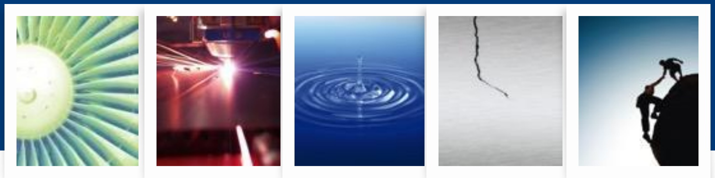

Demise of CFRP materials in atmospheric entry conditions

5th International Space Debris Re-entry Workshop
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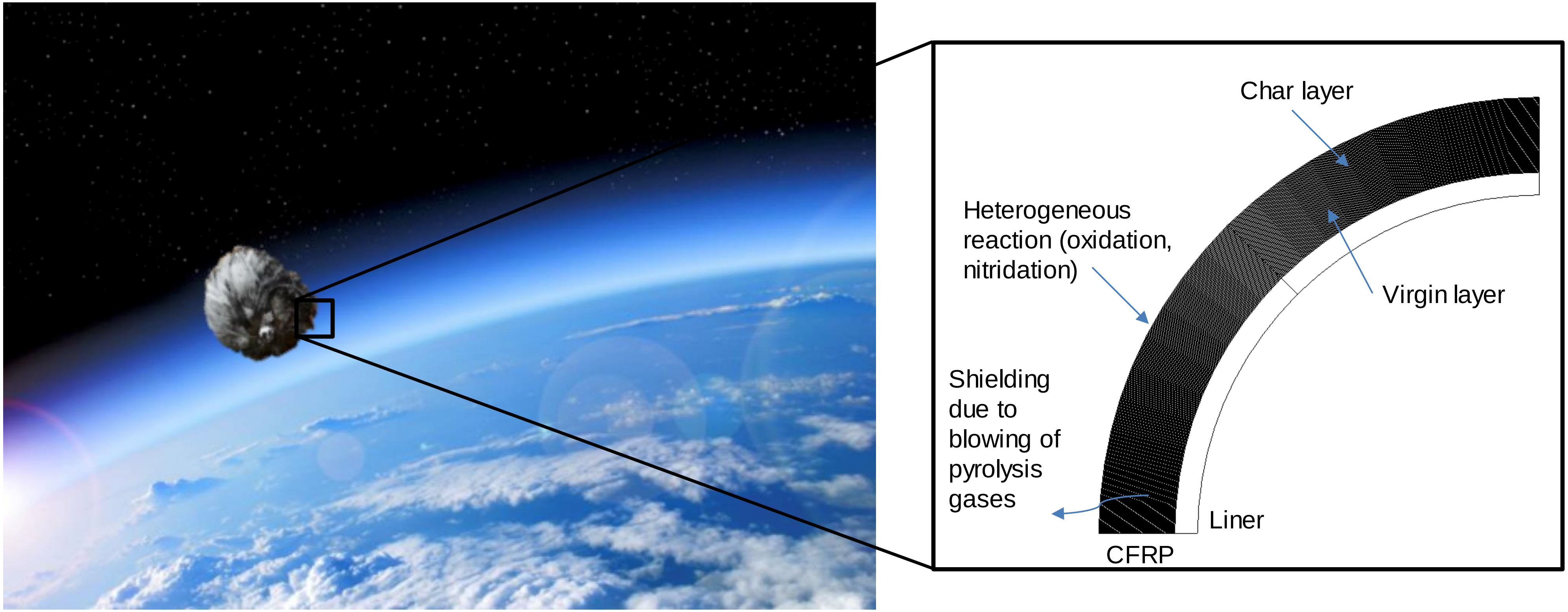
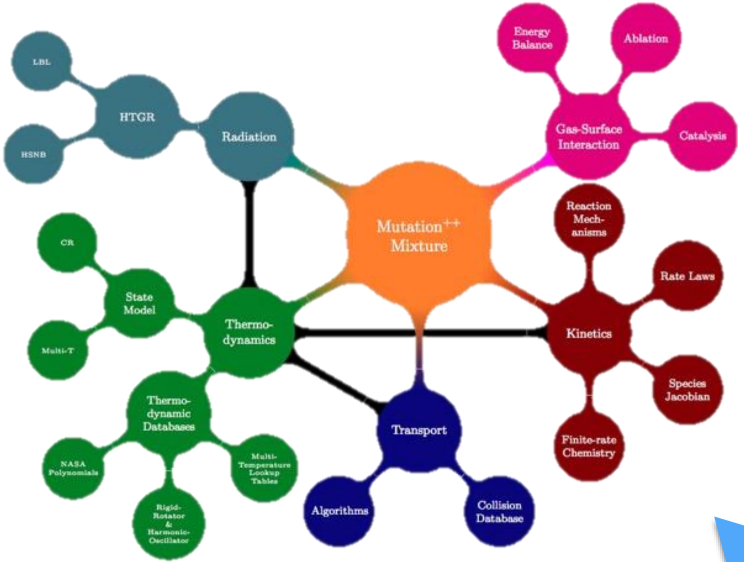
CFRP used to manufacture pressurized vessels are similar to materials used for TPS



