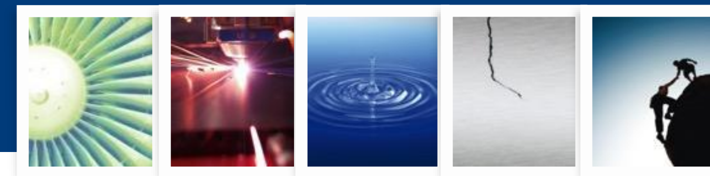

Demise of CFRP materials in atmospheric entry conditions

Aerothermodynamics and Design for Demise (ATD3) Workshop
2nd December 2021

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B. Helber, O. Chazot, T.E. Magin, L. Walpot
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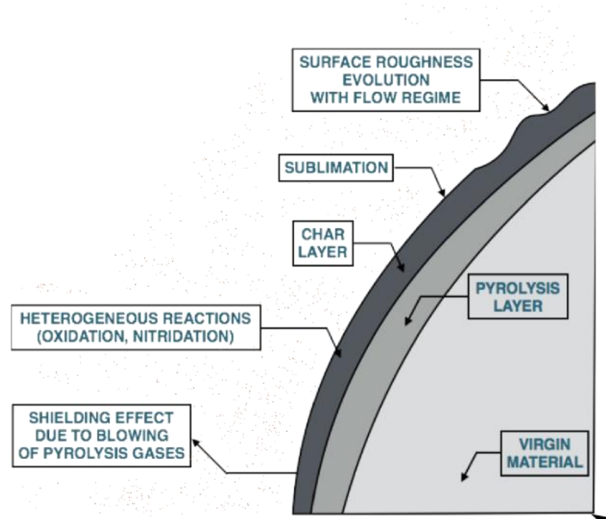
PROD-F-015-02

High fidelity simulations of degrading materials subjected to high enthalpy flows

