Development of evaporation and melting models for meteor phenomenon in the continuum regime

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Annual BRAIN-BE meeting : METRO

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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)

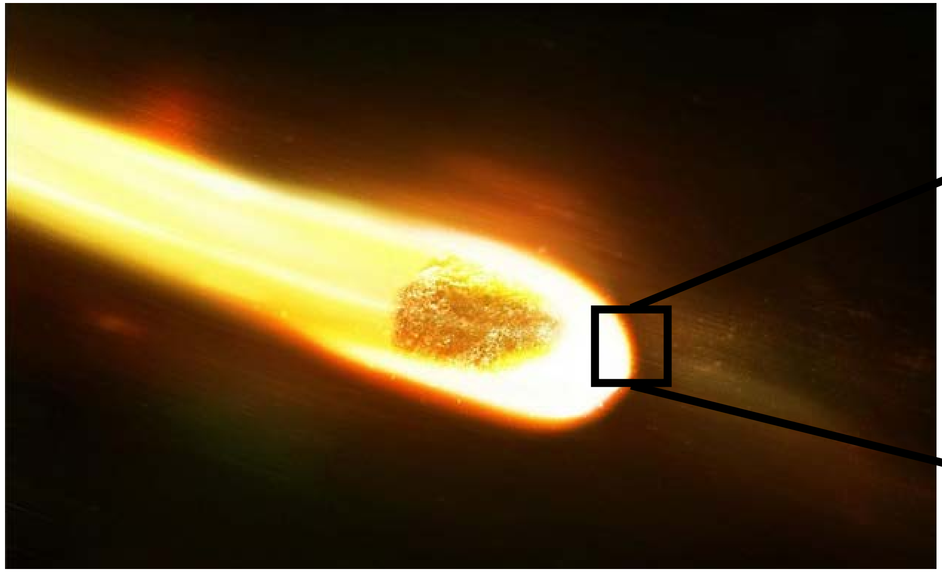
50 -100 tonnes of meteor enter in the earth's atmosphere per day

- **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

The meteor phenomena … it melts (heat shields don't)



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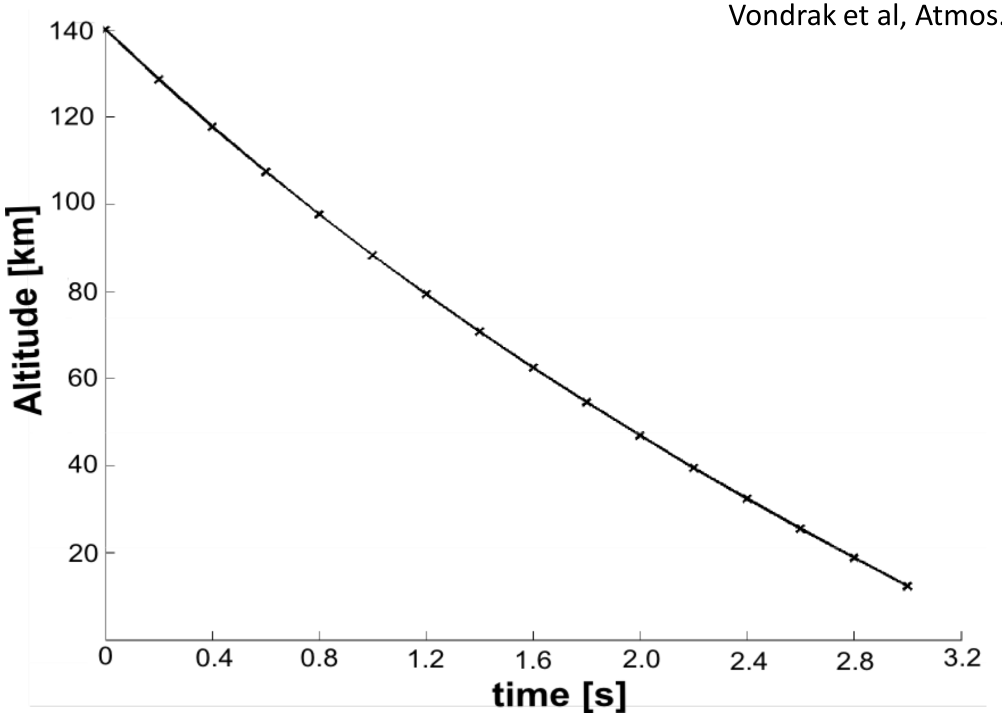
Oxides at high temperatures

(surface temperature > fusion temperature)

State-of-the-art model for meteor entry phenomena

Trajectory: $$\frac{dV}{dt} = -\Gamma V^2 \frac{3\rho_a}{4\rho_m R} + \rho_m g$$

Vondrak et al, Atmos. Chem. Phys., 2008



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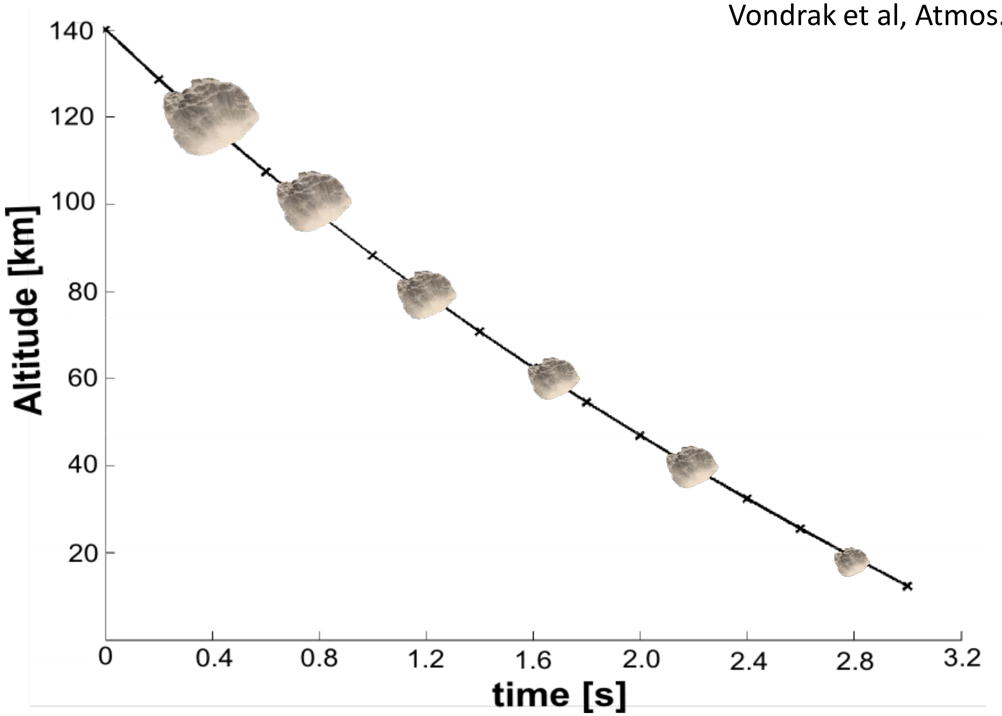

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Energy Balance: $$\frac{1}{2}\pi R^2 V^3 \rho_a \Lambda = 4\pi R^2 \varepsilon\sigma(T^4 - T_{env}^4) + \frac{4}{3}\pi R^3 \rho_m C \frac{dT}{dt} + L\frac{dm}{dt}$$

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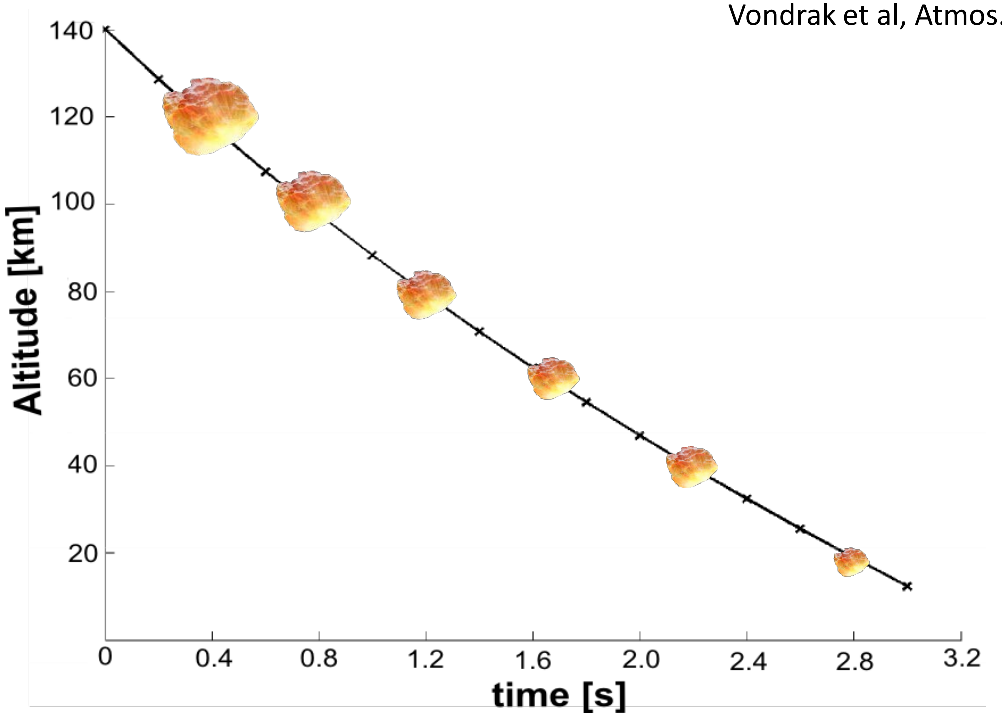

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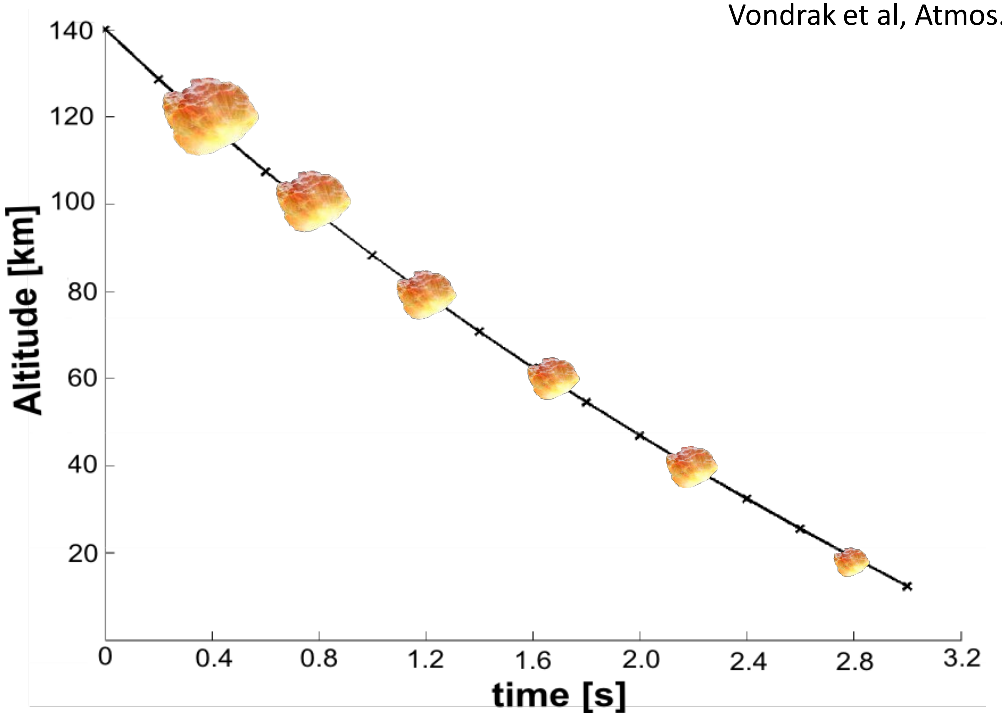
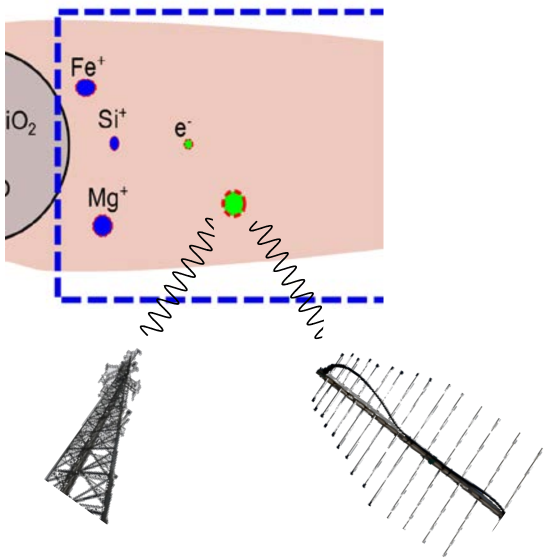




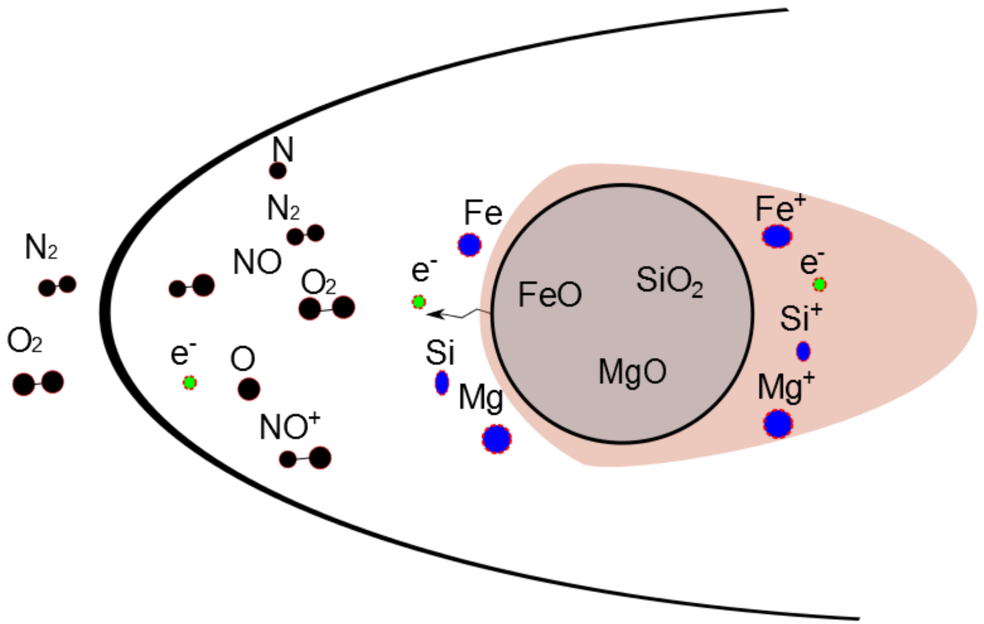
no prediction of the electron concentration