Objectives:

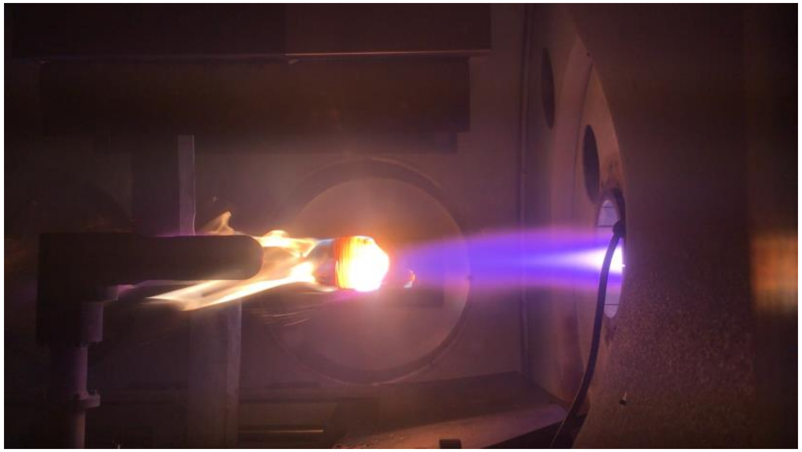
Develop high-fidelity models for Carbon Fibers Reinforced Polymers materials based on numerical and experimental campaign