CFRP materials

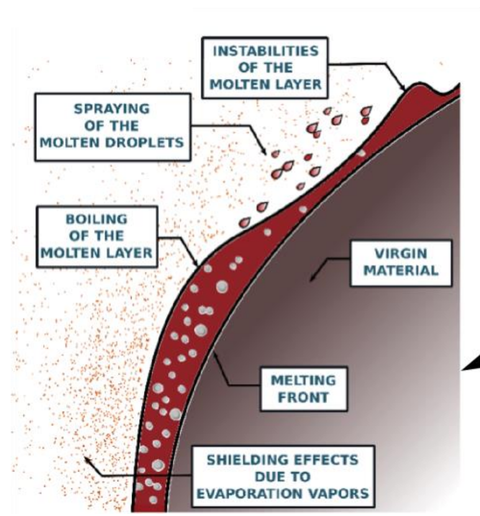
GSTP-4000122710/17/NL/KML

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



Metallic and glassy materials

GSTP-4000125437/18/NL/RA



Next talk @11:20 by B. Helber

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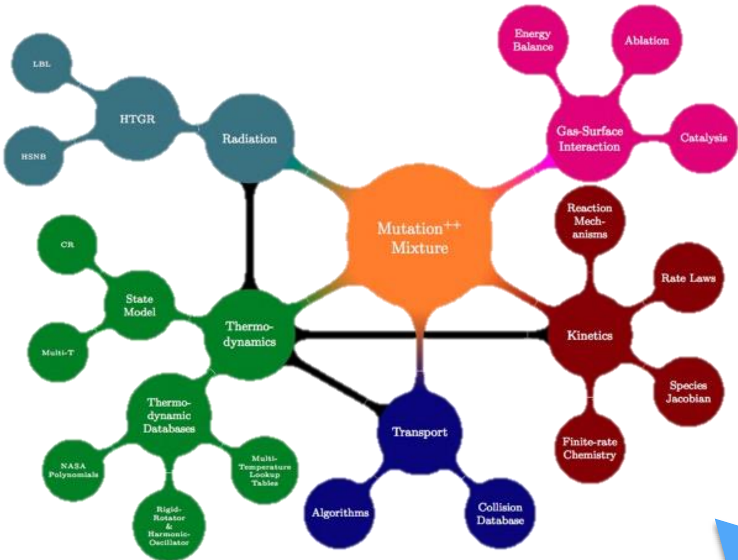
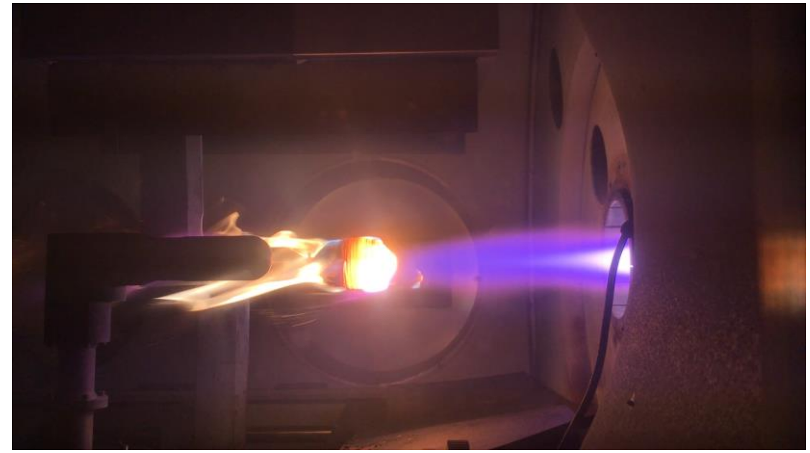
Reproduction of CFRP demise in Plasmatron conditions



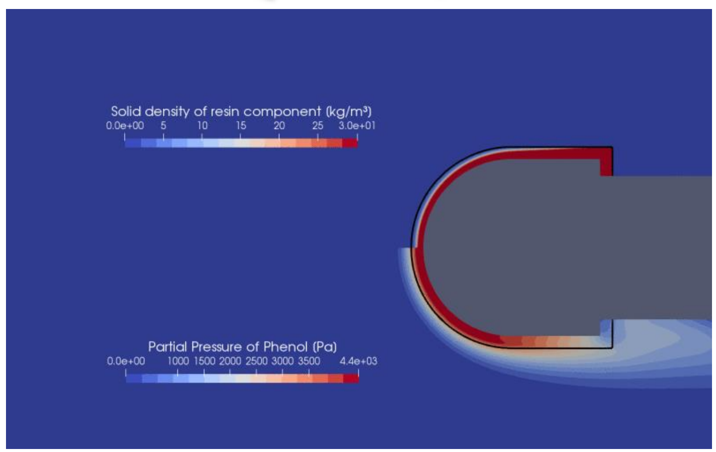
Models

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

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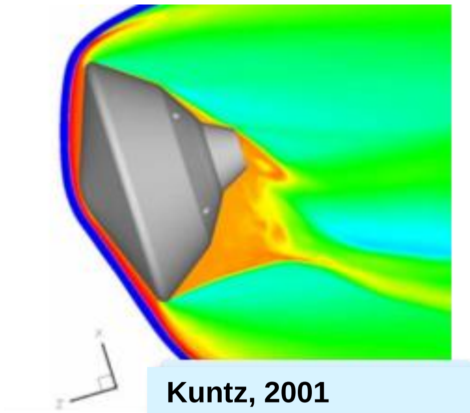
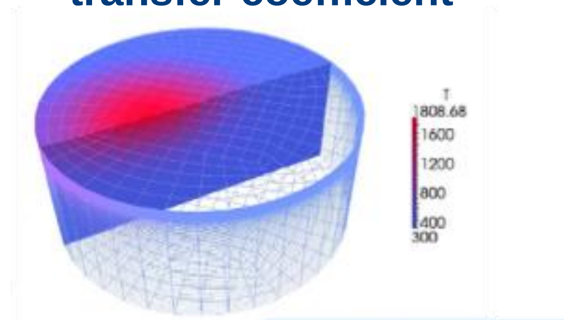
Numerical methods to simulate the response of porous ablative materials

