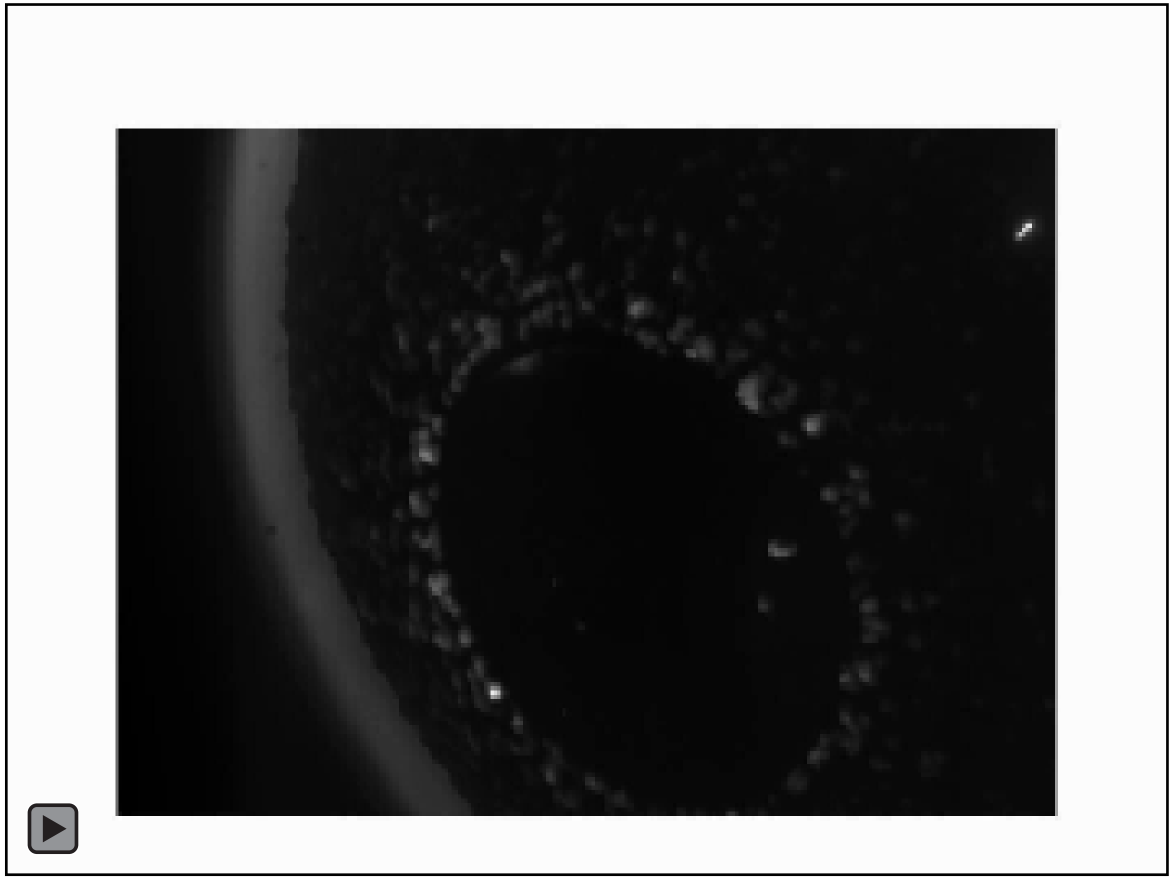
Basalt sample fixed in cork holder



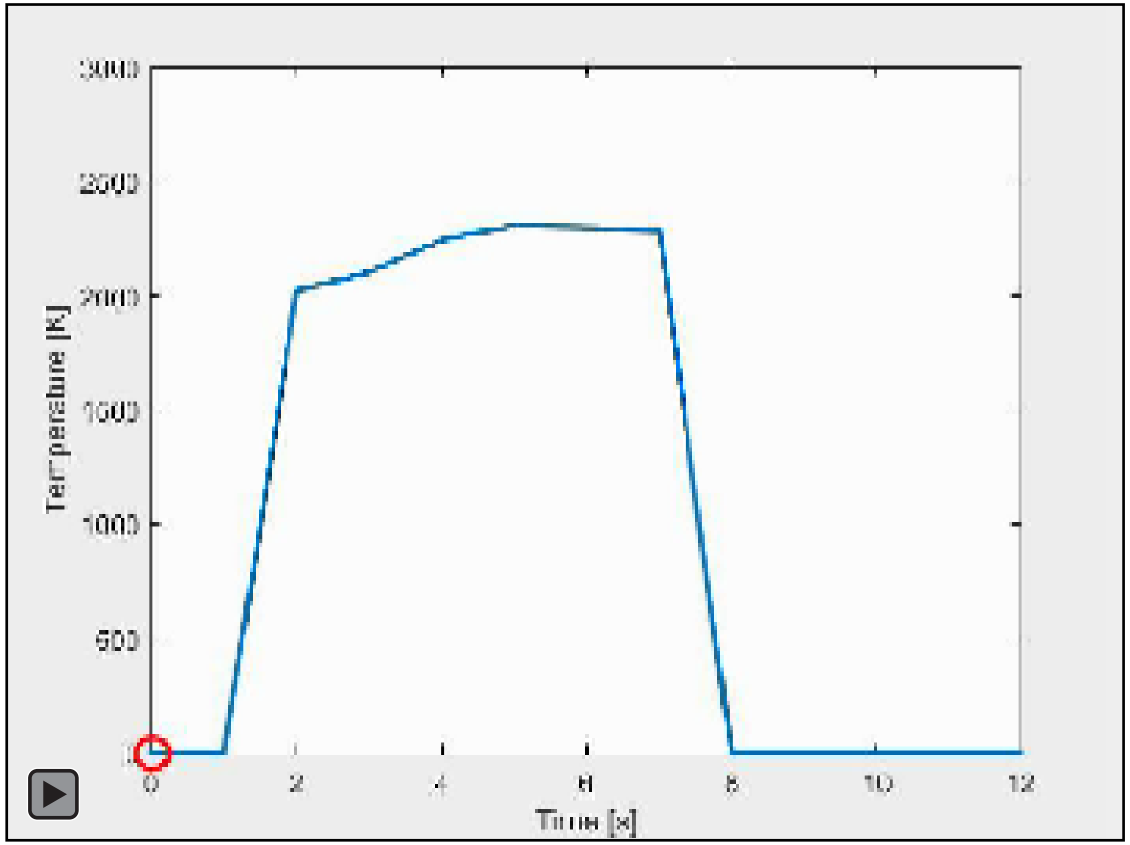
Basalt sample fixed in graphite holder

Plasmatron test with basalt (1 MW/m^2, 220 mbar)