Reproduction of CFRP demise in Plasmatron conditions



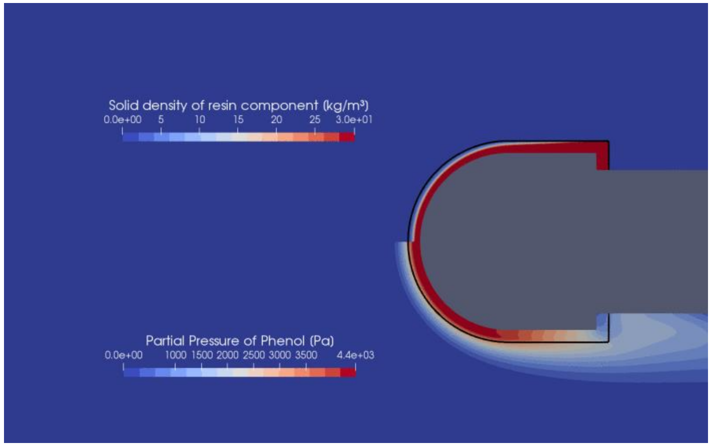
Models

Implementation in state-of-the-art Mutation++ library and linked with Argo code



Experiments

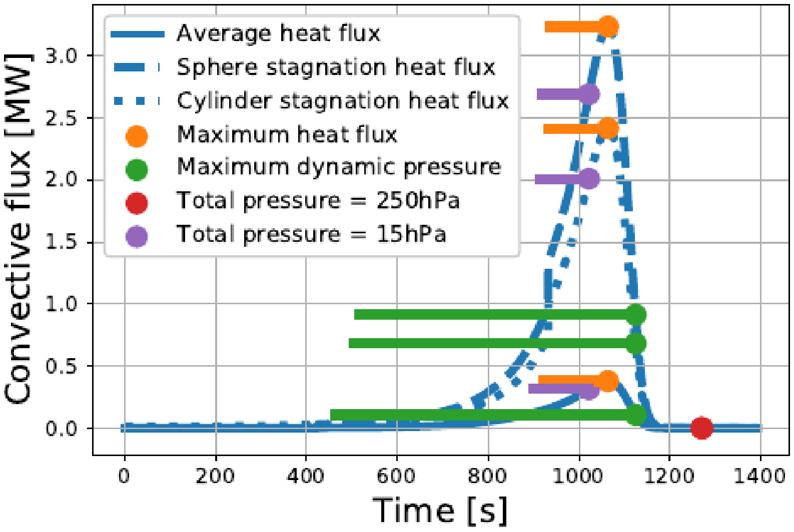
Plasmatron facility to reproduce high enthalpy conditions faced during debris re-entry

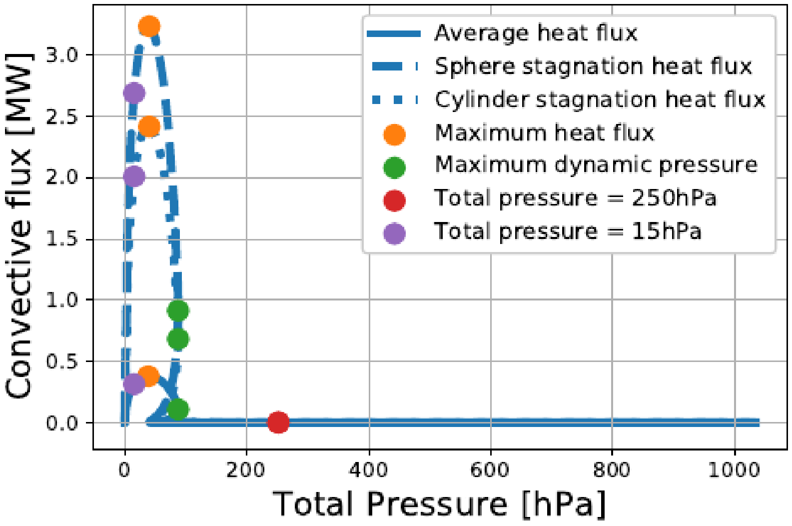


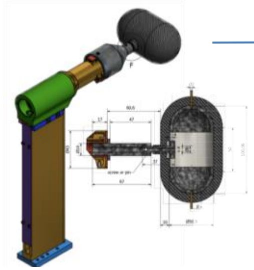
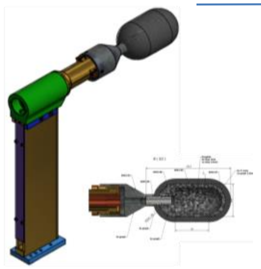
Numerical simulations

High-order Argo code to reproduce experiments and to predict thermal response of degrading materials

Representative sample and conditions to reproduce atmospheric entry of AVUUM tank





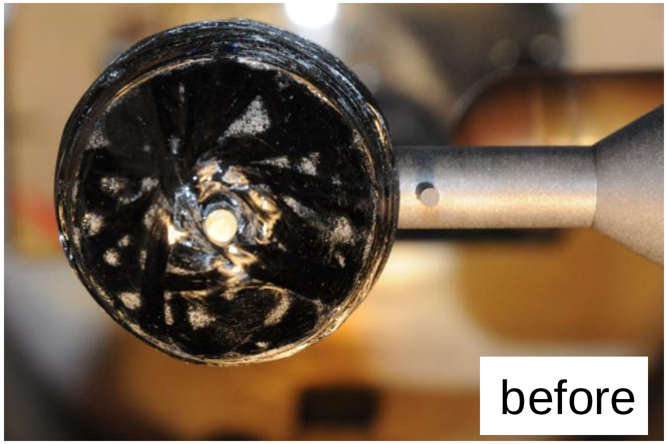
	Tumbling (average heat flux)	Tumbling (stagnation heat flux)
	Qmax = 378 kW/m² Ptot = 40 mbar Time = 141 s	Qmax = 2415 kW/m² Ptot = 40 mbar Time = 132 s
	Qmax = 378 kW/m² Ptot = 40 mbar Time = 141 s	Qmax = 3234 kW/m² Ptot = 40 mbar Time = 94 s