1 CFD code with ablative BC



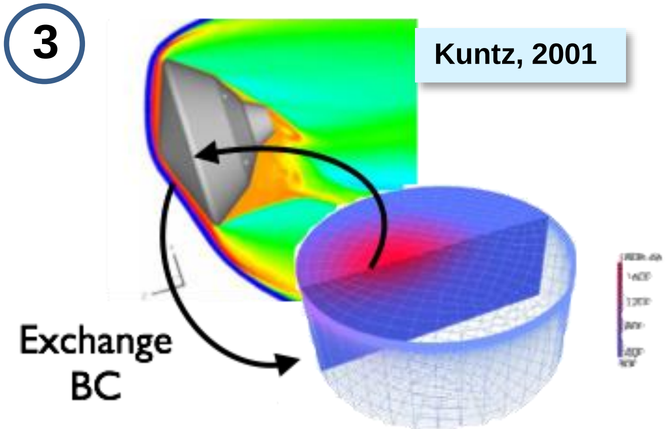
Kuntz, 2001

2 Material response code with heat transfer coefficient



Lachaud et al. (2008)

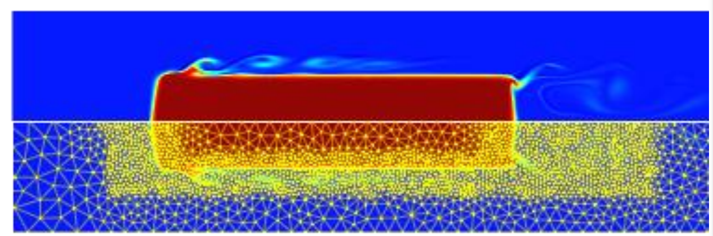
3



Kuntz, 2001

Weak coupling

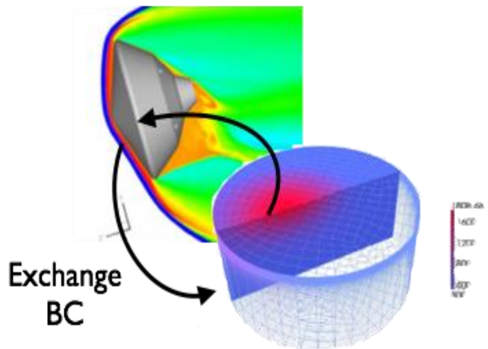
4



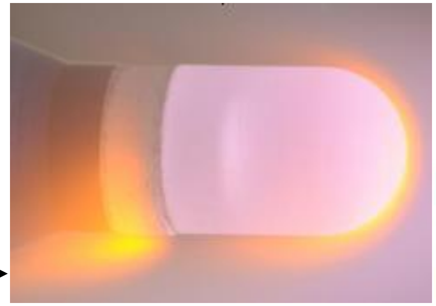
Schrooyen et al., 2016
Weng et al., 2017

Strong coupling

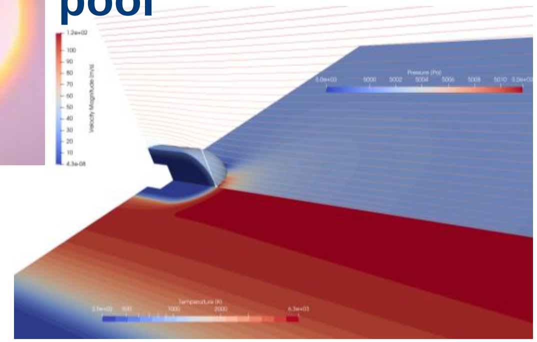
Coupled methods to investigate gas-surface interaction

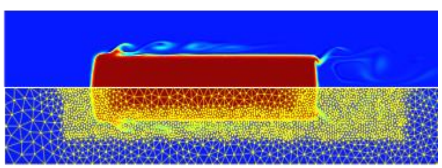


Weak coupling



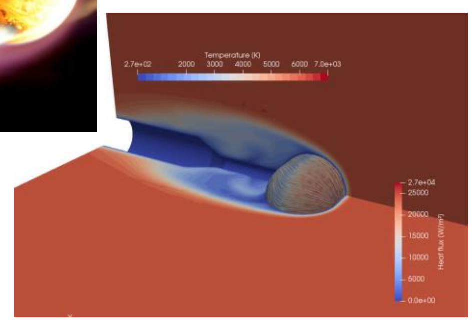
For phase changing material**, weak coupling in between compressible gas phase and hydrodynamic equations describing the melt pool**