High resolution camera

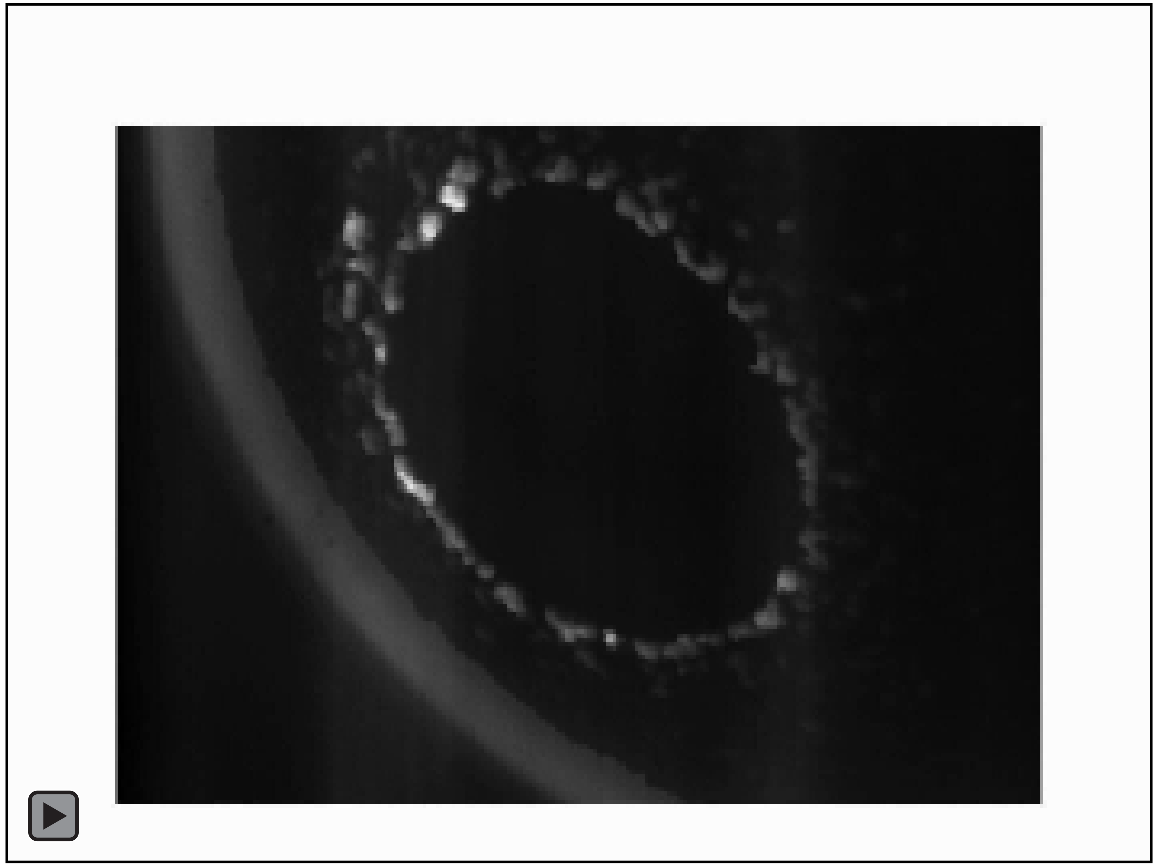


Surface temperature

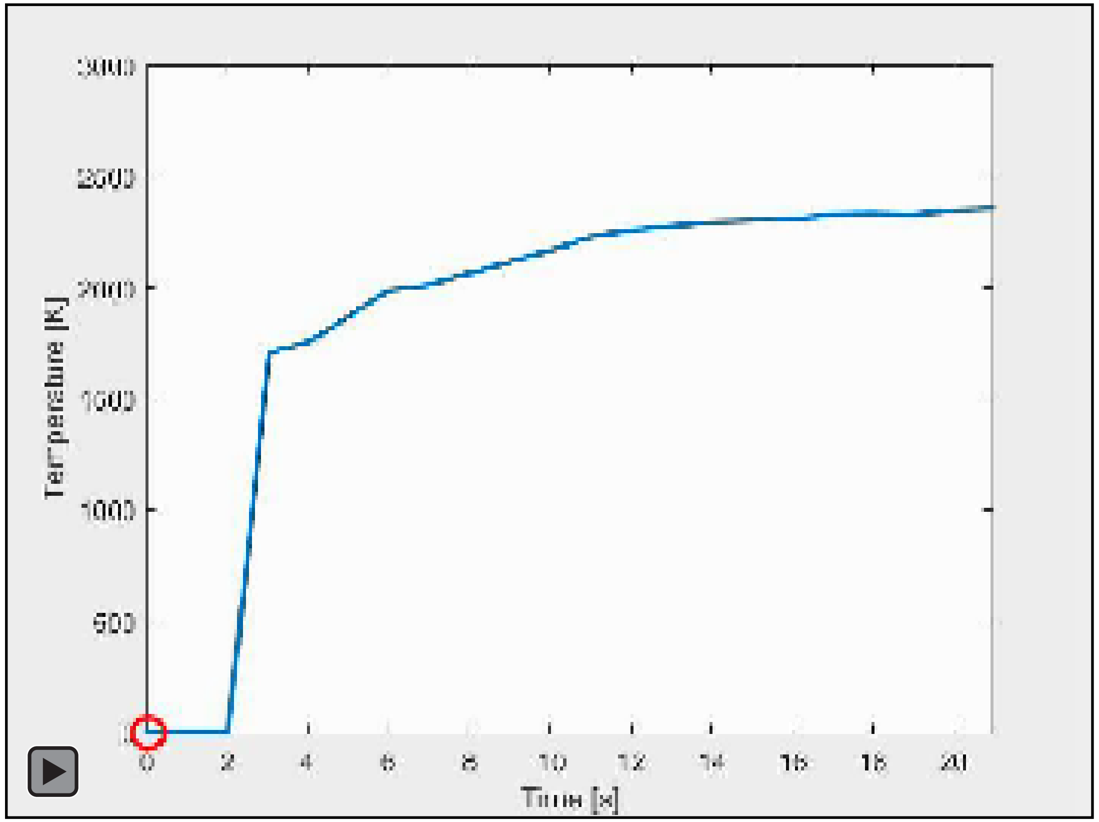


Plasmatron test with ordinary chondrite (1 MW/m^2, 220 mbar)