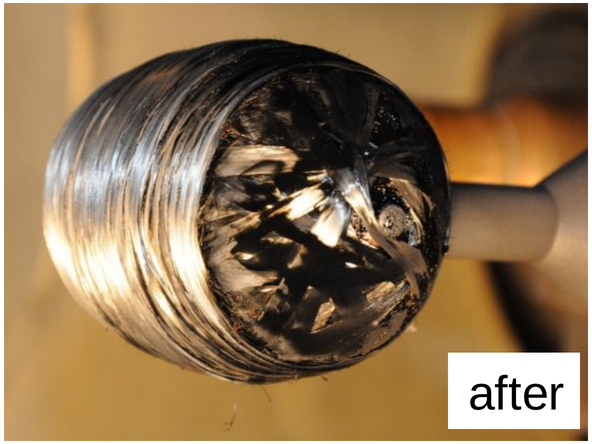
Demise of scaled sample (cylinder configuration) in Plasmatron conditions accounting for tumbling motion

Heat flux	Pressure	time
0.5 MW/m^2	55mbar	141s

- Uniform heating in stagnation region
- Pyrolysis of the epoxy resin
- Barely any ablation in those conditions
- Fibers do no delaminates

Increasing heat flux and exposed until demise

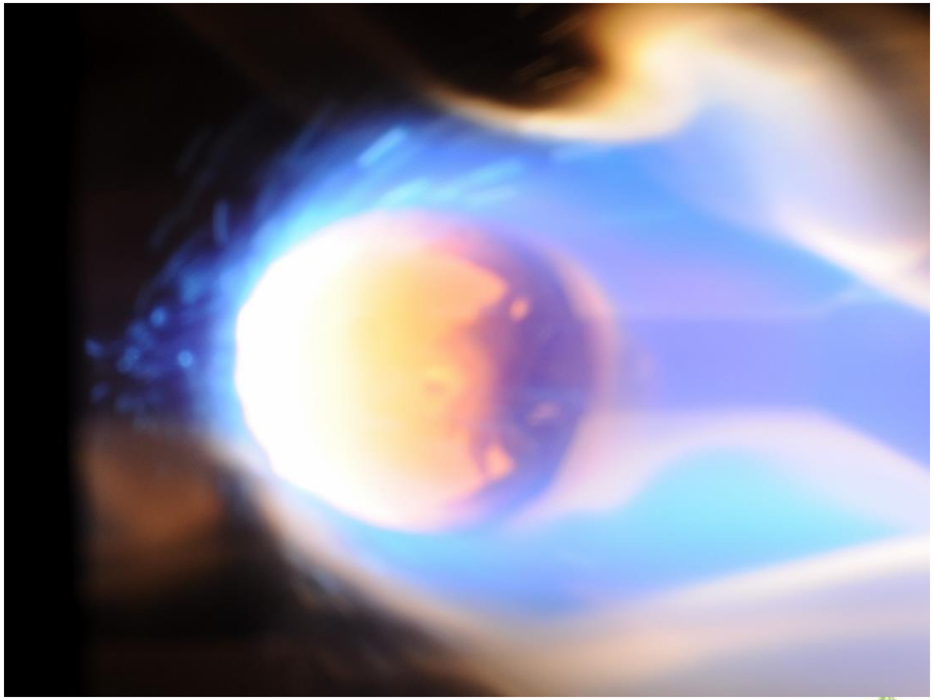




Demise of scaled sample (cylinder configuration) in Plasmatron conditions accounting for tumbling motion

- Large time to demise
- No delamination of the fibers (ablation and spallation)
- Strong metallic species blowing after 10 min of exposure
- Melting and hole in the liner created in the stagnation region