Objectives

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

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

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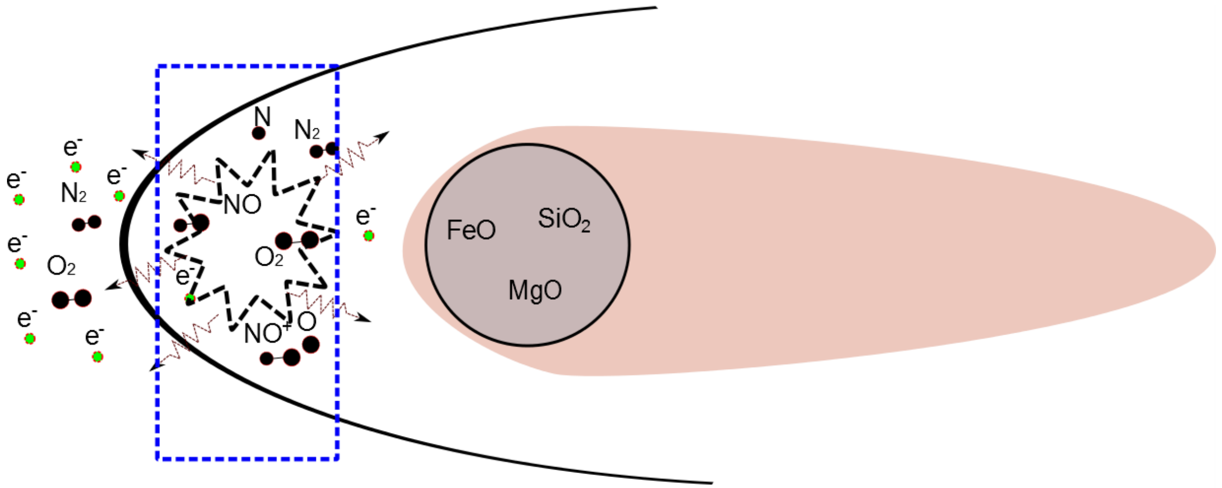
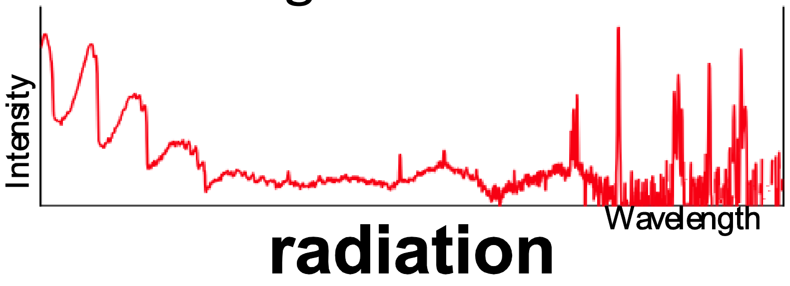
Flow field modeling

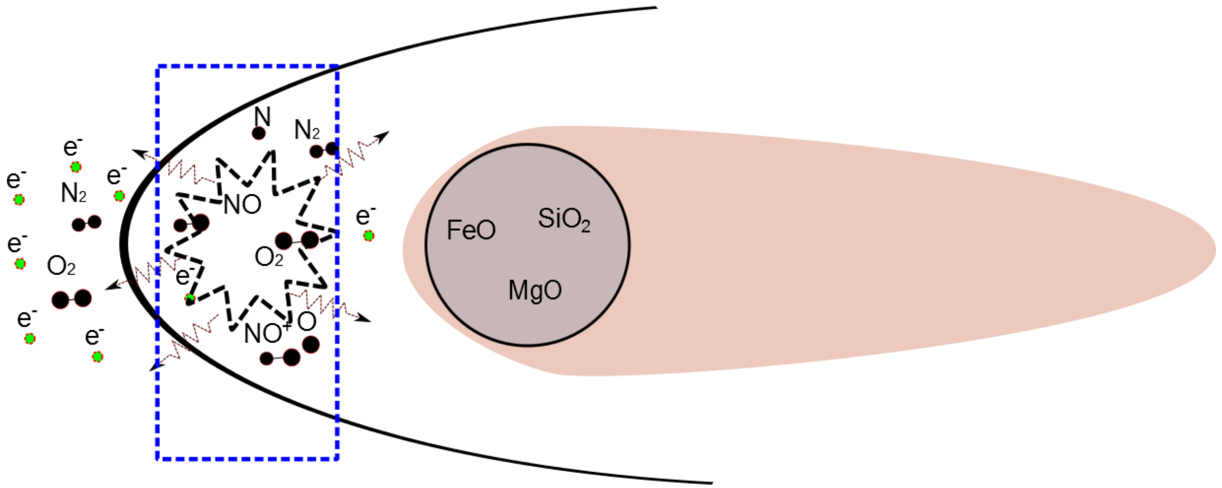


- High entry velocity (11.2 –72.5 km/s)
- High temperatures (*e.g.* 120,000 K): thermal non-equilibrium effects
- Complex chemical reactions (e.g. dissociation and ionization)
- High radiative field: computational expensive



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

Flow field modeling



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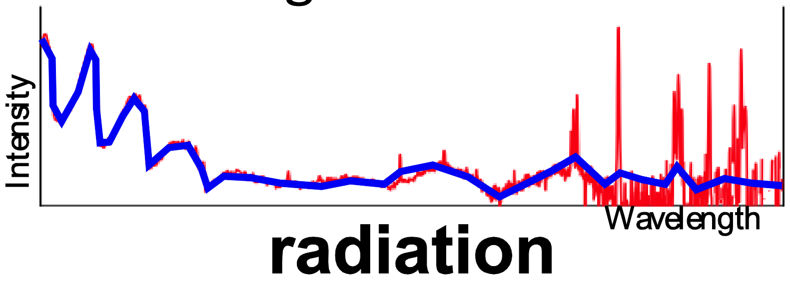
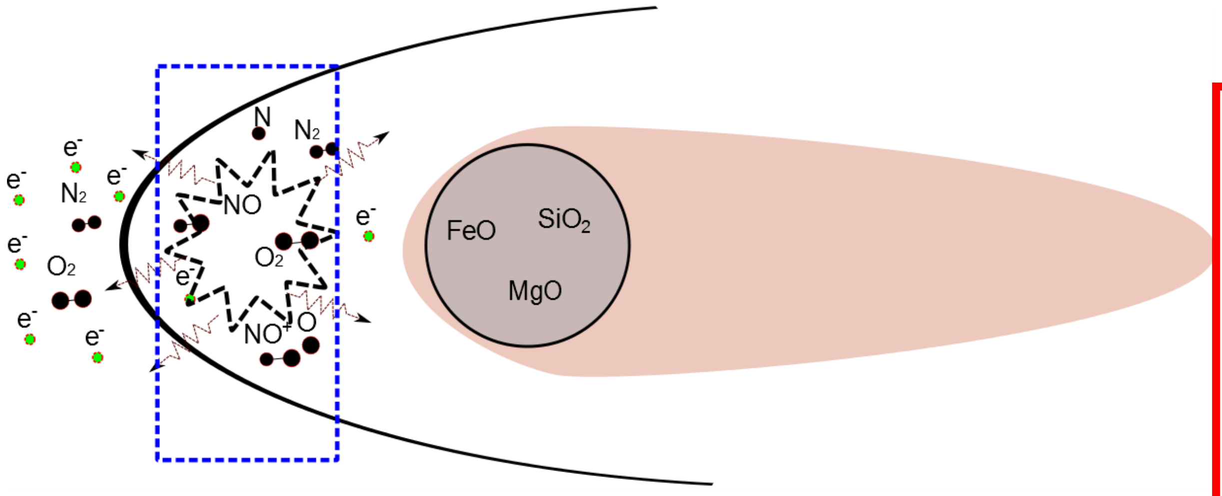


Hybrid Statistical Narrow Band (HSNB) method[1]

- 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

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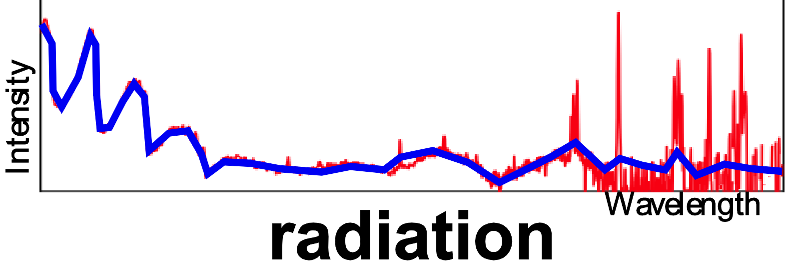

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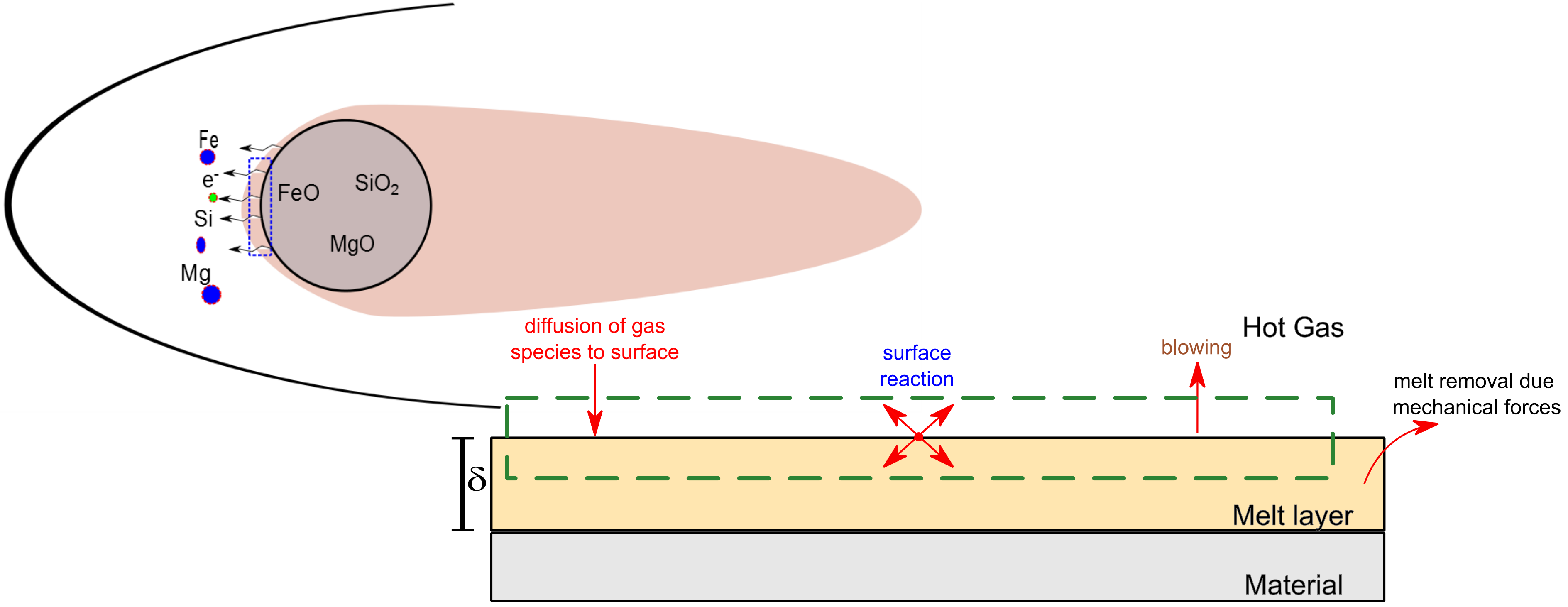
Ablation Model Surface Mass Balance (SMB)



Mass removal due to evaporation :

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

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

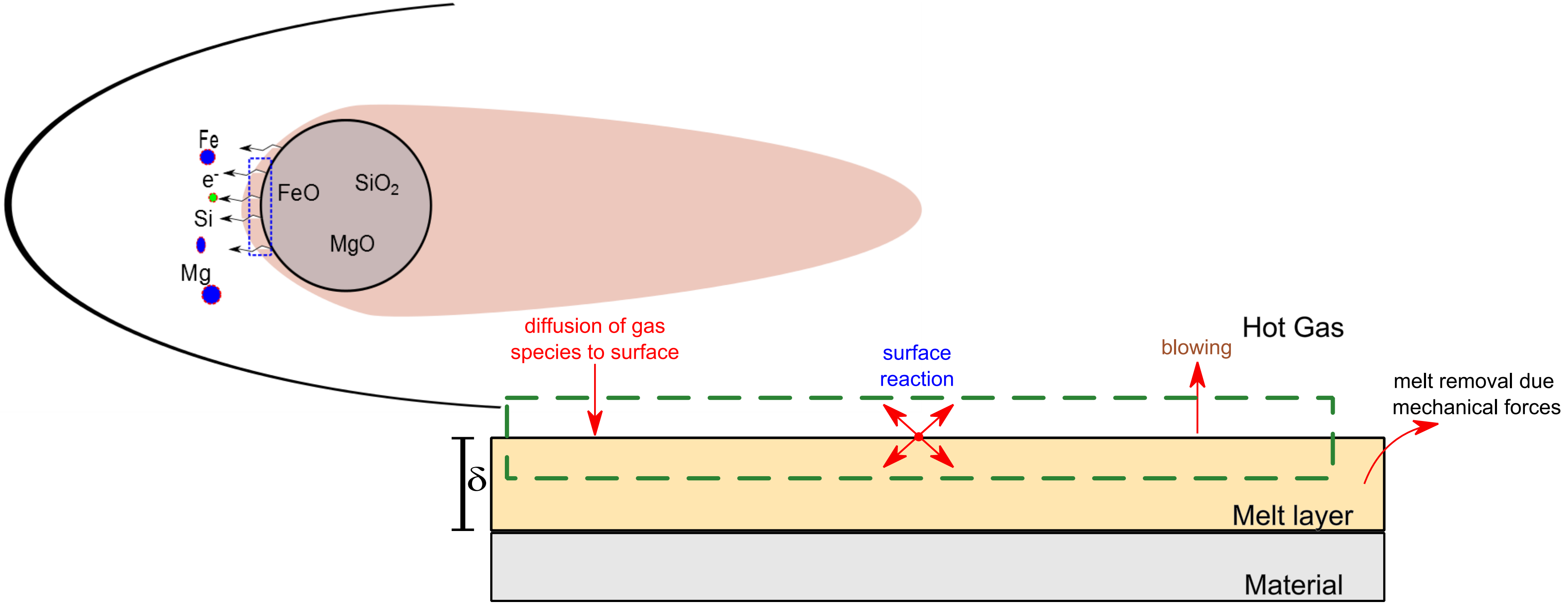
Mass removal due to mechanical forces :

- Tangential velocity[1]:

$$v = \tau_{flow/melt} \int_0^{\delta} \frac{dr}{\mu(T)} + \frac{1}{R}\frac{\partial P}{\partial \theta}_{flow/melt} \int_0^{\delta} \frac{r}{\mu(T)} dr$$

[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, …):

$$\sum_{i=1}^{Ns} \sigma_{i,k} \frac{M_k}{M_i} (1) \Rightarrow J_{i,k} + \dot{m}_{evap} \; y_{k,s} = (\rho u)_w \; y_{k,w} \quad \text{k=1,…,}\epsilon$$