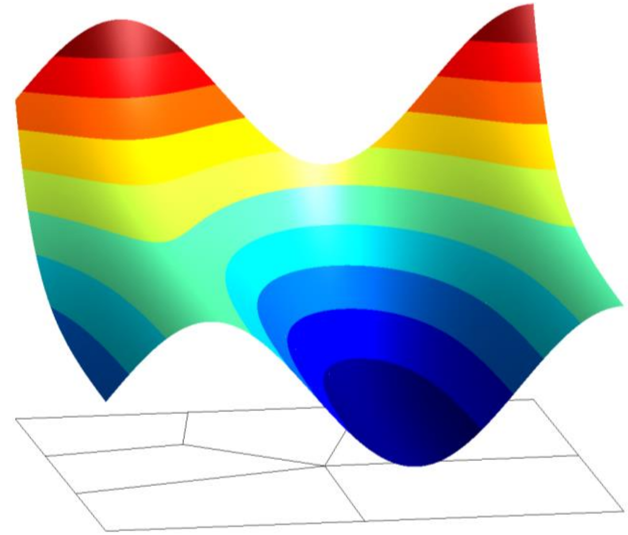
Strong coupling

Unified method to treat compressible flow and porous material **response**

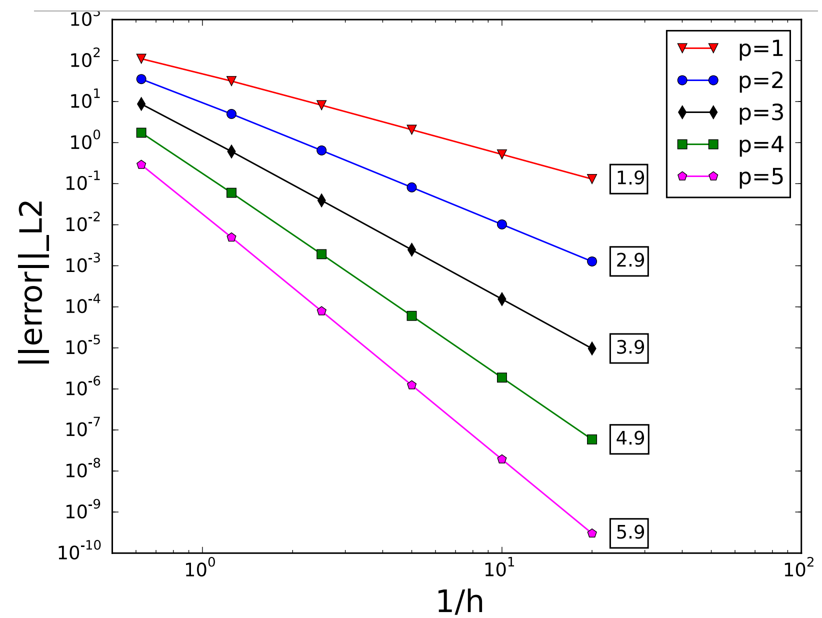


High order Discontinuous Galerkin is advantageous for accuracy and efficiency but lacks of robustness

- Advantages
  - Ability to handle complex geometries
  - Guaranteed order of convergence p+1 on unstructured meshes
  - No degradation near size jumps/walls
  - Good dispersion-dissipation properties
  - hp-adaptation
  - Hybrid structured/unstructured mesh
  - Shared operations (parametric)
  - Local operations
  - Low transfer work and operation hiding possible (parallel efficiency)
- Drawbacks
  - Duplication of the degrees of freedom on the element boundaries (costly)
  - Sensitive to under-resolved features