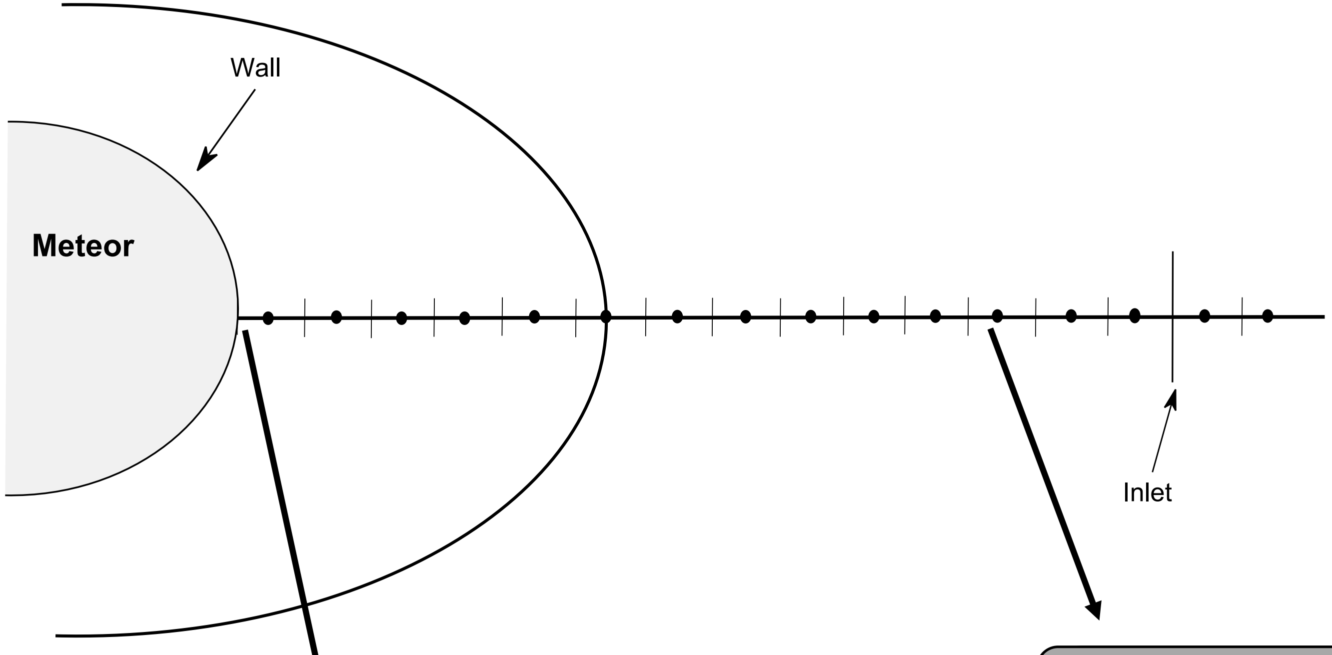
High resolution camera



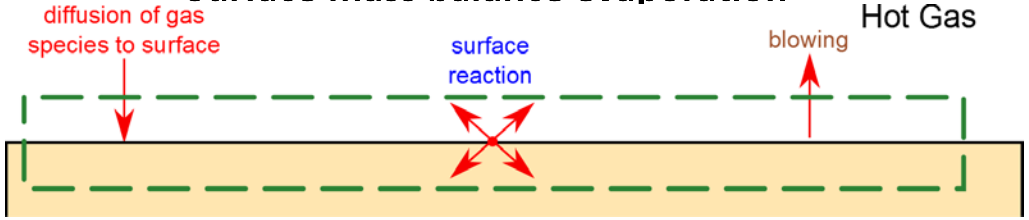
Surface temperature



Meteor ablation flow solver



Surface mass balance evaporation



Stagnation-Line Code CFD Solver [1]

- 1D Stagnation-Line solver in spherical coordinates
- Cell-centered finite volume
- Roe's Riemann solver
- Fully implicit time-integration

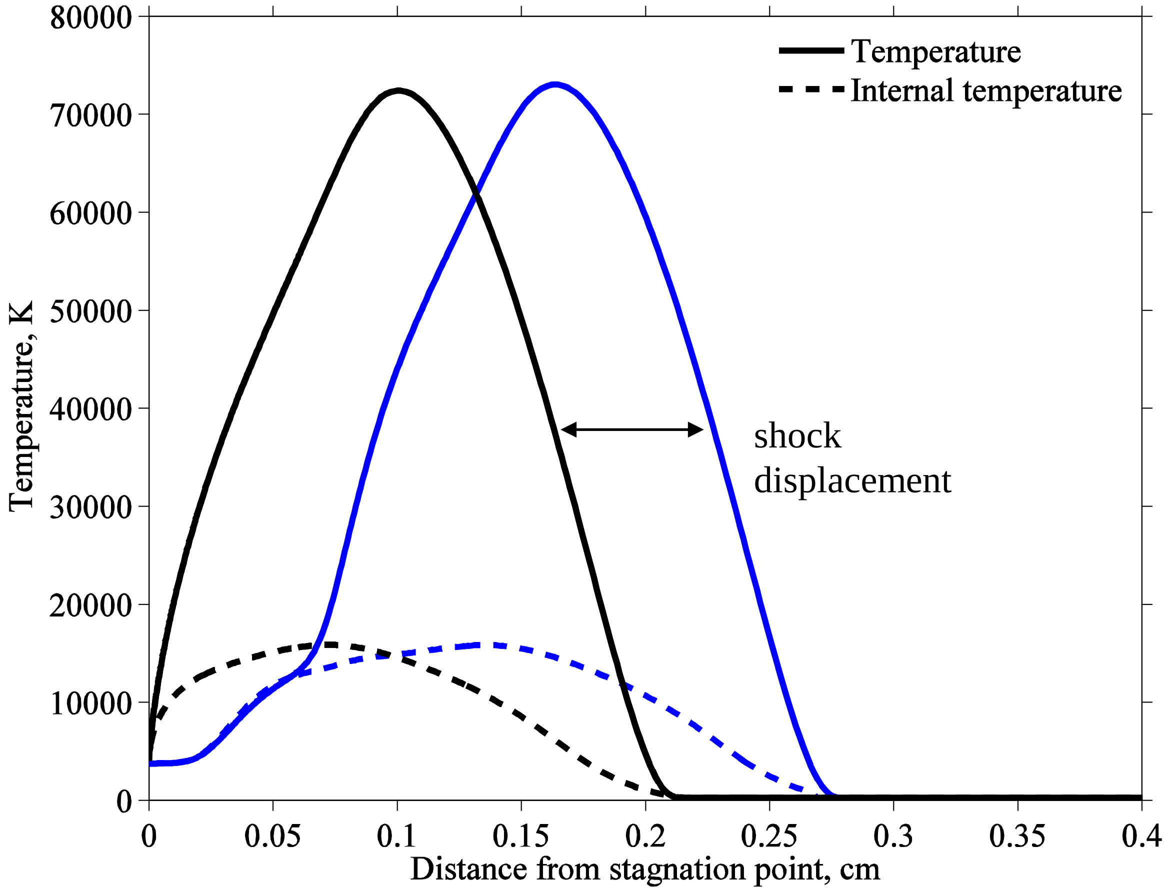
$$\frac{\partial}{\partial t}\mathbf{U} + \frac{\partial}{\partial r}\mathbf{F}^{\mathbf{inv}} + \frac{\partial}{\partial r}\mathbf{F}^{\mathbf{vis}} + \frac{\mathbf{G}^{\mathbf{inv}} + \mathbf{G}^{\mathbf{vis}}}{r} = \mathbf{S}$$

Mutation^{++} library [2]

- Thermodynamic properties : RRHO model
- Transport properties : rigorous Chapman-Enskog expansion derived from Kinetic Theory
- Air chemistry : Arrhenius law (reaction rates obtained from *Park et al,* J Thermophys Heat Tr Vol.15, No.1 (2001))
- Multiphase Equilibrium Solver : minimization Gibbs free energy[3]