Heat flux	Pressure	time
1,7 MW/m^2	55mbar	900s



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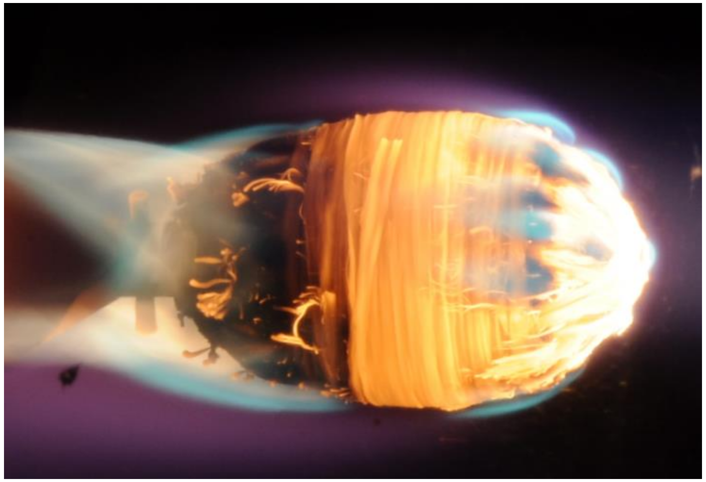
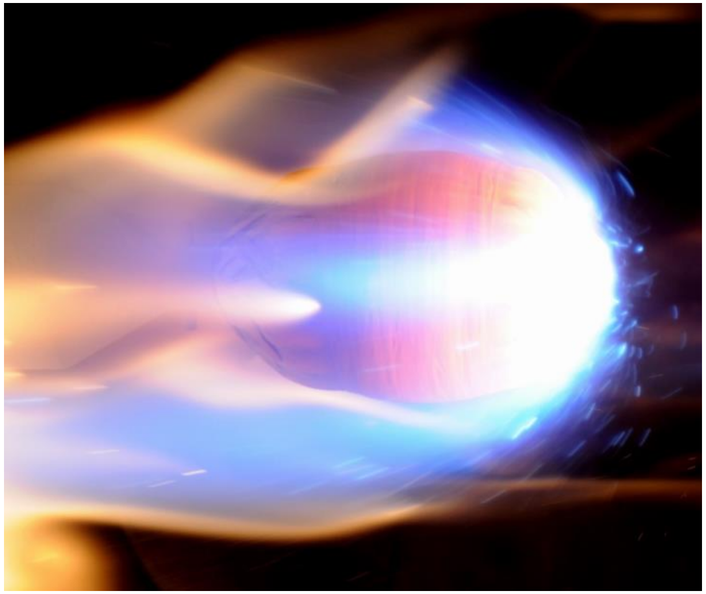
Demise of scaled sample (hemisphere configuration) in Plasmatron conditions accounting for tumbling motion