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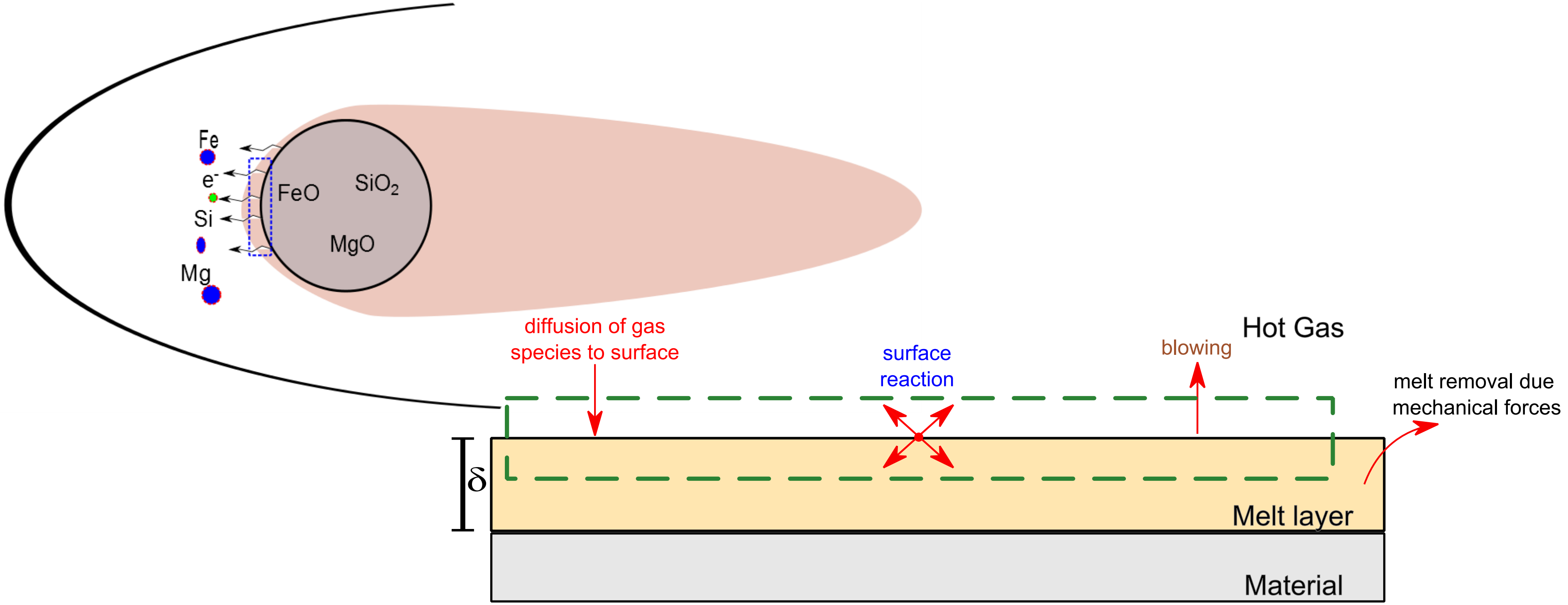


Total mass removal

Mass removal due to evaporation :

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

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

+

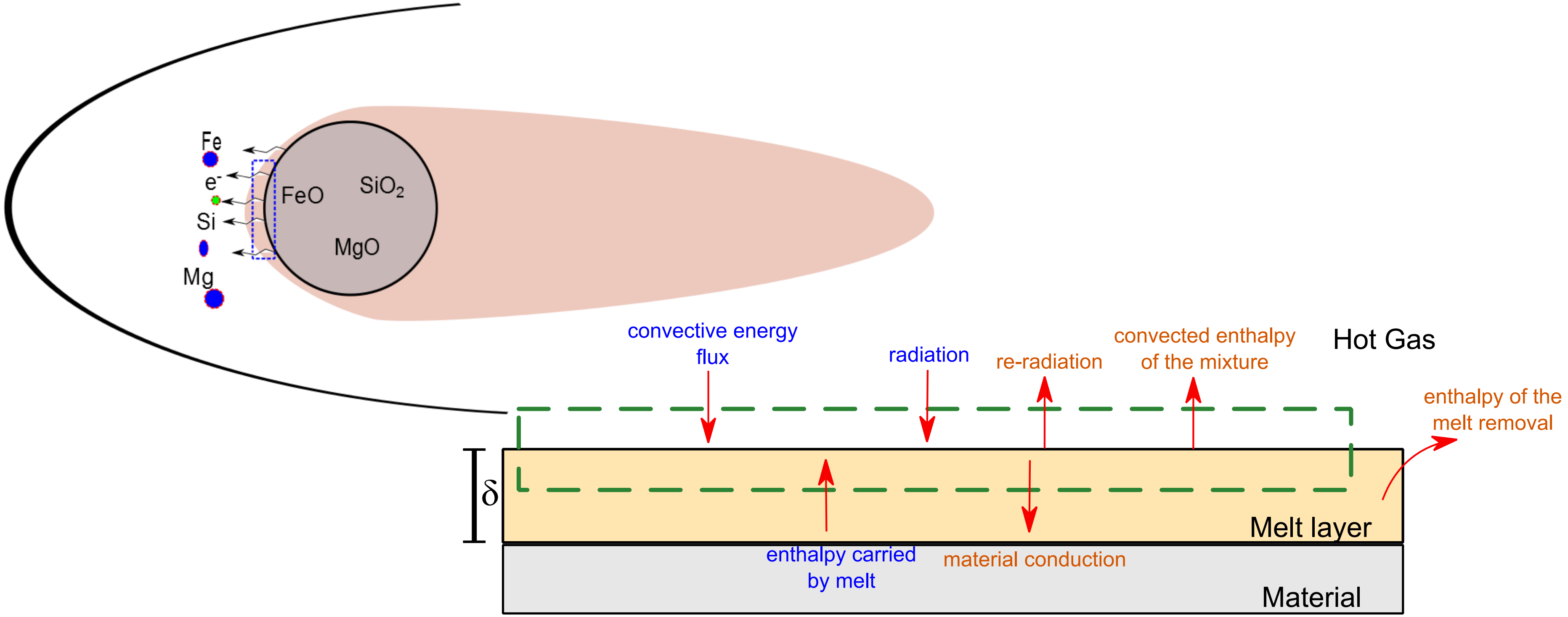
Mass removal due to mechanical forces :

- mass removal :

$$\dot{m}_{melt} = \rho_{melt} v$$

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

Ablation Model Surface Energy Balance (SEB)



- Energy Balance:

$$q_{convective} + (\dot{m}_{evap} + \dot{m}_{melt})h_c + q_{rad,in} = q_{rad,out} + \dot{m}_{evap}h_w + k\frac{\partial T}{\partial r} + \dot{m}_{melt}h_c$$

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:

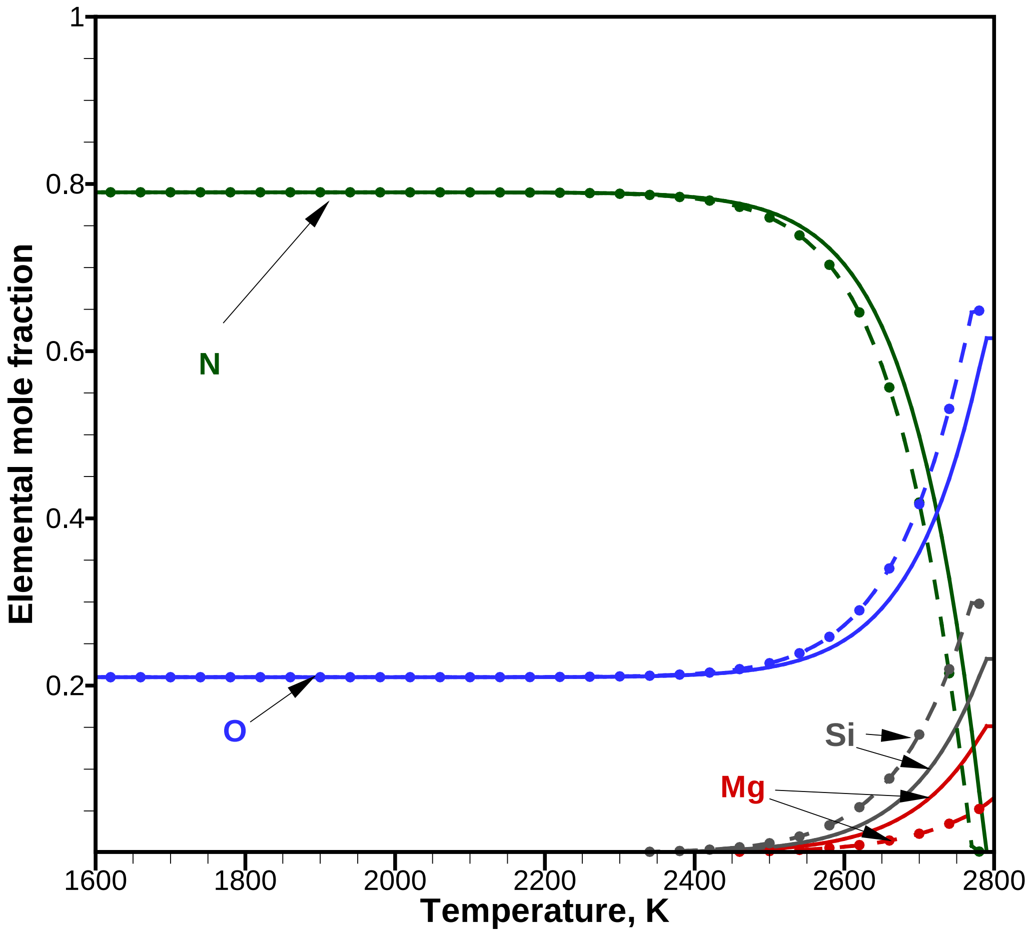
$$\frac{x_{Si}}{x_{Mg}} = const$$

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

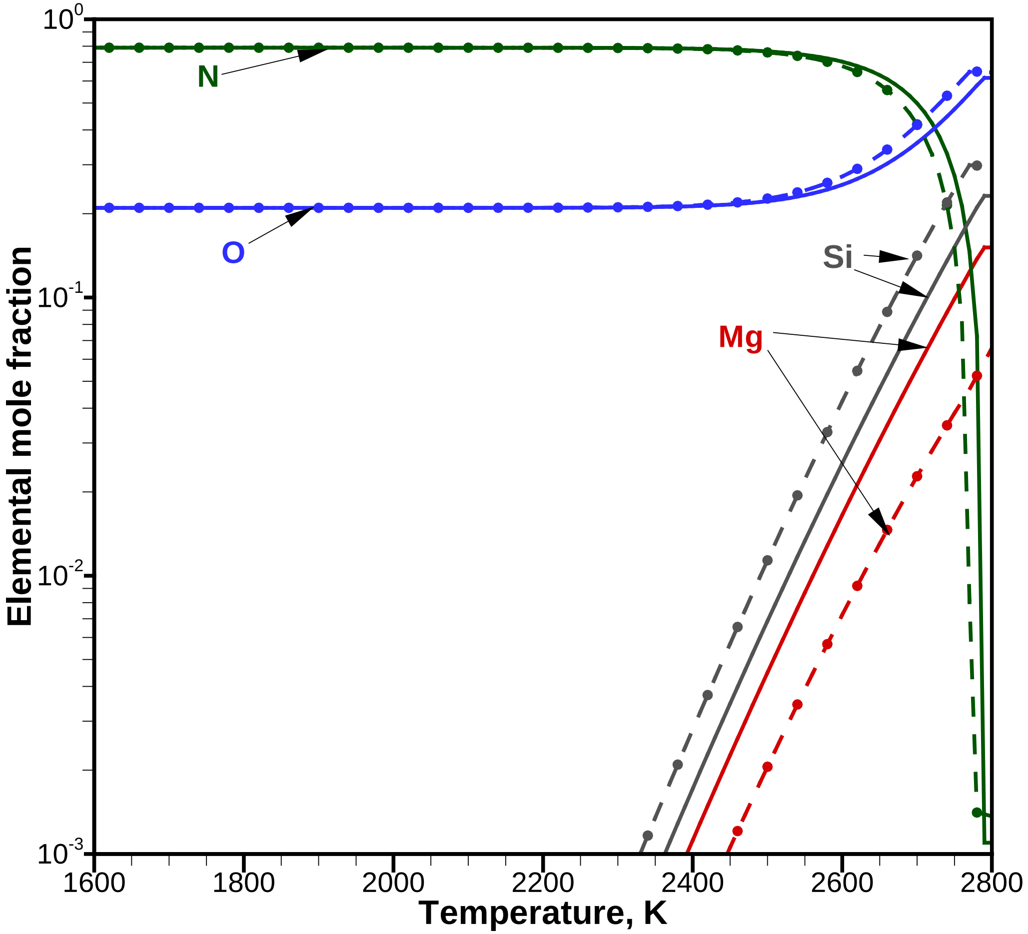
[2] Developed by *Scoggins et al,* Combust. Flame 2015

[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

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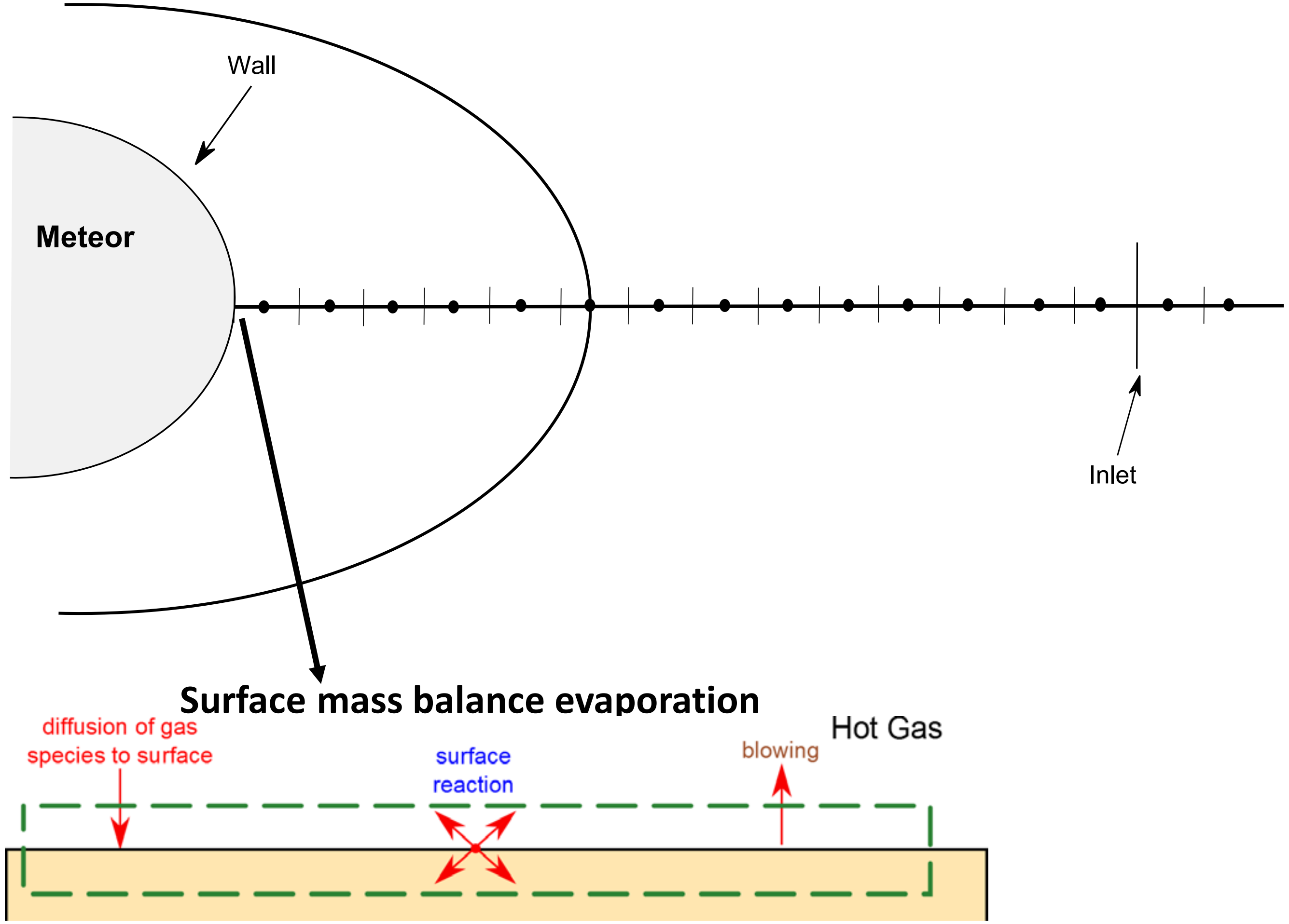
Meteor ablation flow solver