[1] *Munafò et al*, Phys. Fluids 26, 097102 (2014)
[2] *Scoggins et al,* AIAA 2014-2966 (2014)
[3] *Scoggins et al, Combust. Flame* 162(12):4514-4522 (2015)

Comparison flow w/o ablation



Without ablation:

$$q_{flow} = 121.06\ MW / m^2$$

With ablation:

$$q_{flow} = 0.108\ MW / m^2$$

A surface composed by multiple constituents

Classification	Composition	Elemental composition
Simplify Ordinary Chondrite	SiO_2: 0.606 MgO: 0.394	Si: 0.232 Mg: 0.152 O: 0.616

Meteor surface properties

How to compute $y_{k,w}$ for a multi element surface?[1]

Multiphase Equilibrium solver[2]

- Multiphase Gibbs function continuation (MPGFC)[3]
- Impose any linear constraint to the system:

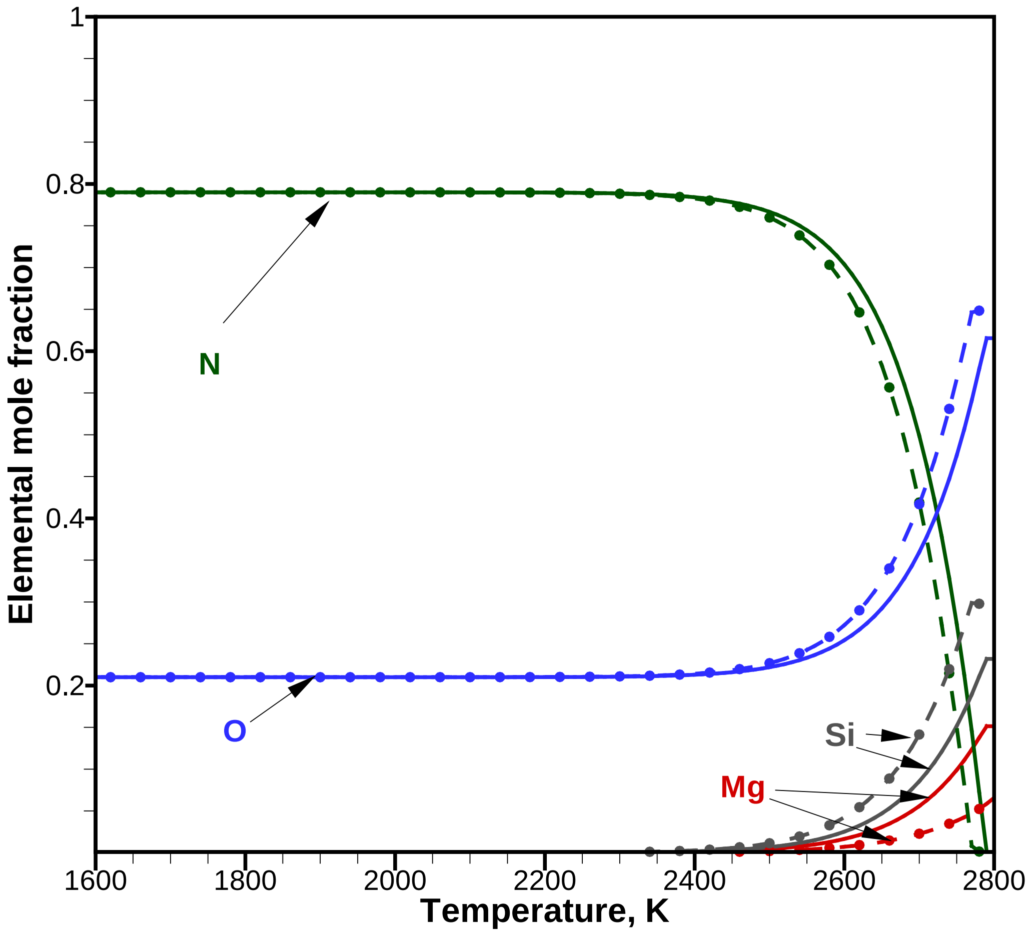
$$\frac{x_{Si}}{x_{Mg}} = const$$

[1] First addressed by *Milos et al*, AIAA 97-0141 (1997)

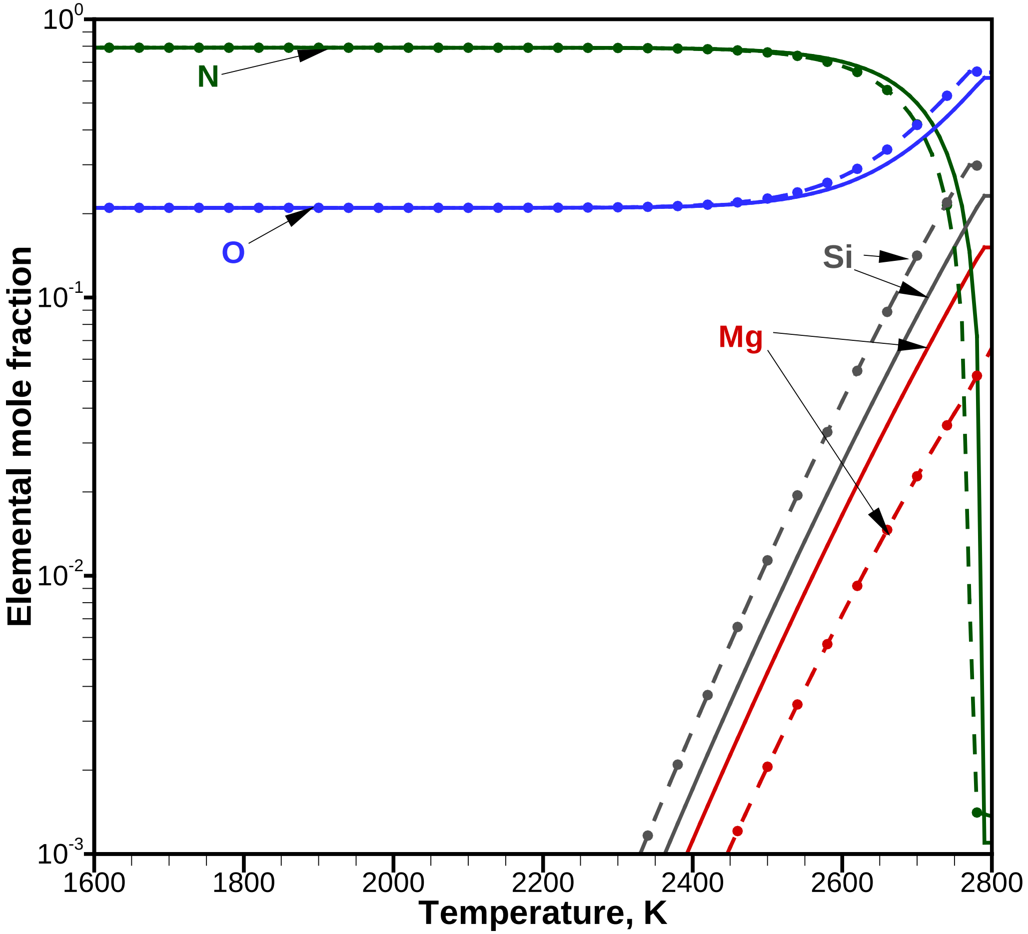
[2] Developed by *Scoggins et al,* Combust. Flame 2015