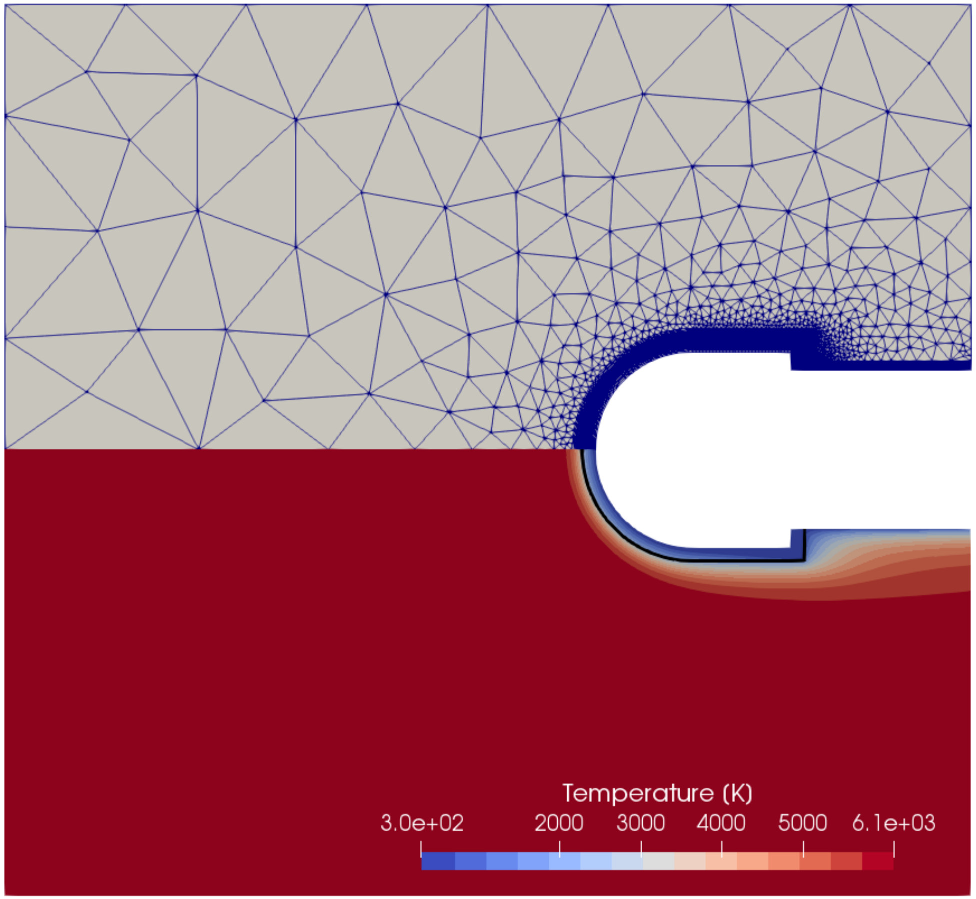




Heat flux	Pressure	time
0.5 MW/m^2	55mbar	141s
1,8 MW/m²	55mbar	400s

- Challenges to manufacture small scale sample with filament winding and hemispherical shape
- Similar trend as for side way configuration
- Few delamination of the fibers until demise
- Average heat flux in tumbling conditions not sufficient to ablate the material (mainly pyrolysis)
- Uniform heating but melting of the liner off stagnation point (due to manufacturing issues)

Strong coupling approach to model flow and porous medium in the same domain of computation



Mass :

- *Gas (9 species considered)*

$$\begin{aligned}\frac{\partial \epsilon_g \langle\rho_i\rangle_g}{\partial t} + \nabla\cdot(\epsilon_g\langle\rho_i\rangle_g\langle u\rangle_g) = \\ \nabla\cdot\left(\epsilon_g \frac{D_{i,m}}{\eta}\langle\rho_i\rangle_g \frac{W_i}{W}\nabla X_i\right) + \langle\dot\omega\rangle + \Pi_g\end{aligned}$$

- *Solid (fibers + char + resin)*

$$\frac{\partial \epsilon_s\langle\rho_s\rangle_s}{\partial t} = \langle\dot\omega^{het}\rangle - \Pi_g$$

Momentum :

$$\begin{aligned}\frac{\partial(\epsilon_g\langle\rho u\rangle_g)}{\partial t} + \nabla\cdot(\epsilon_g\langle\rho\rangle_g\langle u\rangle_g\langle u\rangle_g) = \\ -\epsilon_g\nabla\langle P\rangle_g + \nabla\cdot\langle\tau\rangle + F\end{aligned}$$