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

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

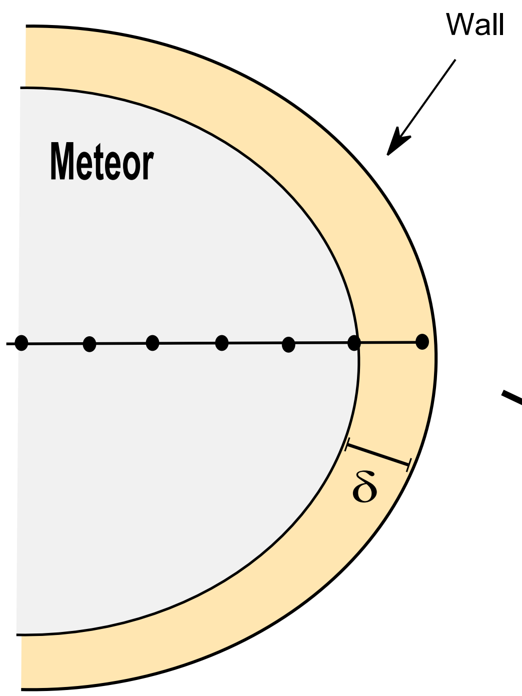
coupled

Mutation^{++} library [2]

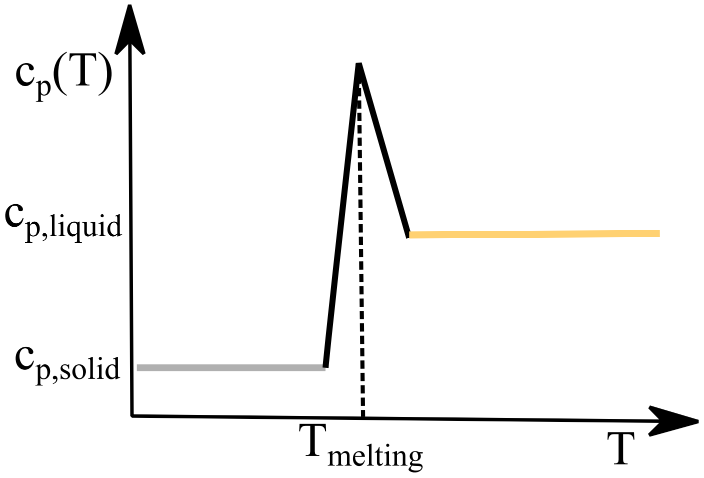
- Thermodynamic properties
- Transport properties
- Air chemistry
- Multiphase Equilibrium Solver[3]

[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:

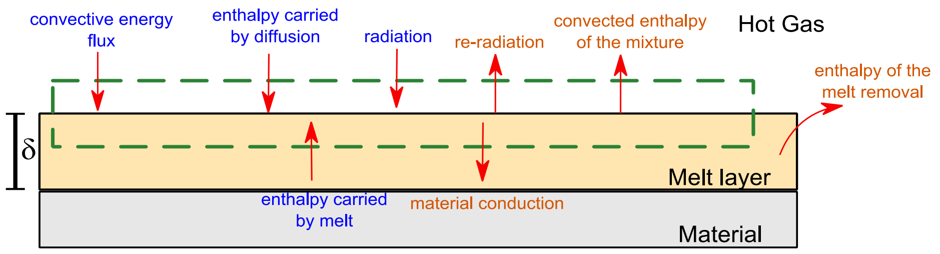


Melting material solver

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

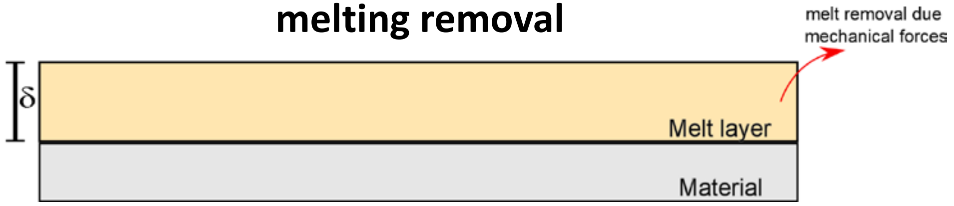
$$\rho c_p(T)\frac{\partial T}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 k \frac{\partial T}{\partial r}\right)$$

Surface energy balance

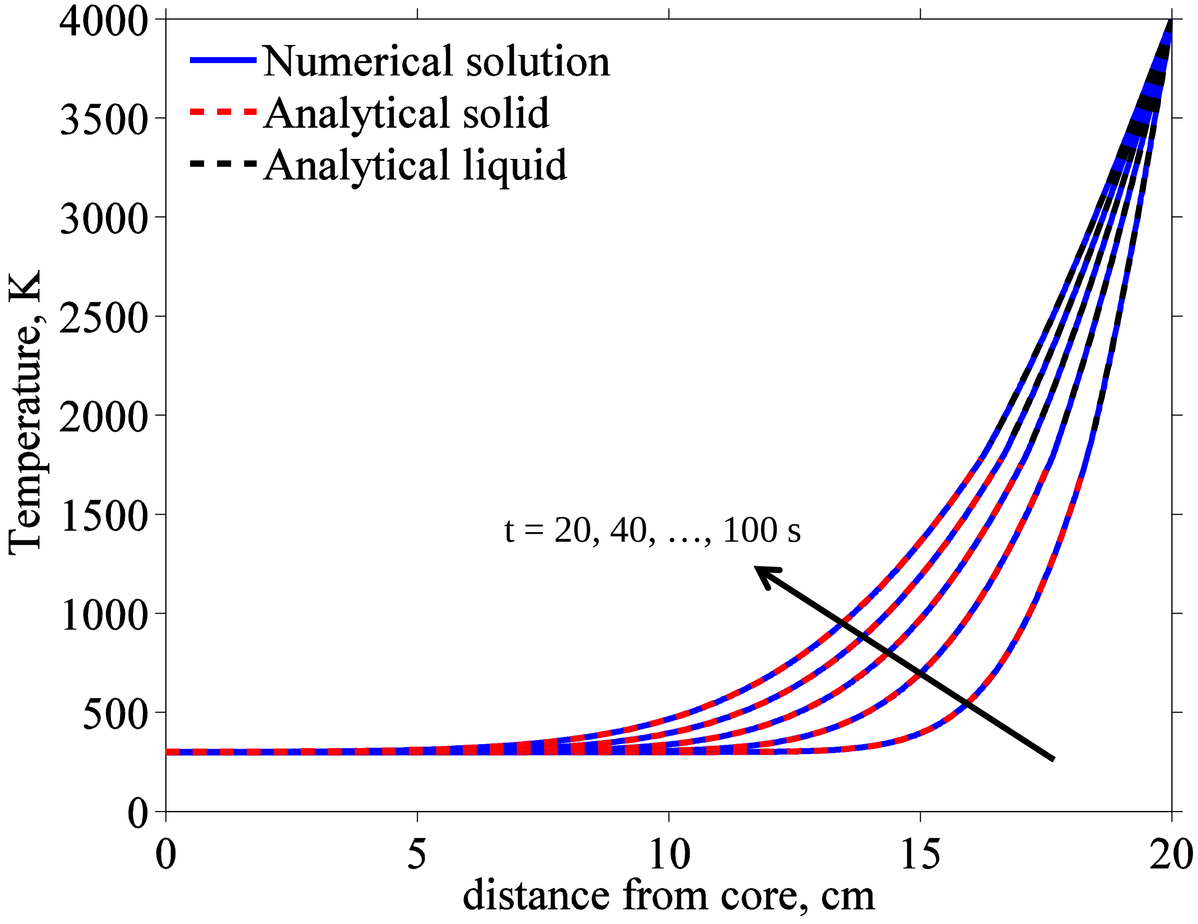


+

melting removal



Comparisson with analytical solution[1]



$$\lambda = \frac{x_{s,l}}{2\sqrt{\mu_l t}} \qquad \overset{*}{x} = \frac{x}{2\sqrt{\mu t}} \qquad \mu = \frac{k}{\rho c_p}$$

$$\begin{cases} \dfrac{e^{-\lambda^2}}{\operatorname{erf}\lambda} - \dfrac{k_s}{k_l}\sqrt{\dfrac{\mu_l}{\mu_s}}\dfrac{(T_m - T_0)}{(T_w - T_m)}\dfrac{e^{(-\lambda^2\mu_l/\mu_s)}}{\operatorname{erfc}\left(\lambda\sqrt{\dfrac{\mu_l}{\mu_s}}\right)} = \dfrac{\lambda L\sqrt{\pi}}{c_{p_l}(T_w - T_m)} \\ T_l = T_w - \dfrac{(T_w - T_m)}{\operatorname{erf}(\lambda)}\operatorname{erf}\left(\overset{*}{x}_l\right), \quad \lambda < \overset{*}{x} < \infty \\ T_s = T_0 + \dfrac{(T_m - T_0)}{\operatorname{erfc}\left(\lambda\sqrt{\dfrac{\mu_l}{\mu_s}}\right)}\operatorname{erfc}\left(\overset{*}{x}_s\right), \quad 0 < \overset{*}{x} < \lambda \end{cases}$$

$$T_m = 1800K \qquad T_w = 4000K$$

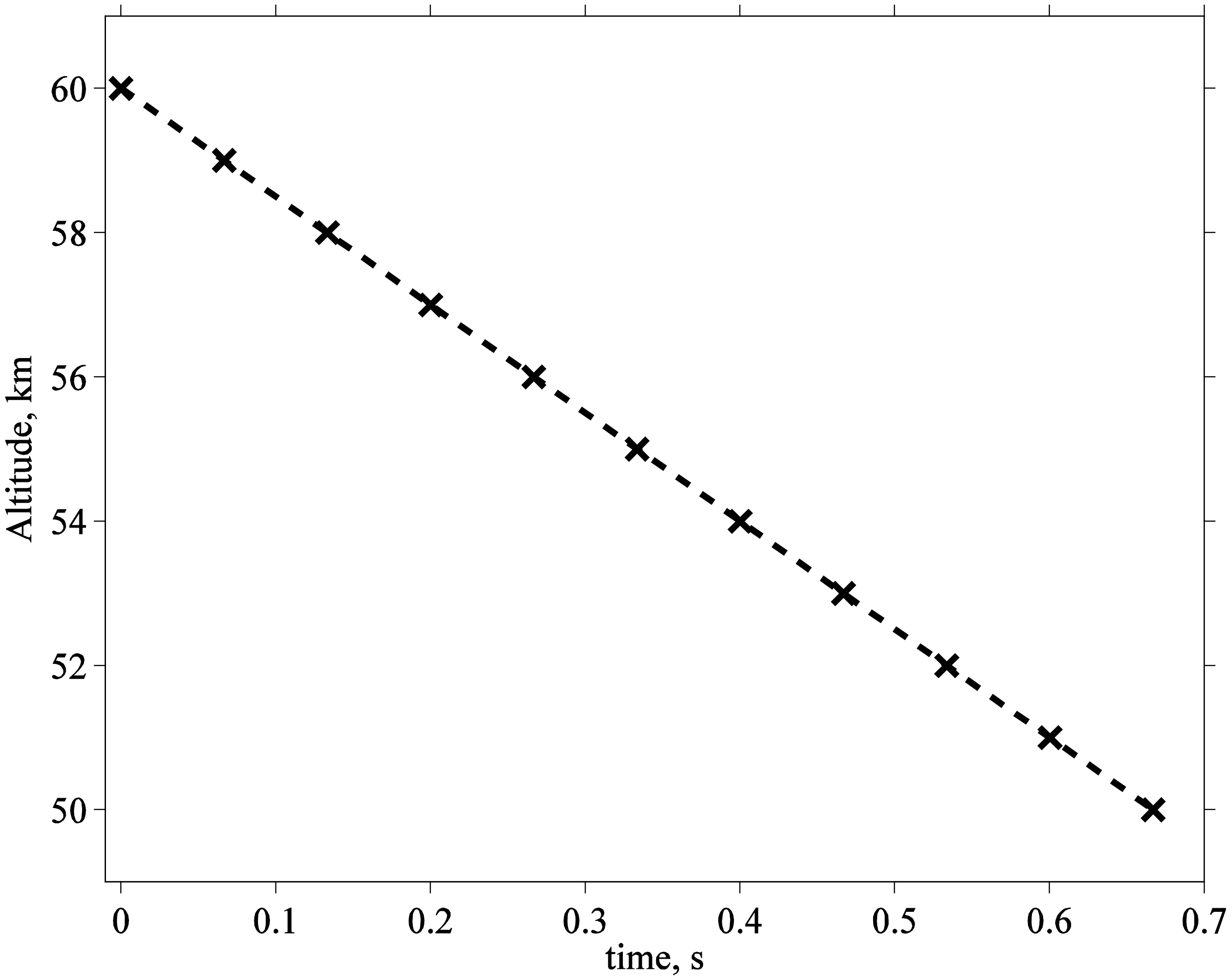
[1] Carslaw, H. S., and J. C. Jaeger. 1959. *Conduction of heat in solids*. Oxford: Clarendon Press.