[3] Extension Gibbs Function Continuation(GFC) by *Pope et al,* FDA 03-02 (2003)

Multi species surface equilibrium



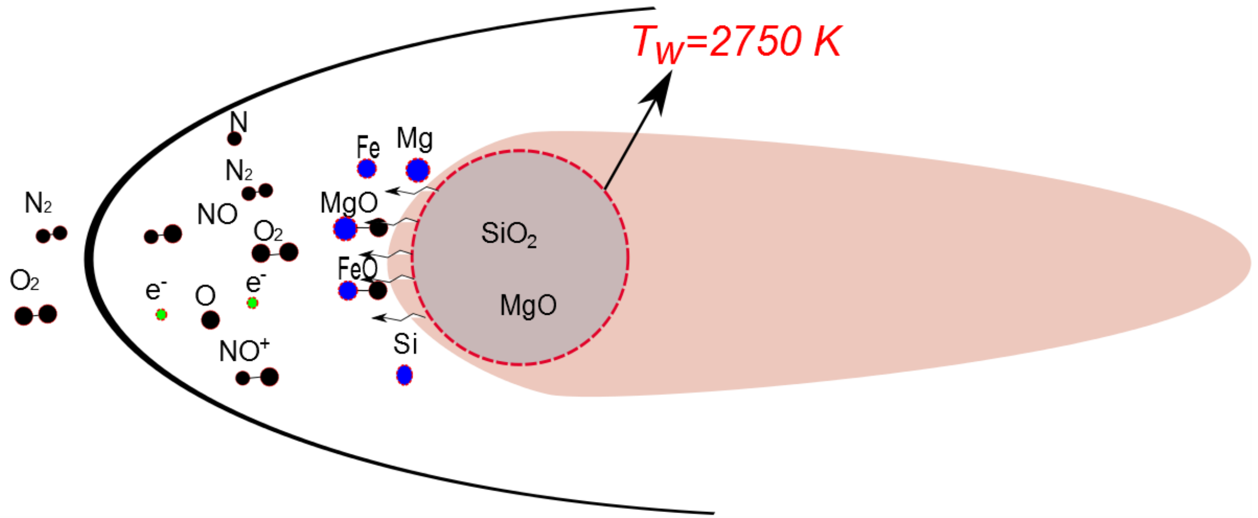
Constraint vs Unconstrained

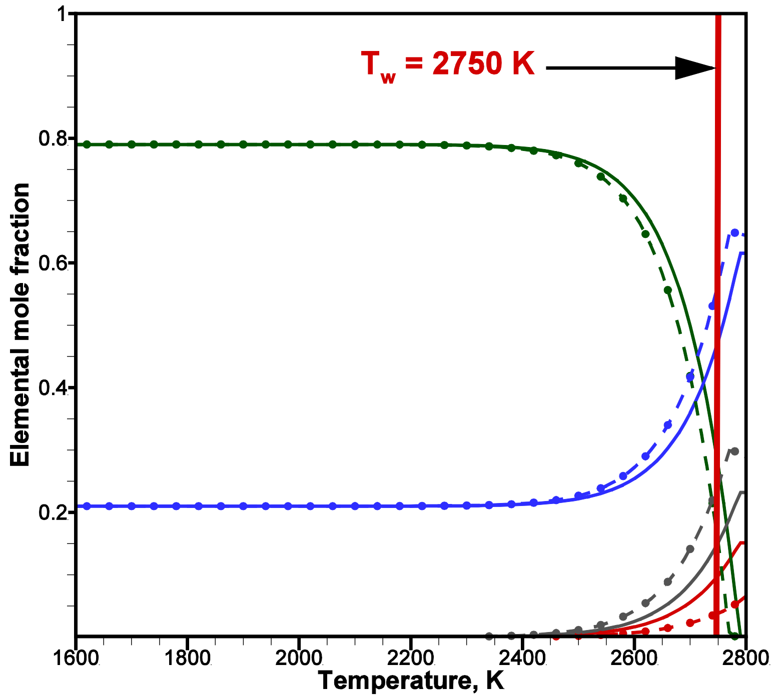


Constraint vs Unconstrained (log scale)

Gaseous Elemental mole fraction vs Temperature, 0.09 atm;
—— constrained, –•– unconstrained equilibrium

Lets analyze the flow with ablation products using Mutation^{++}...





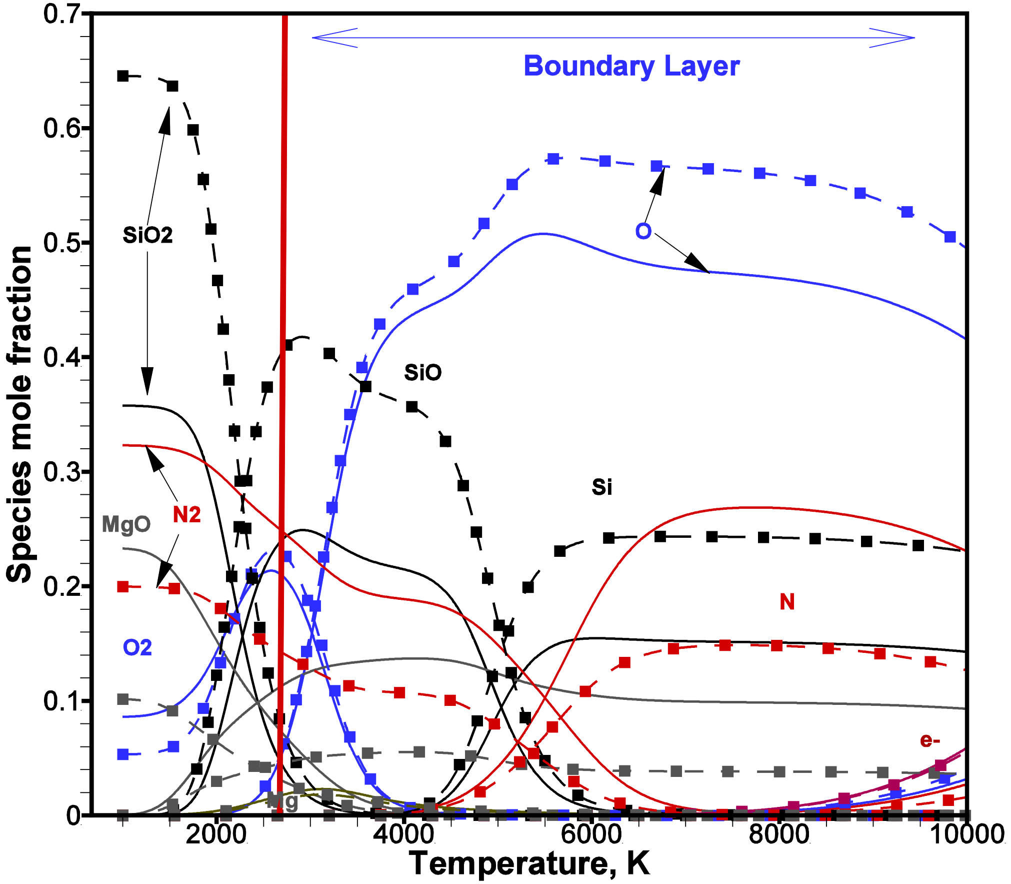
unconstrained elemental composition:

- N : 0.151
- O: 0.566
- Mg: 0.03
- Si: 0.244

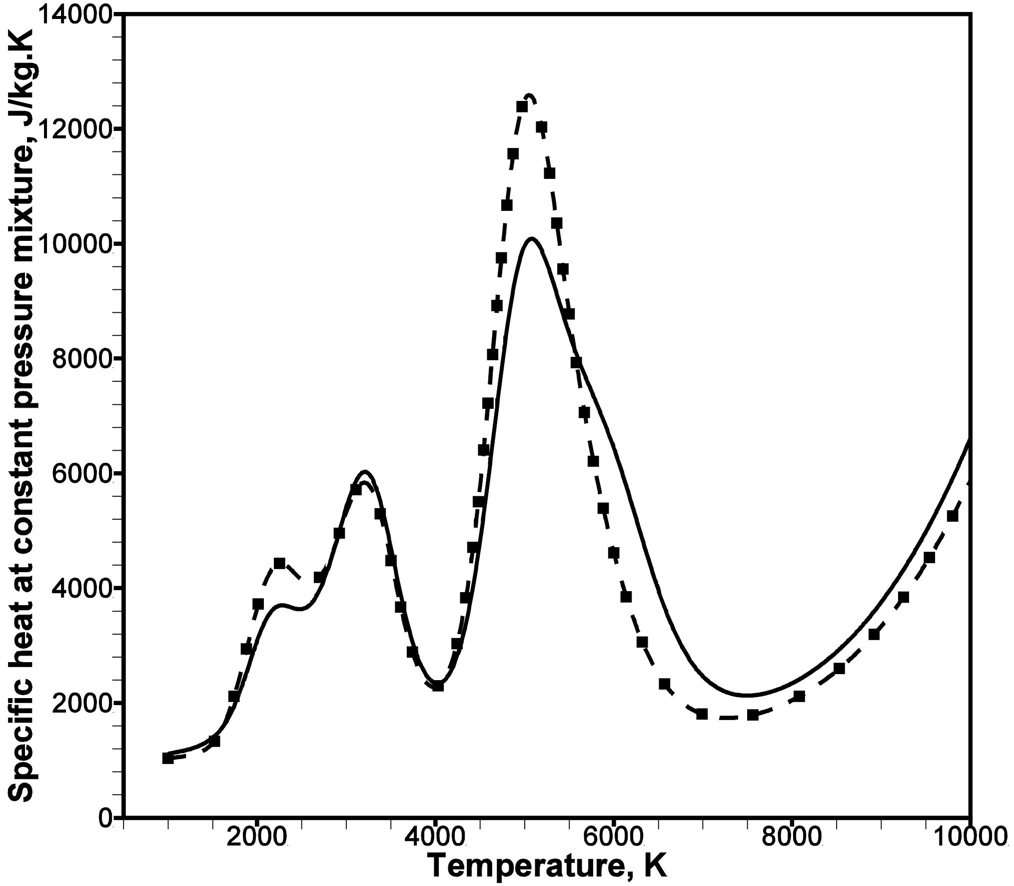
constrained elemental composition:

- N : 0.2740
- O: 0.4752
- Mg: 0.0989
- Si: 0.1517

Thermodynamic properties Mutation^{++} unconstrained vs constrained equilibrium



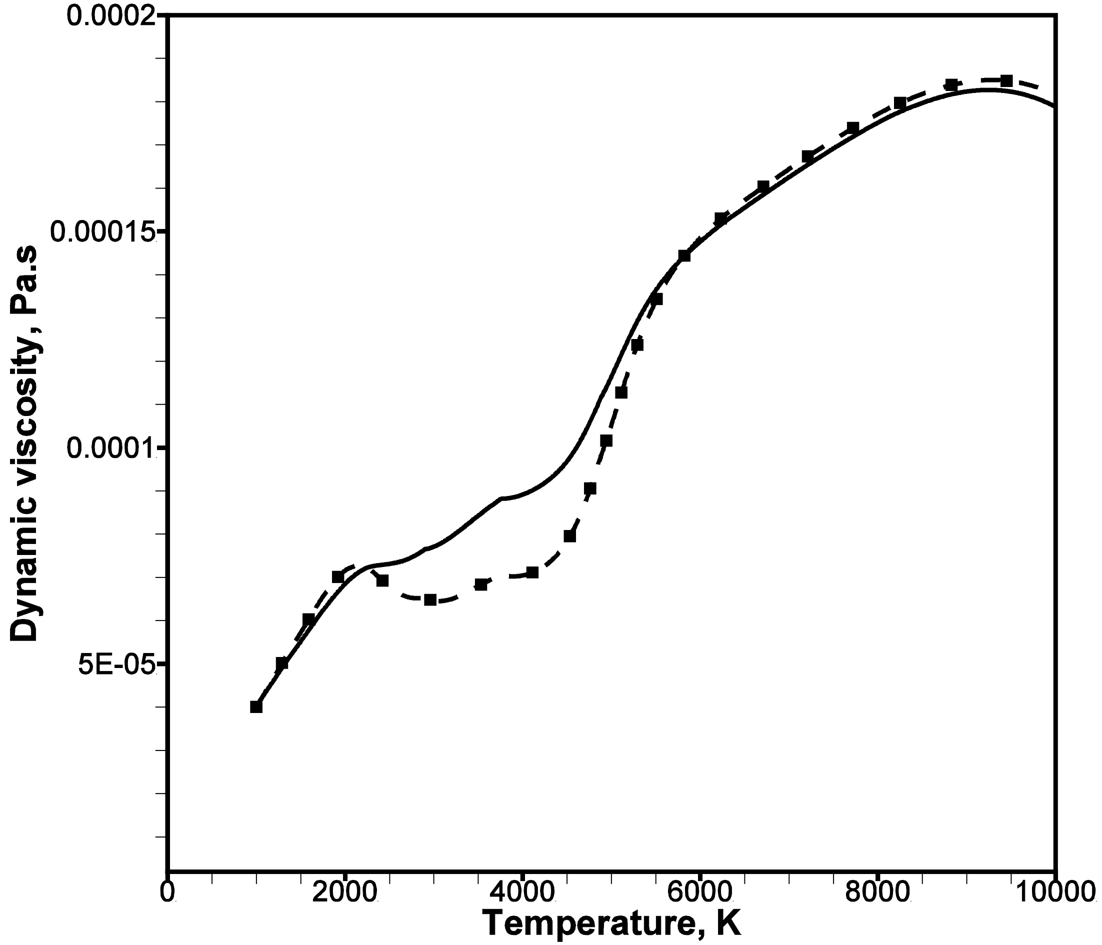
Gases equilibrium composition, 0.09 atm



Specific heat at constant pressure, 0.09 atm

constrained, –■– unconstrained equilibrium (Mutation^{++})