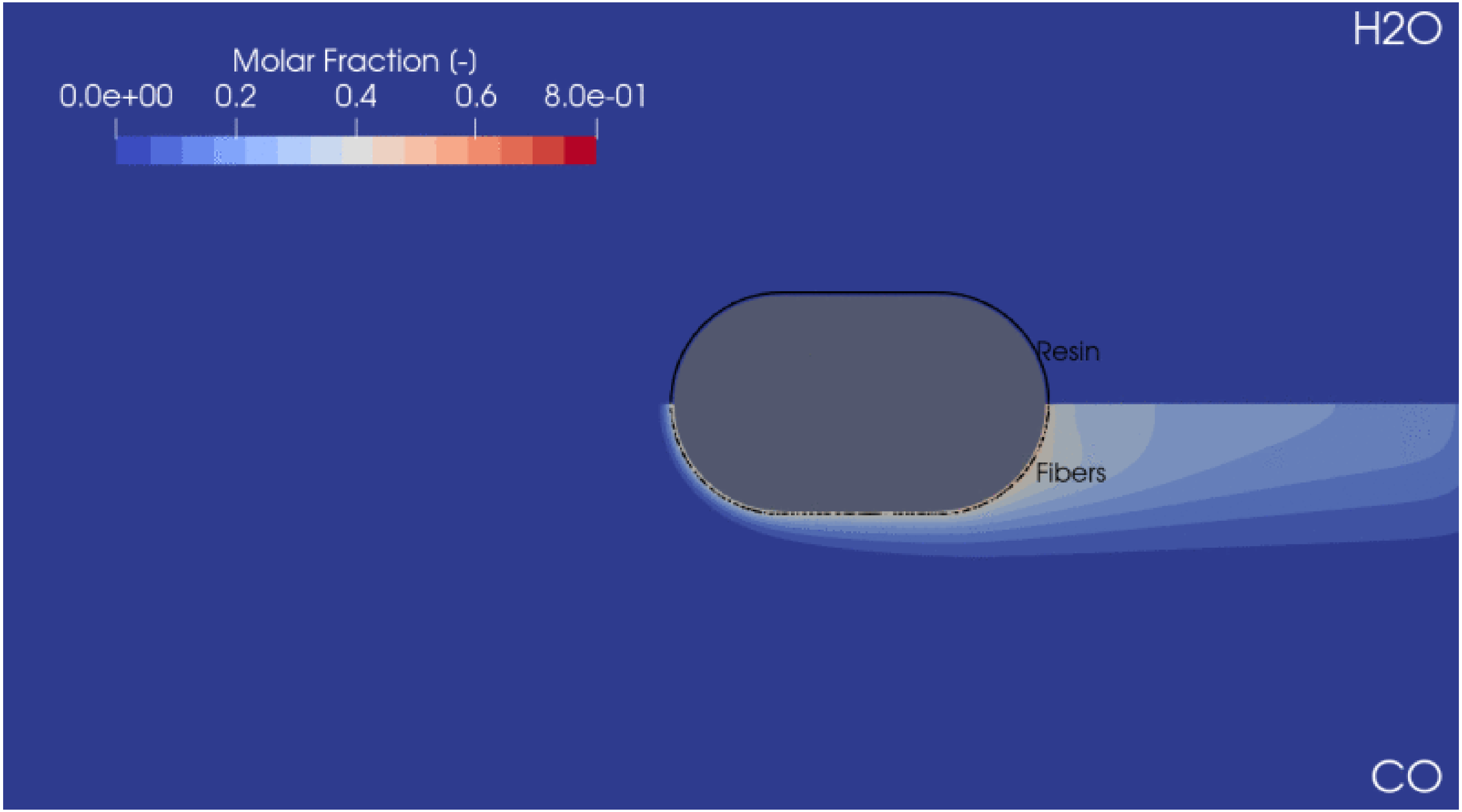
Energy :

$$\begin{aligned}\frac{\partial\langle\rho E_{tot}\rangle}{\partial t} + \nabla\cdot(\epsilon_g\langle\rho\rangle_g\langle H\rangle_g\langle u\rangle_g) \\ = \nabla\cdot(\lambda_{eff}\nabla T) + \nabla\cdot(\langle\tau\cdot u\rangle)\end{aligned}$$

Strong gradients to be captured in unified method for dense material responses

Properties	Value for CFRP (high density composite material)	Values for TACOT (low density composite material)
Virgin density [kg/m³]	1574,56	280
Virgin porosity [-]	0,04	0,8
Char density [kg/m³]	1158,76	220
Char porosity [-]	0,31	0,85
Conductivity	anisotropic	Isotropic
Initial radius of the fibers [µm]	3,25	5
Tortuosity [-]	1,1	1,1
Permeability [m²]	1,6e-11	1,6e-11
Emissivity [-]	0,9	0,9

Preliminary experimental results



Conclusion and perspectives

Objectives:
Develop high-fidelity models for Carbon Fibers Reinforced Polymers materials based on numerical and experimental campaign

- Extension of unified approach to treat dense anisotropic charring materials

- Reproduction of similar atmospheric entry conditions for COPV tanks
  - Design and manufacturing of small scaled samples tanks (to avoid delamination)
  - Definition of representative test matrix in Plasmatron
  - Test campaign performed on first batch of sample

- Preliminary numerical campaign to study dense material response in Plasmatron conditions
  - Reproduction of experimental cases
  - Comparison with experimental data (time to demise, surface temperature, recession rate, thermocouple data)

Thank you for your attention and thanks to

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