Flow/ material solver coupling strategy

Simulation conditions:

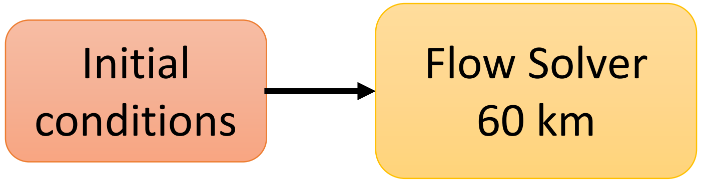
- Meteor composition in the atmosphere:
  - Simplify Ordinary Chondrite

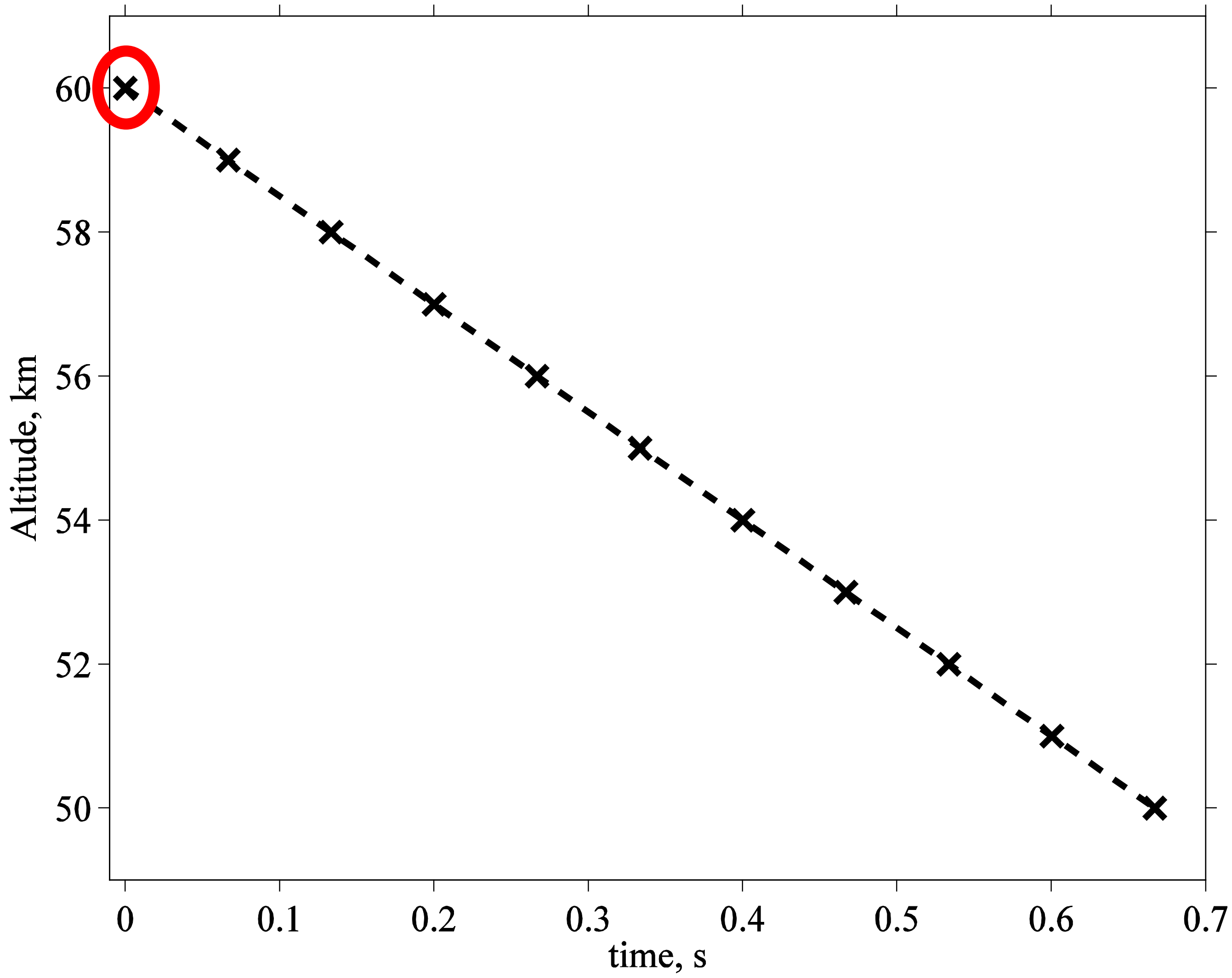
  (SiO_2: 0.65, MgO: 0.35) meteor, 1 cm radius
- Entry velocity: 15 km/s



Flow/ material solver coupling strategy

Implicit coupling approach:





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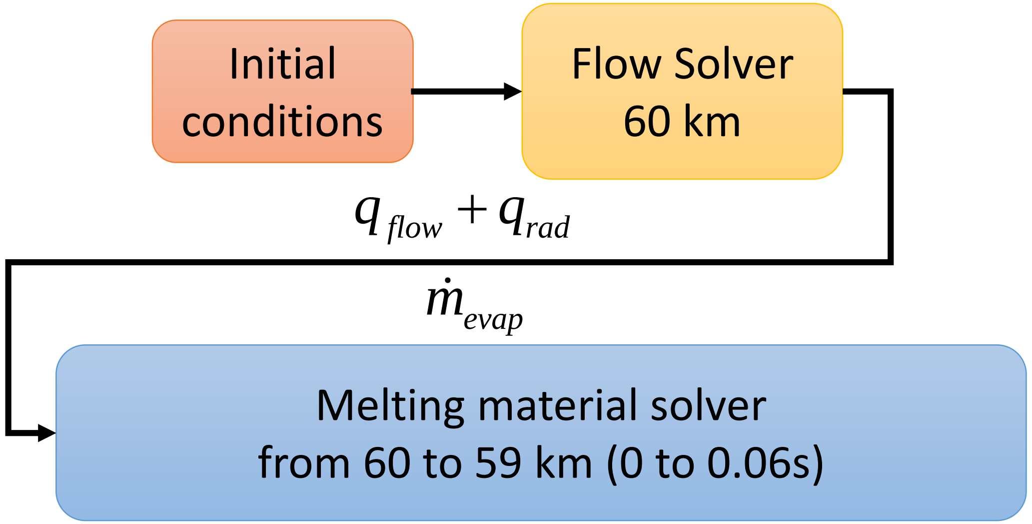

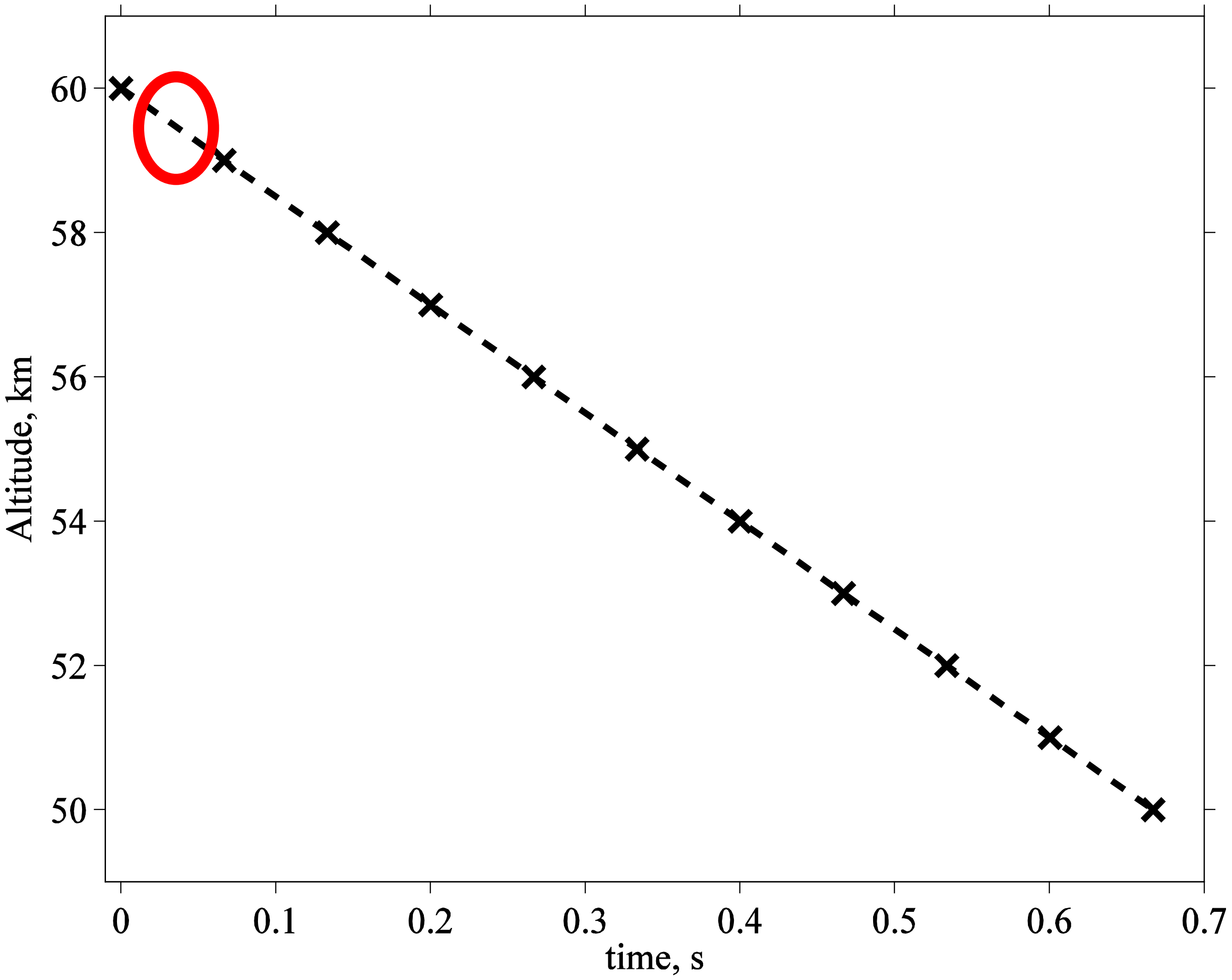

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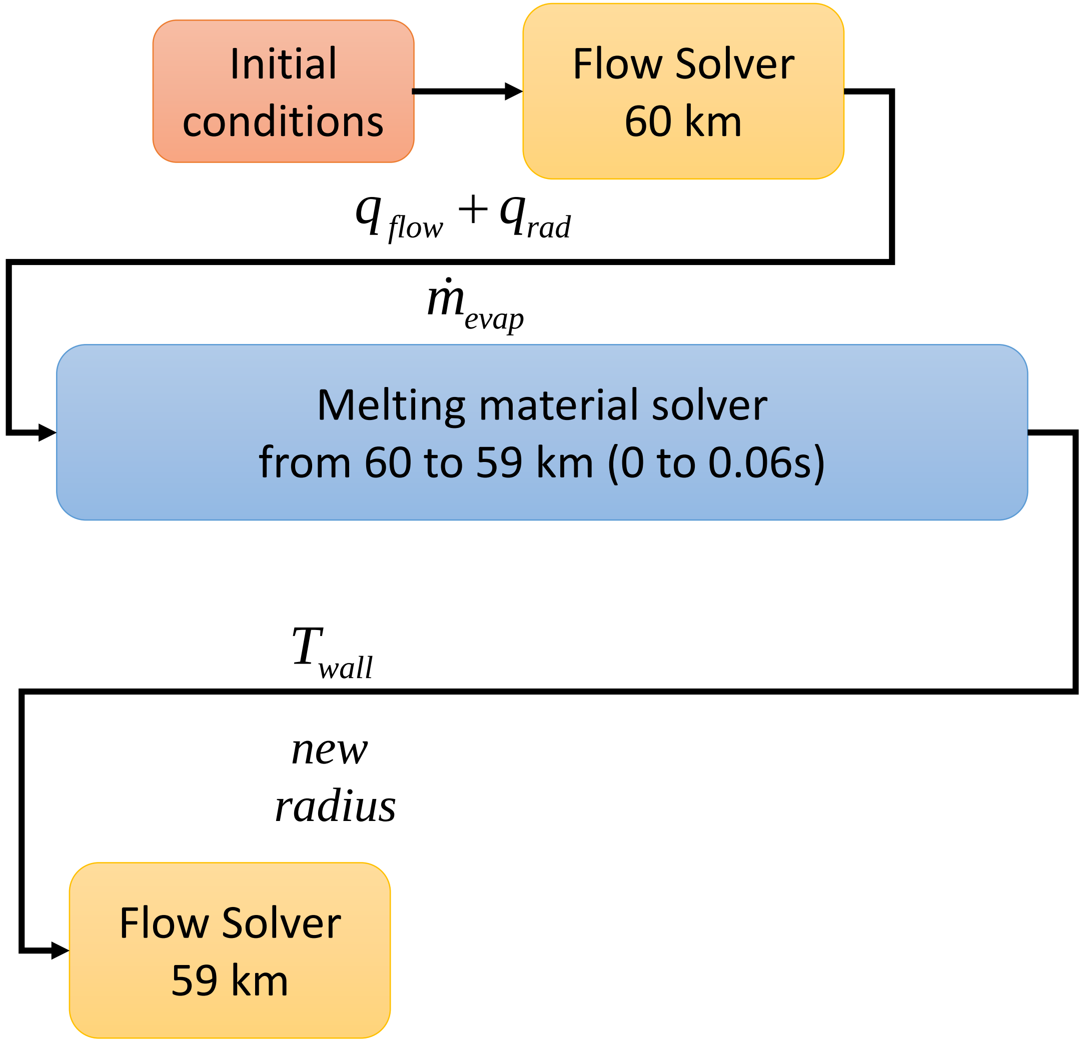