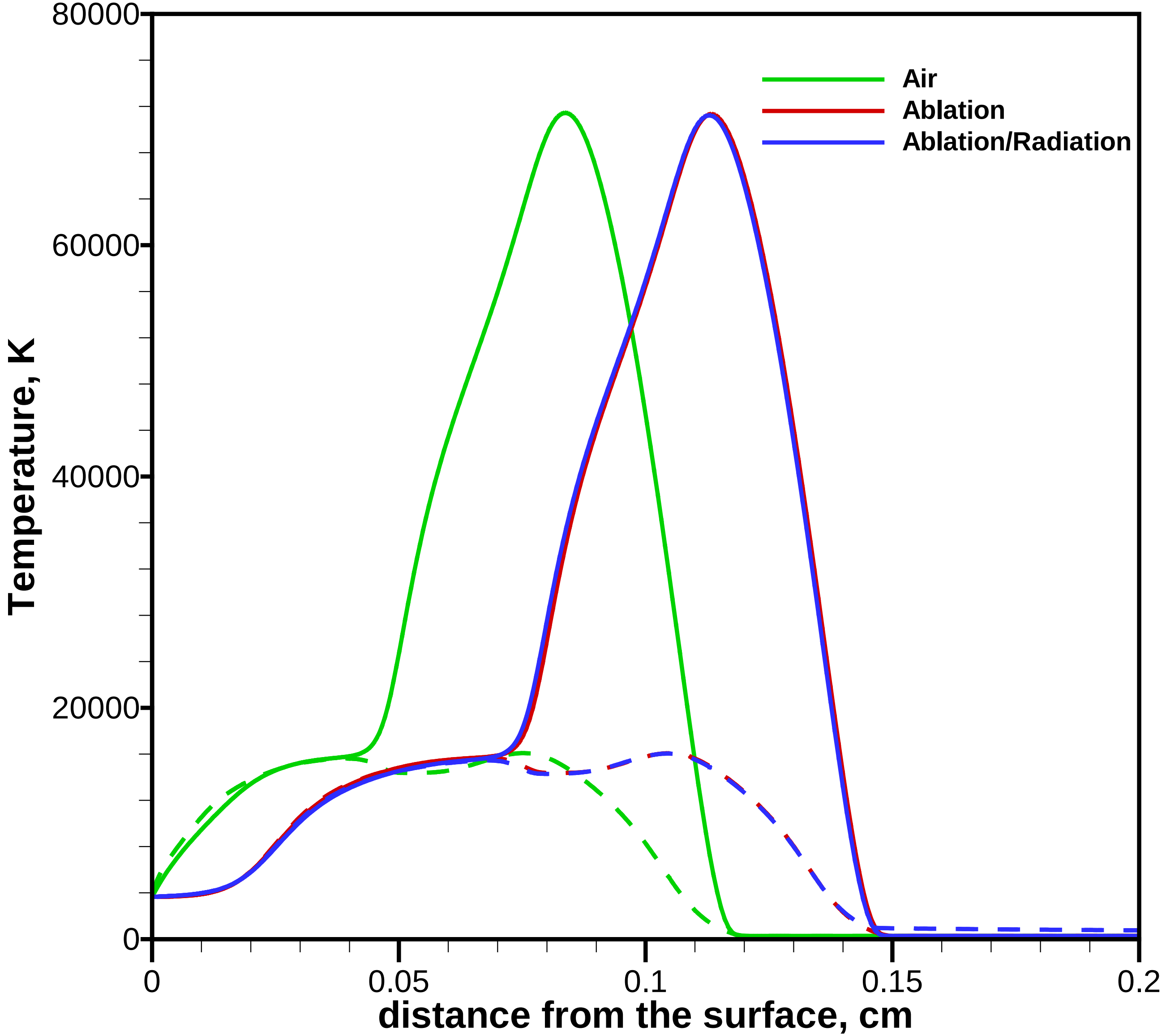
Transport properties Mutation++...

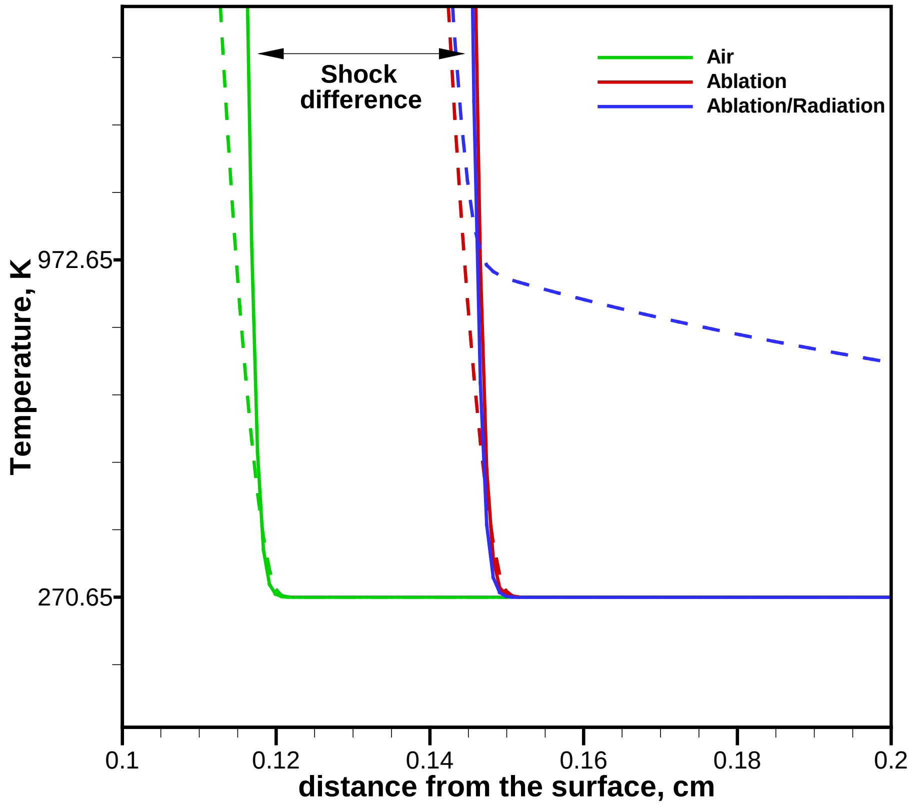


Dynamic viscosity, 0.09 atm

Temperature along stagnation streamline

Translational temperature ——— and internal temperature - - -

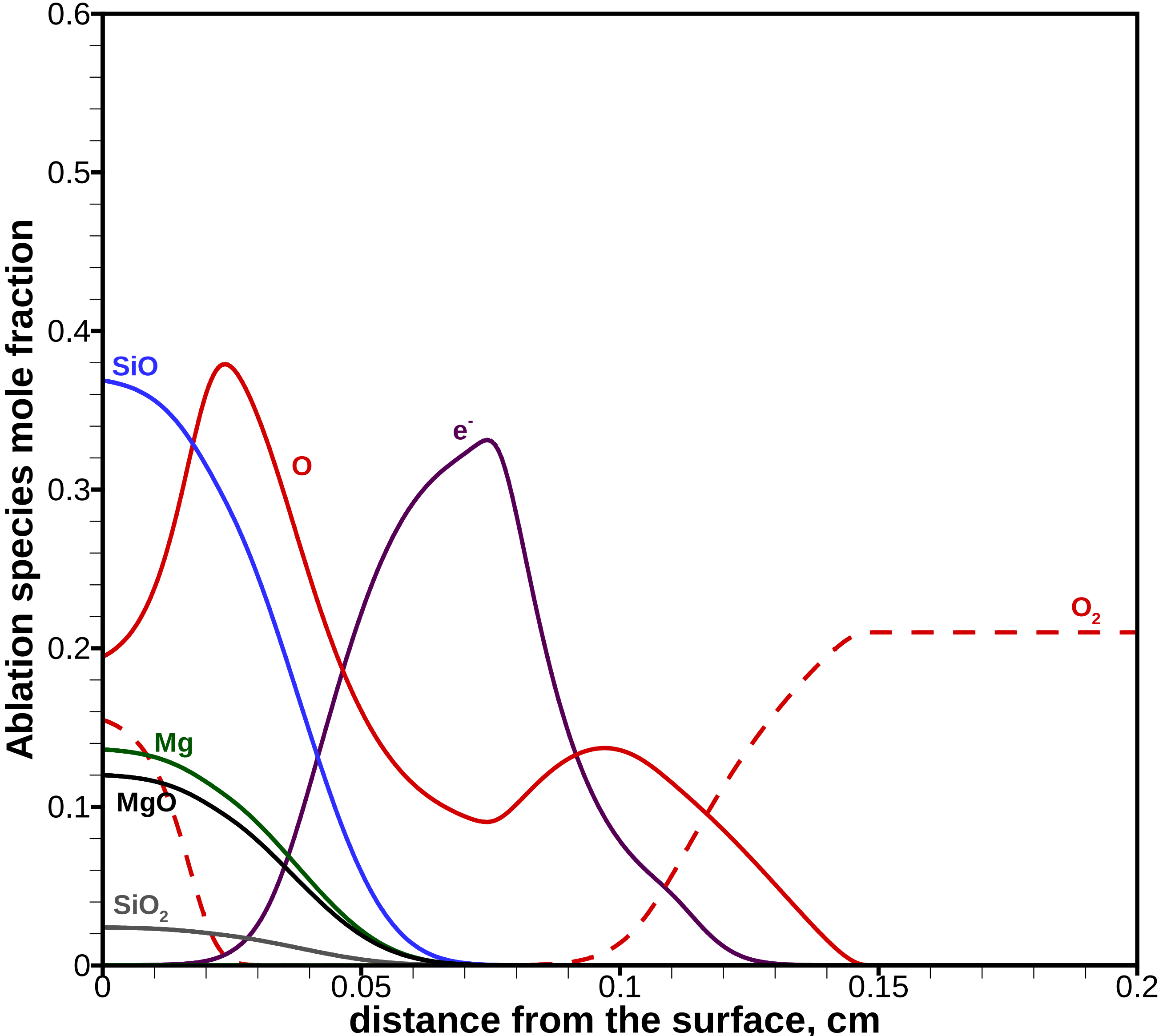


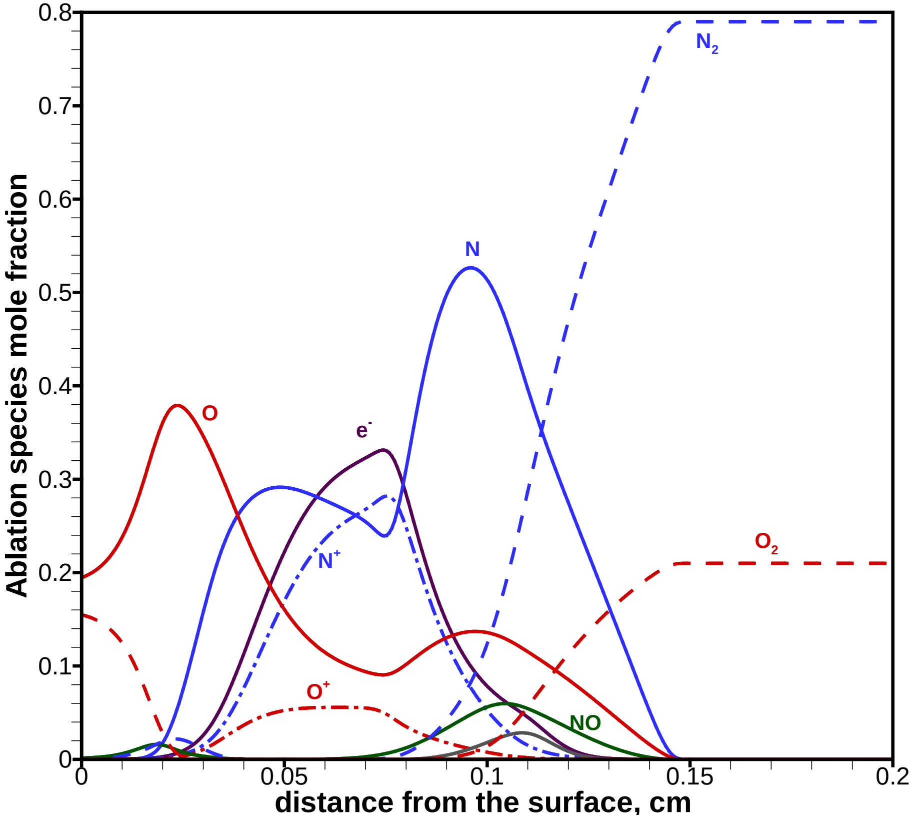


$$T_w = 3645\ K$$

Composition along stagnation streamline

Species diffusion





$$\dot{m} = 9.54\ \mathrm{kg/m^2/s}$$

To summarize the ablation properties:

r = 1 cm

$$\rho = 2800 \text{ kg/m}^3$$

$$\dot{m} = 9.54 \text{ kg/m}^2\text{/s} \rightarrow \text{mass lost} = 11.9 \text{ g/s}$$

Meteor

To summarize the ablation properties:

r = 1 cm

$$\rho = 2800\ \text{kg/m}^3$$

$$\dot{m} = 9.54\ \text{kg/m}^2\text{/s} \rightarrow \text{mass lost} = 11.9\ \text{g/s}$$

Meteor