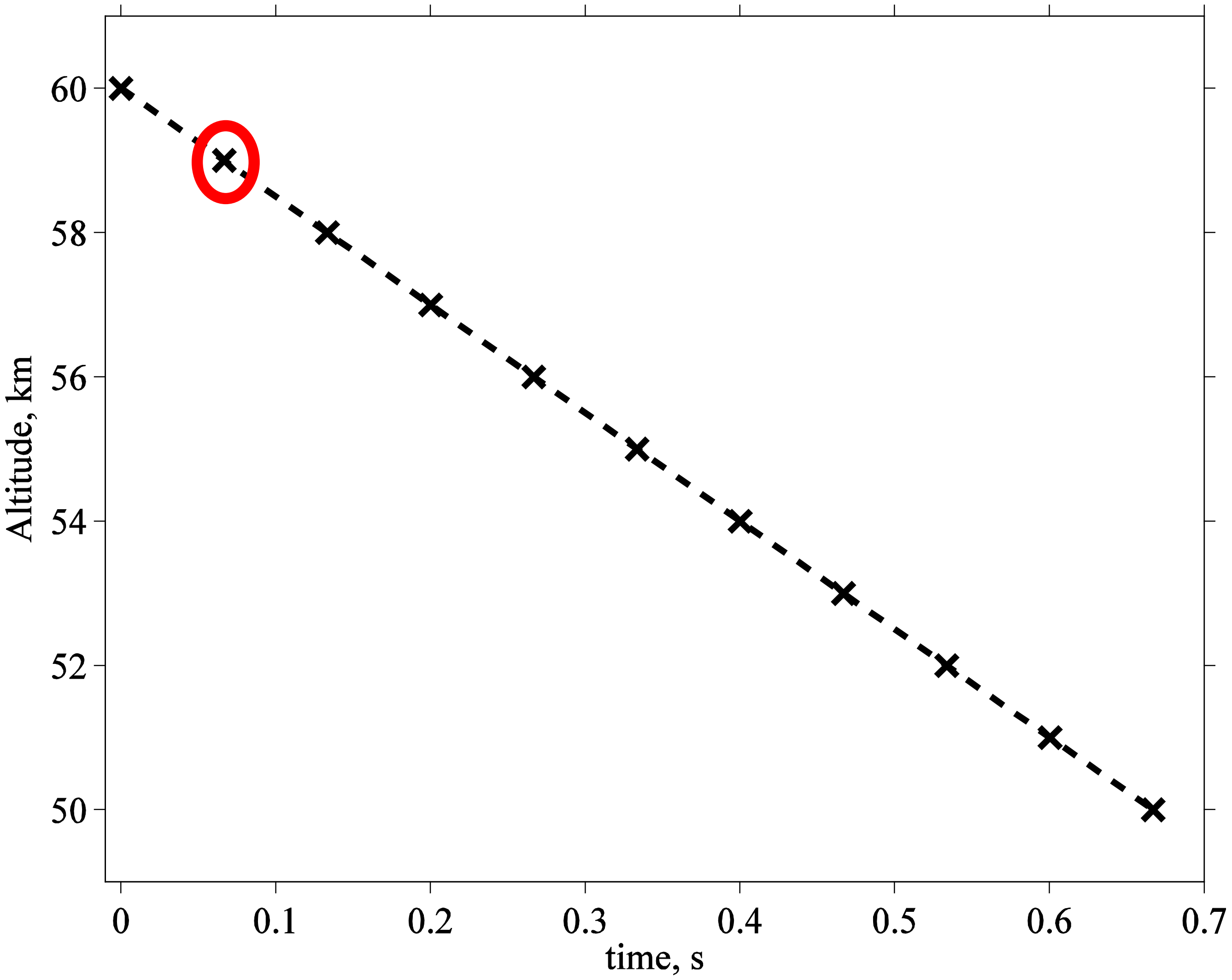

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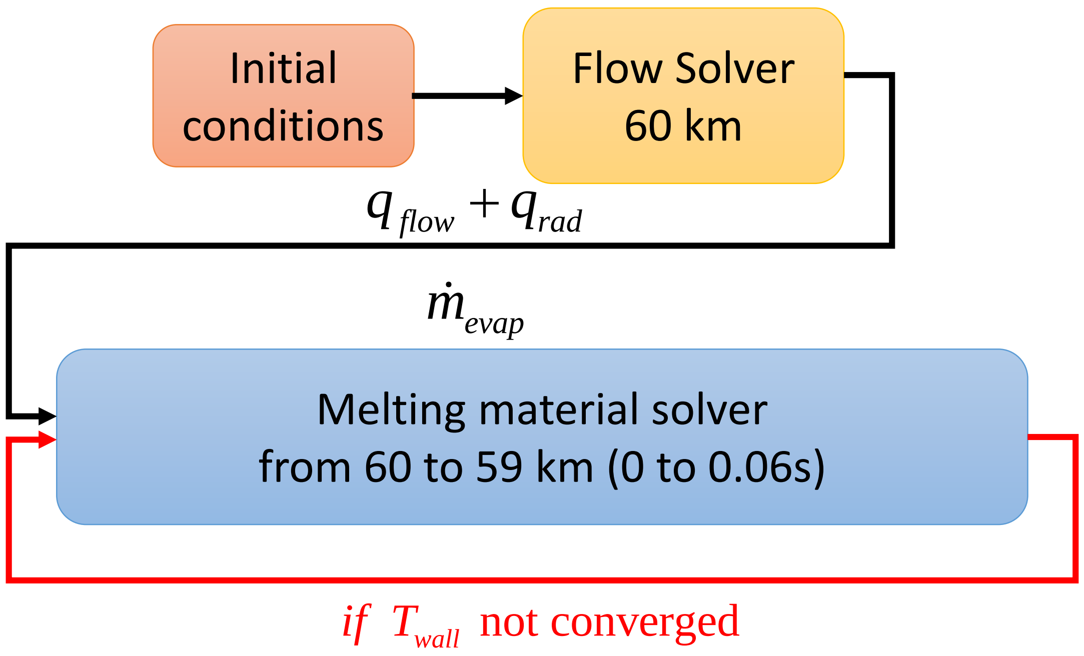
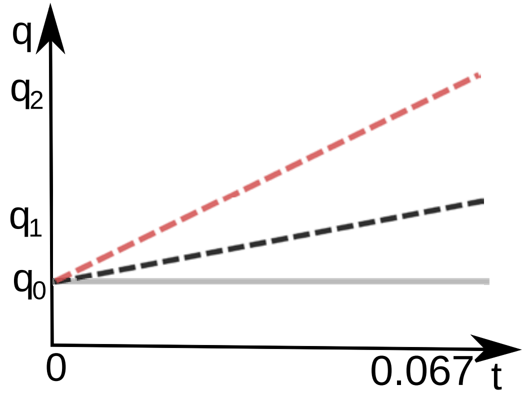
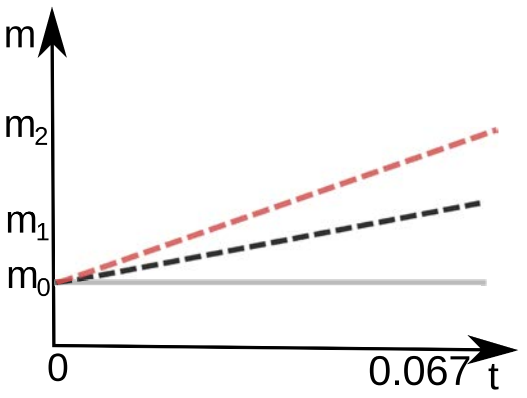
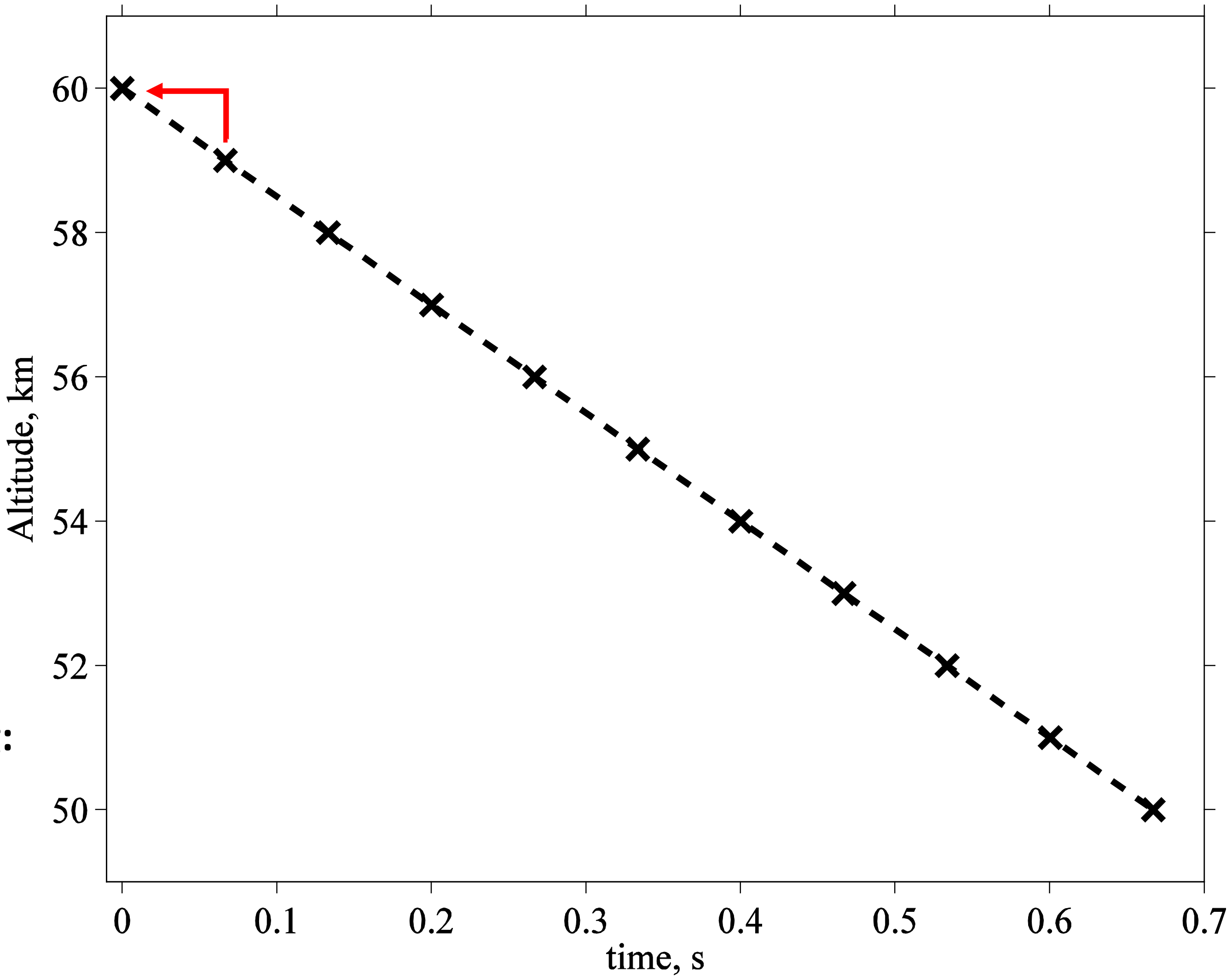


Heat flux ramping:



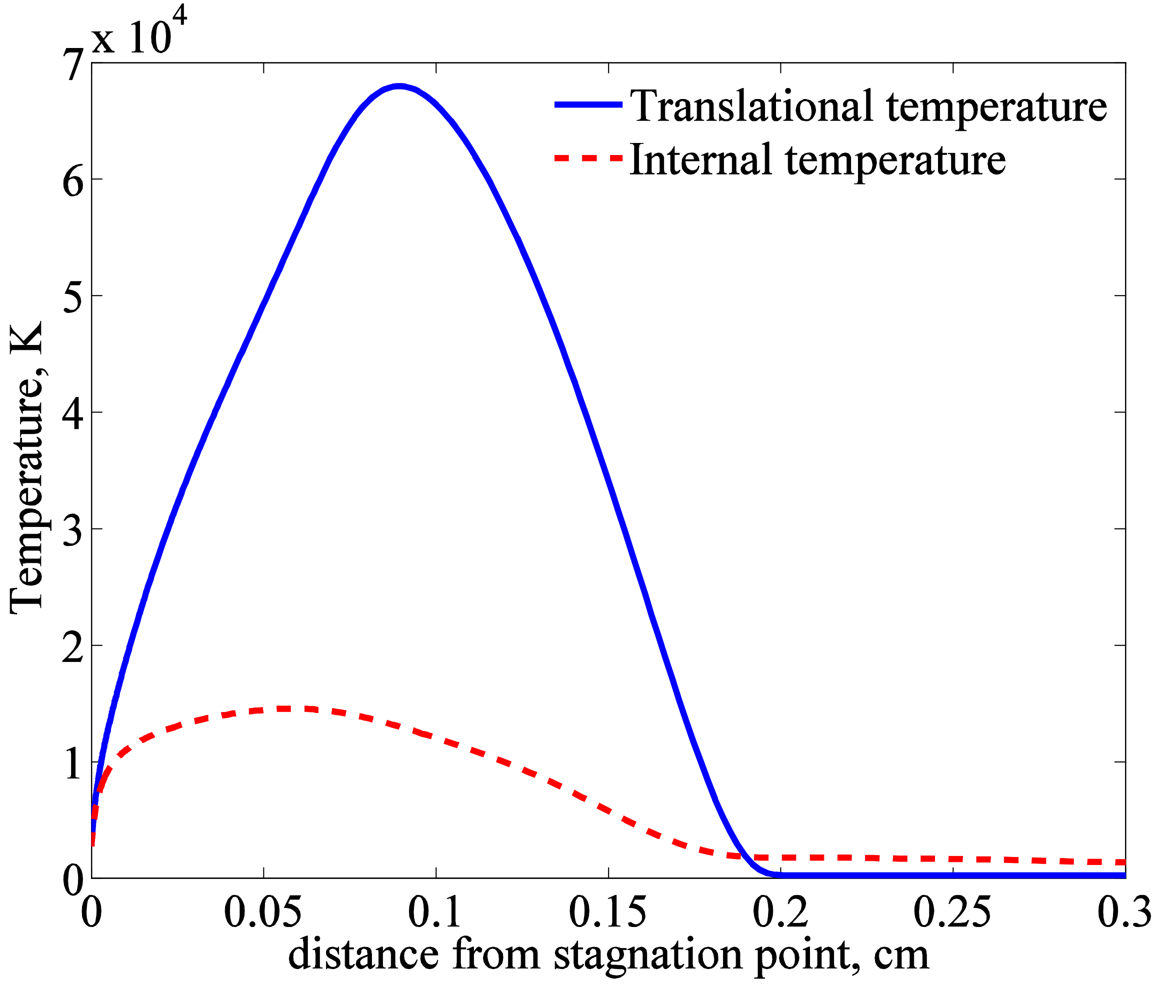
Evaporation rate ramping:



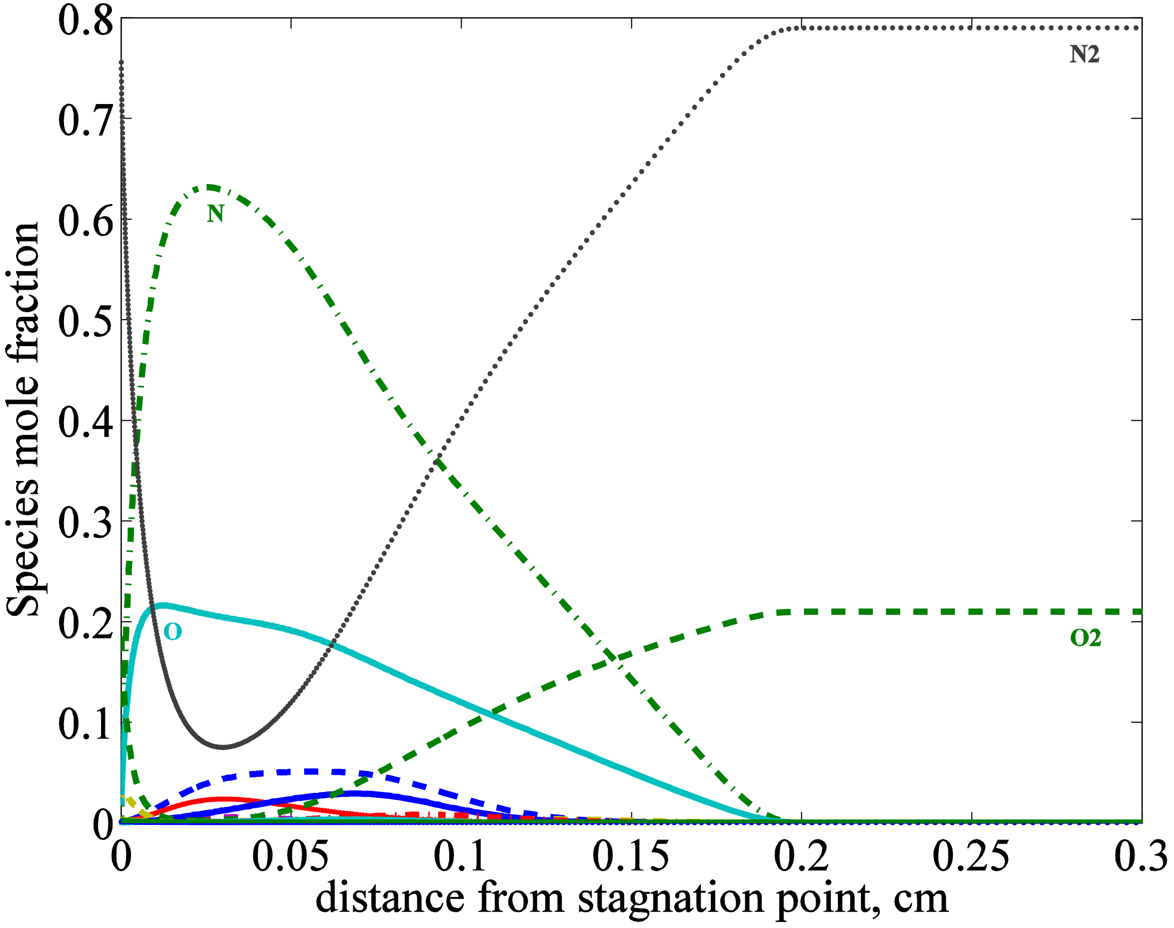


Flow field at 60 km

Temperature along stagnation streamline

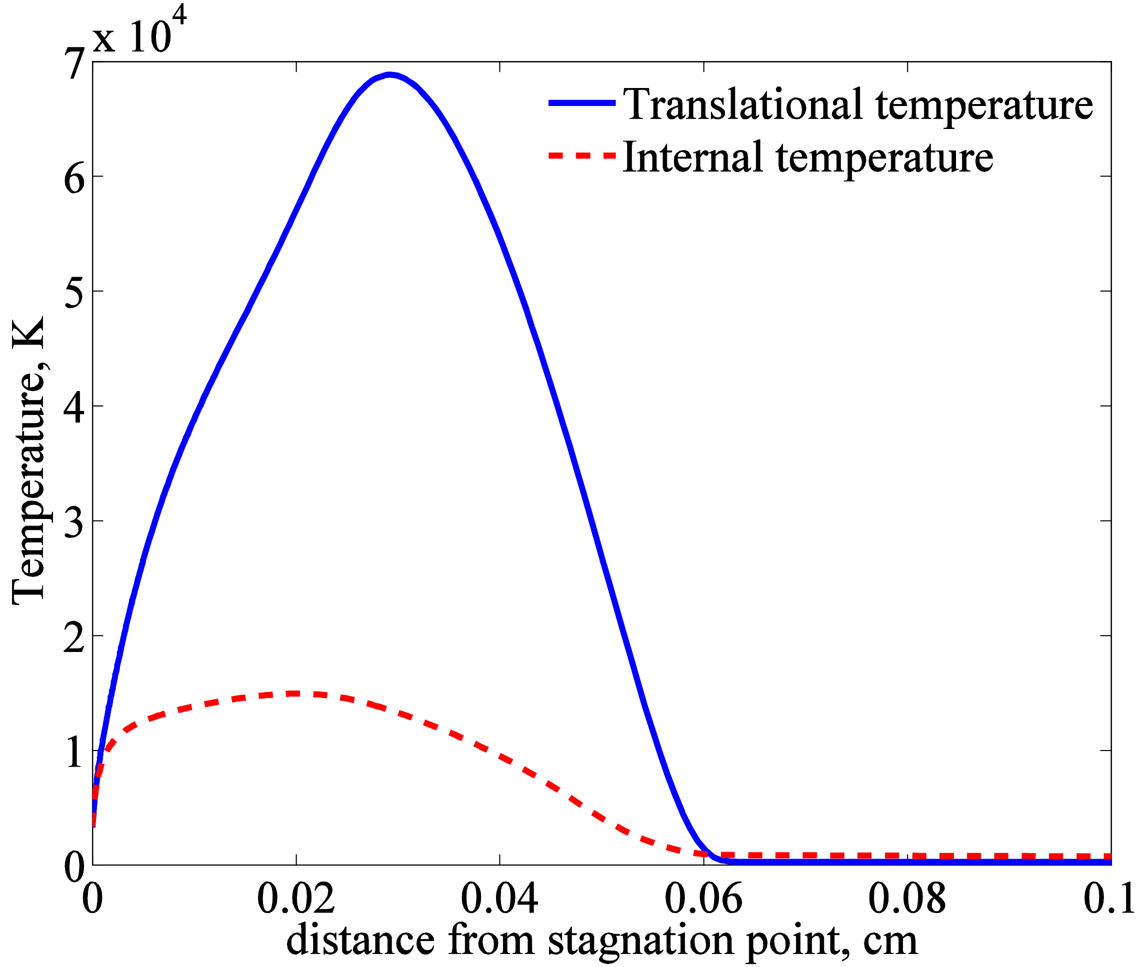


Species diffusion along stagnation streamline

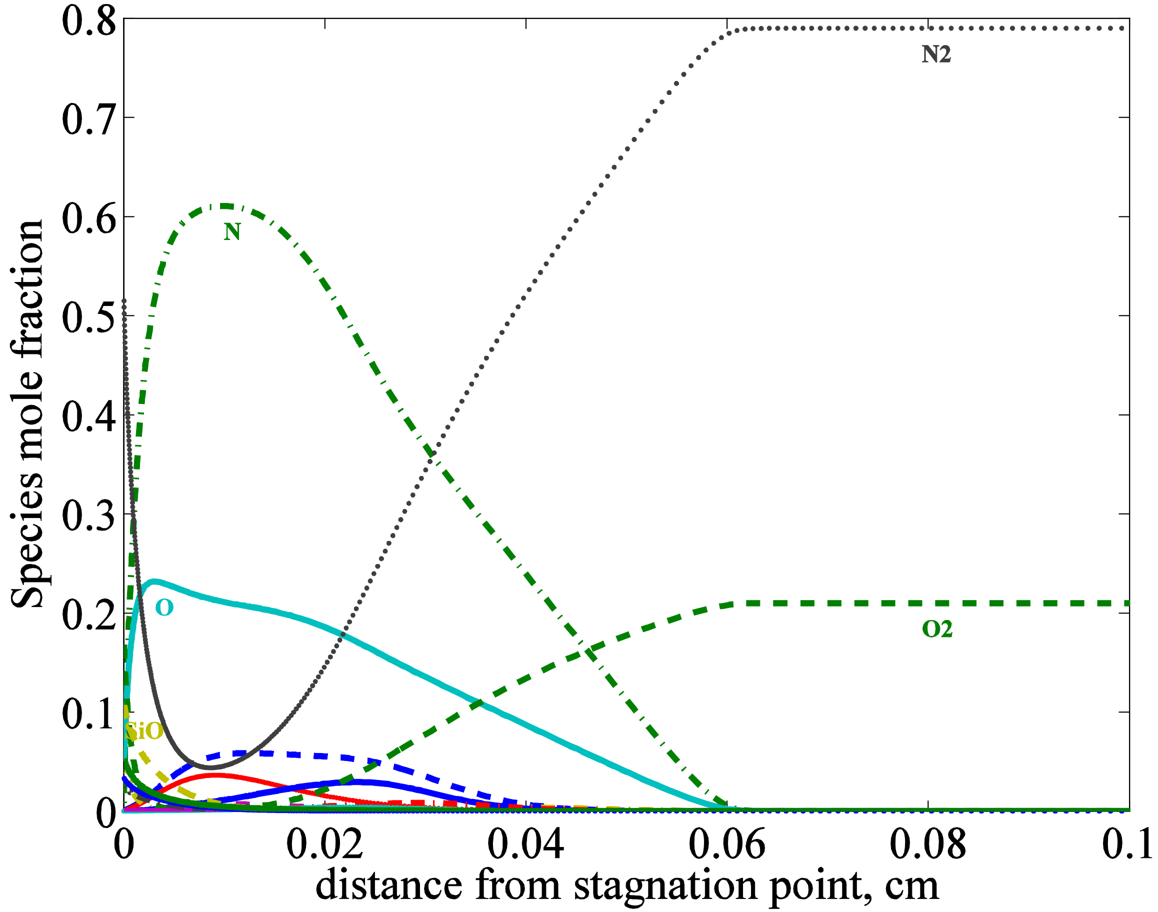


Flow field at 50 km

Temperature along stagnation streamline

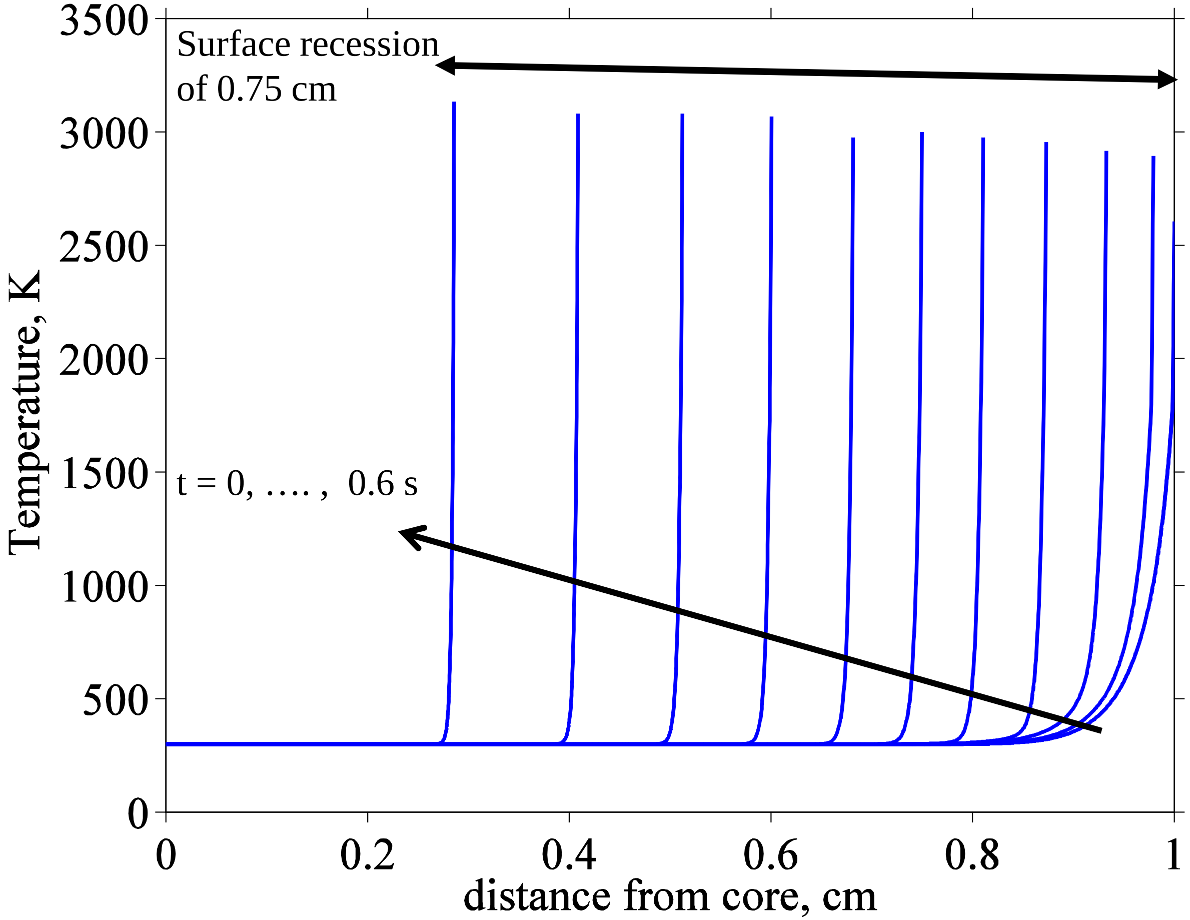


Species diffusion along stagnation streamline

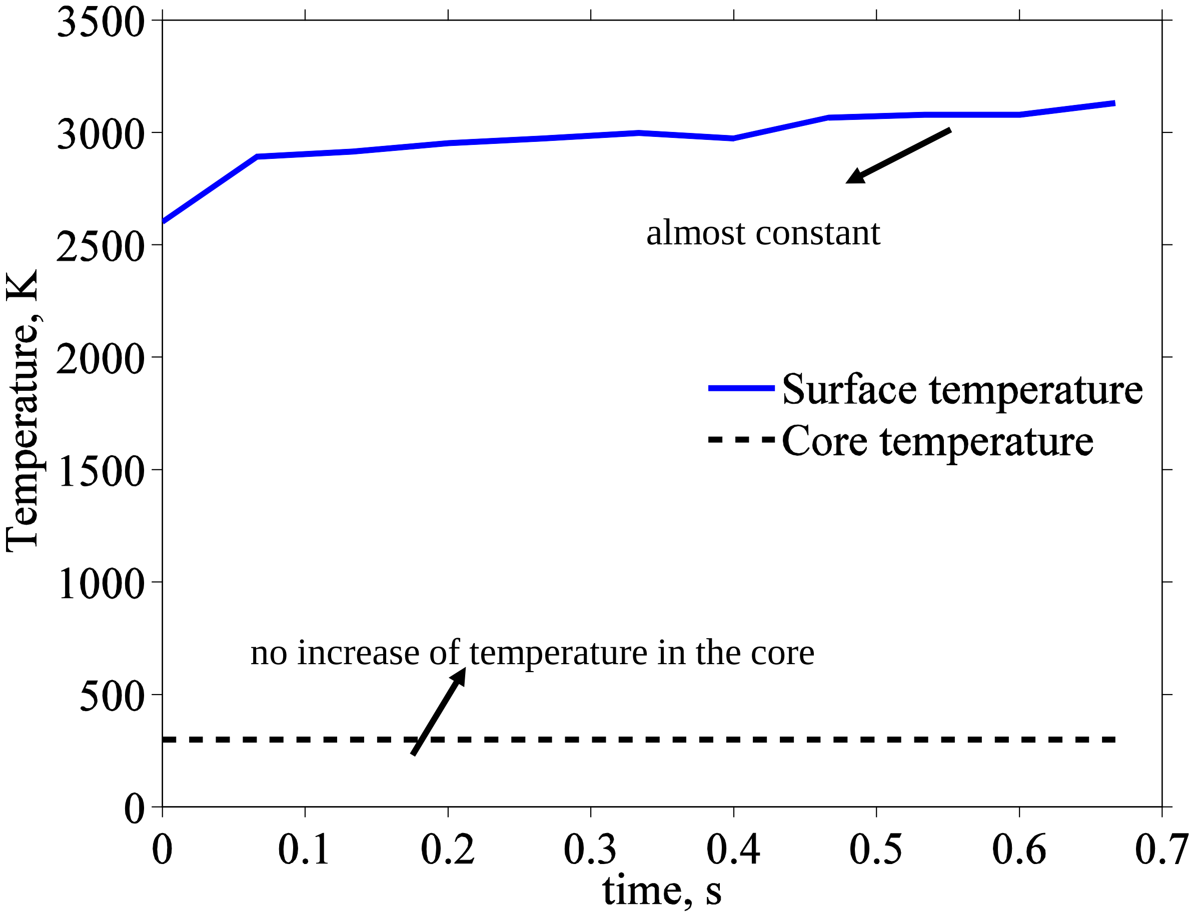


Material response from 60 to 50 km (temperature)

Temperature distribution along the material

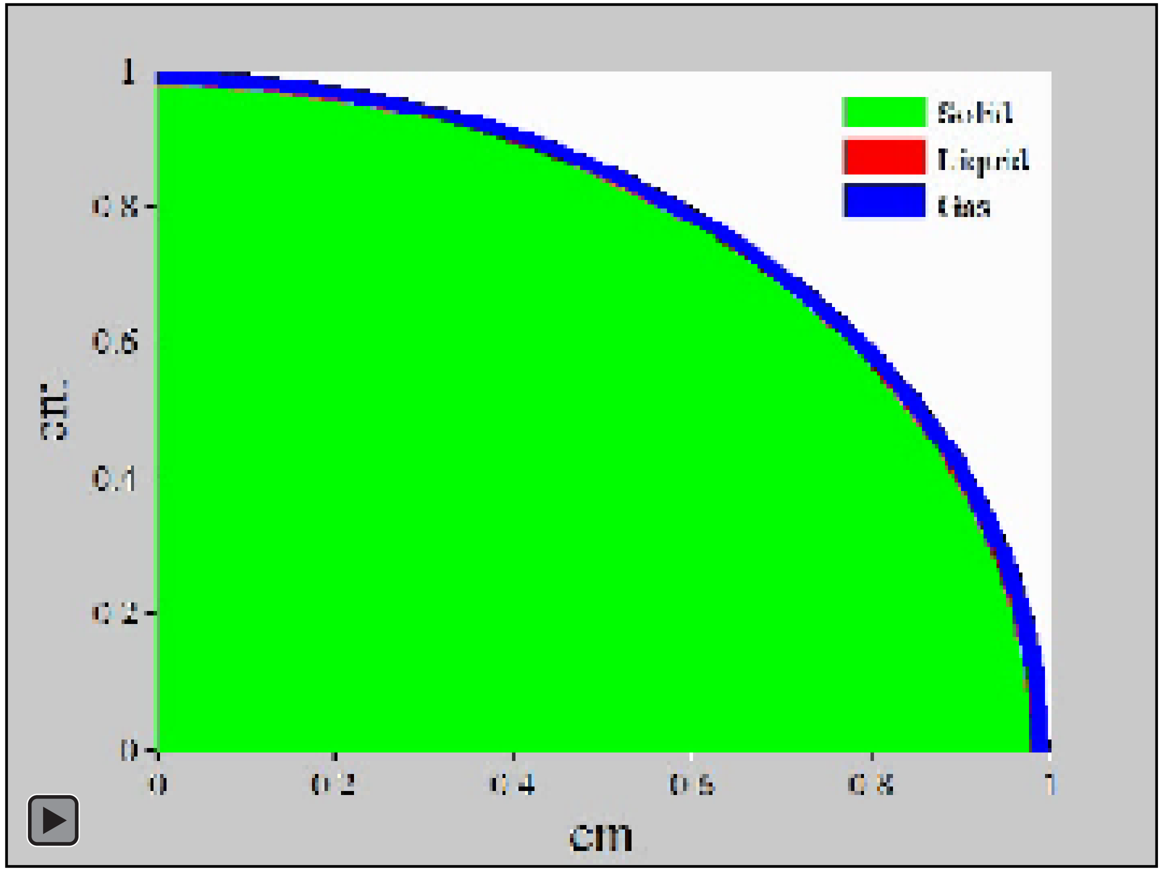


Temperature at the surface and at the core

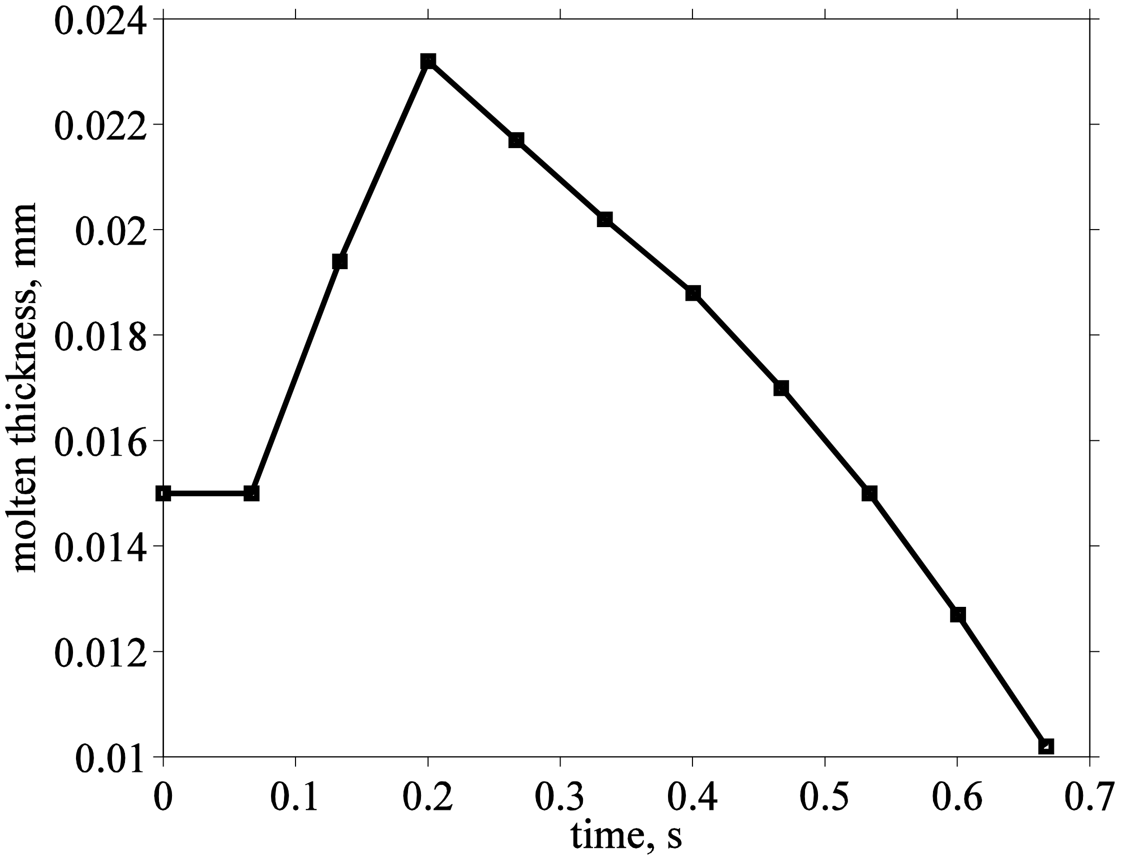


Material response from 60 to 50 km (evaporation and melting front)

Animation of moving fronts

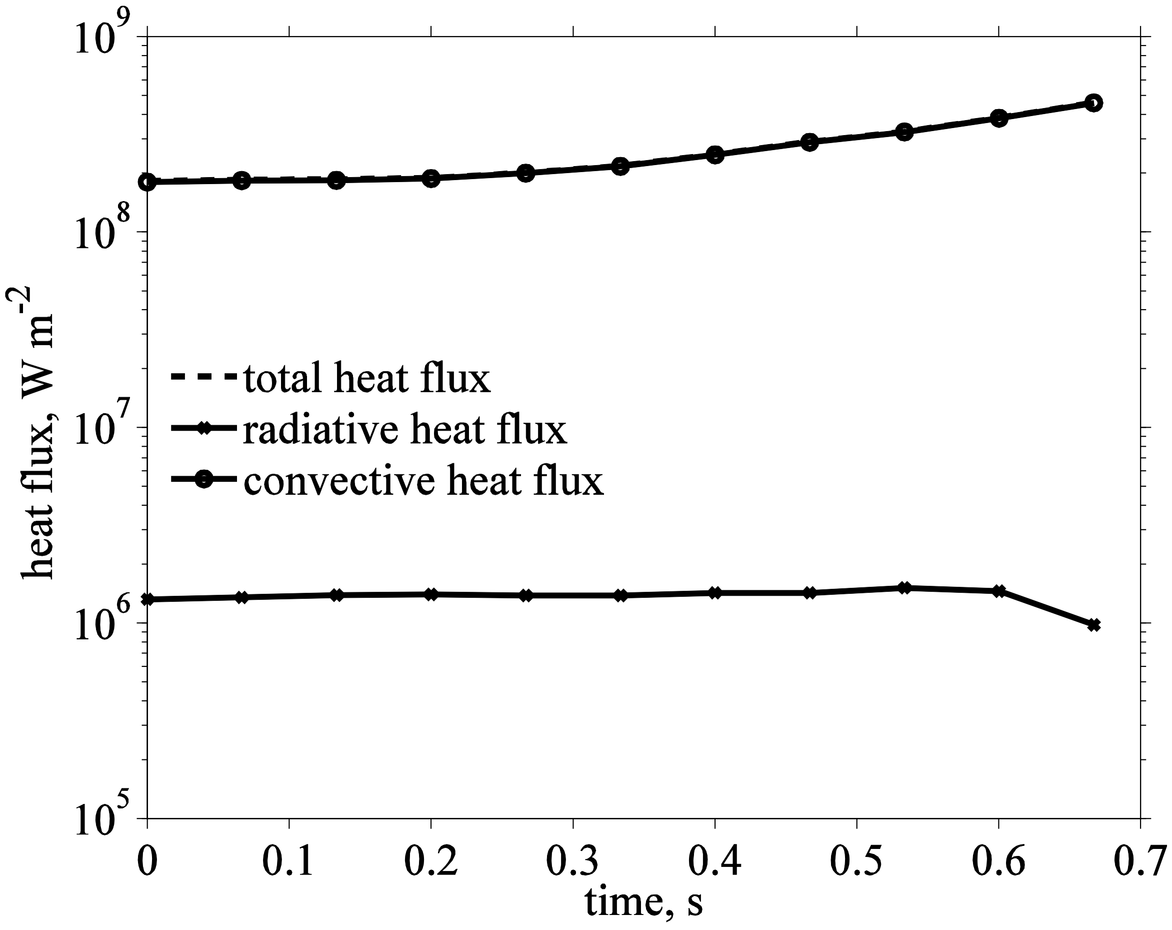


Melt layer

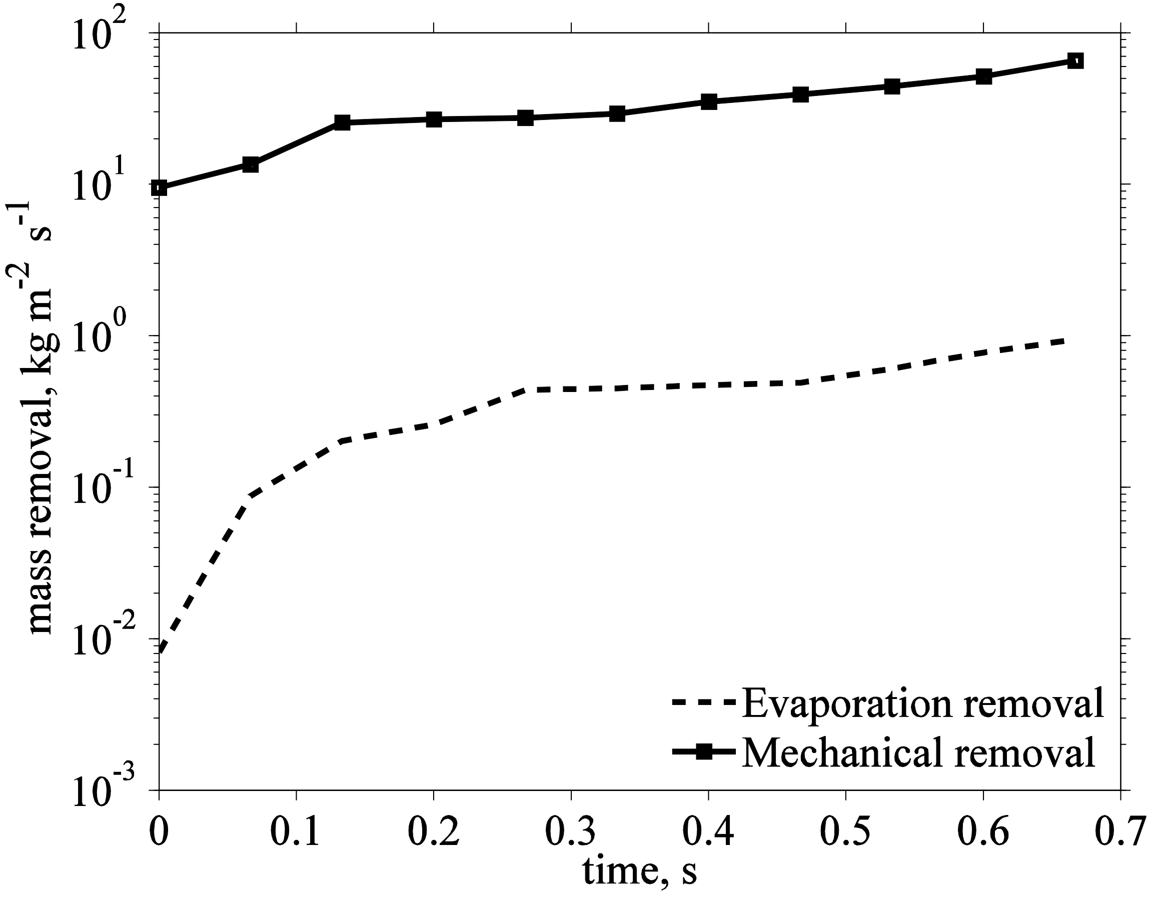


Heat flux and mass removal from 60 to 50 km

Heat flux contribution to the material



Mass removal due evaporation and mechanical forces



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 ablative boundary condition was developed with an approach similar to re-entry vehicles
    - Melting phenomenon was included to the gas-surface interaction model
    - The material and flow solver were coupled through an implicit procedure

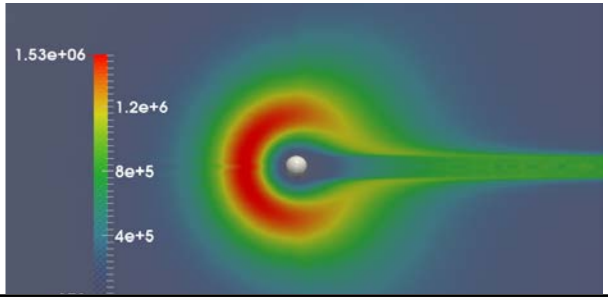
- Important results have been obtained using engineering tools:

    - The initial conditions for the flow solver are very important
    - The melting layer remains very thin due to a high mass removal
    - Decrease of the melting layer along the trajectory
    - The major source of mass lost is through mechanical removal
    - Radiative heat flux is much smaller than convective contribution

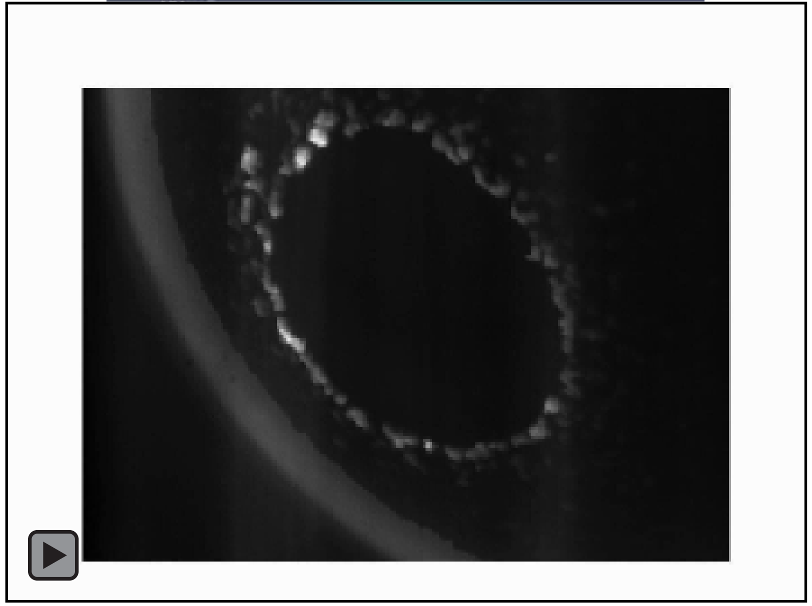
On-going work

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

- Development of DSMC tools for
rarefied regimes[3] (Sparta simulation) (Federico talk)



- Experimental studies of real meteors in the Plasmatron[1] (Thierry talk)



[1] Zavalan, VKI RM (2016)
[2] Schrooyen, PhD thesis (2016)
[3] Federico Bariselli, PhD student

Development of evaporation and melting models for meteor phenomenon in the continuum regime

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