p=6



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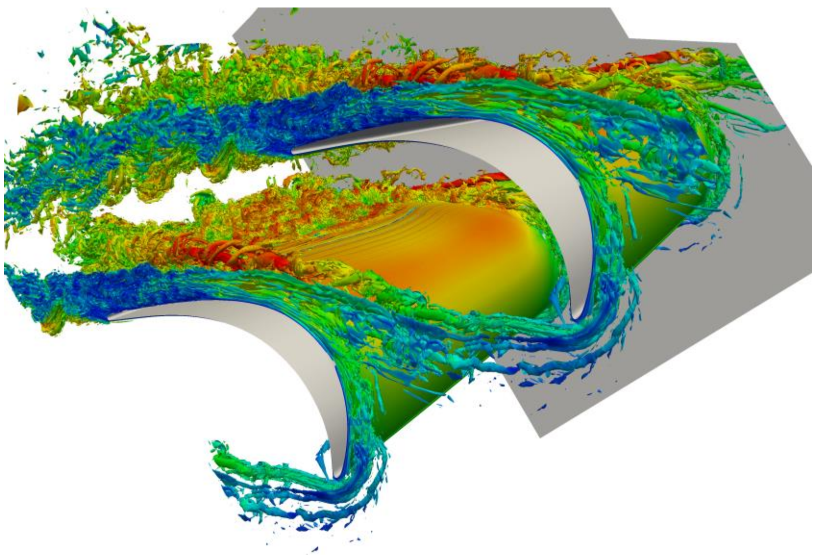
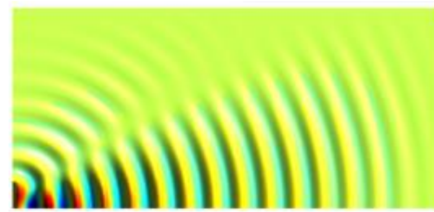
Argo is a multiphysics high resolution and high performance platform based on DGM

Function spaces and bases	Adaptive curved mesh database	Constitutive laws / physical models	Solvers and time integrators	$\int_e \frac{\partial \phi_i}{\partial x^k}$ Discretisation and data structures

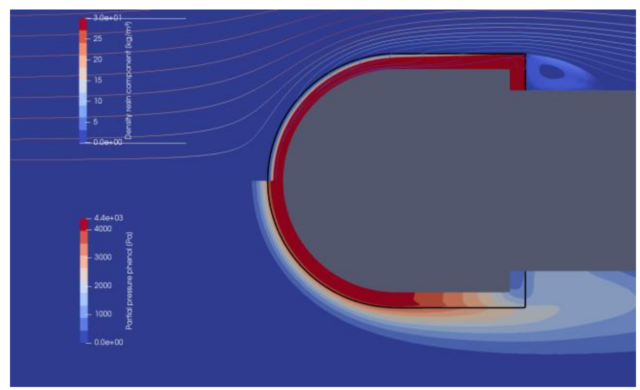
DGFluid: *Scale resolving simulations (DNS, LES) of practical turbulent flows*



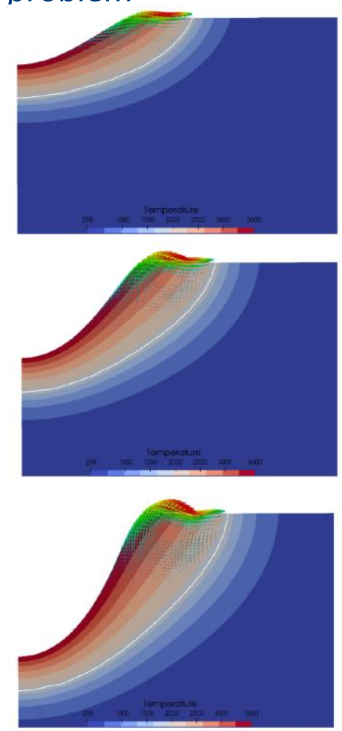
DGAcoustics *: near field acoustics*



DGAblation: *ablative porous materials and reactive flow*



DGAM *: Hydrodynamics, thermal and mechanical problem*



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Weak coupling for simulating melting material

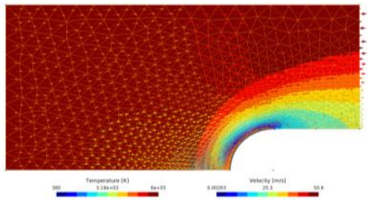
Solve steady state flow using Argo

Heat flux
Shear stress
Pressure distribution

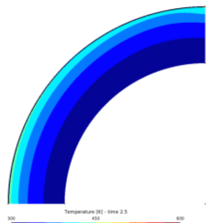
Solve material solver (time marching accounting for surface recession)

Surface position
Wall temperature

New mesh for the external flow



Argo flow solver



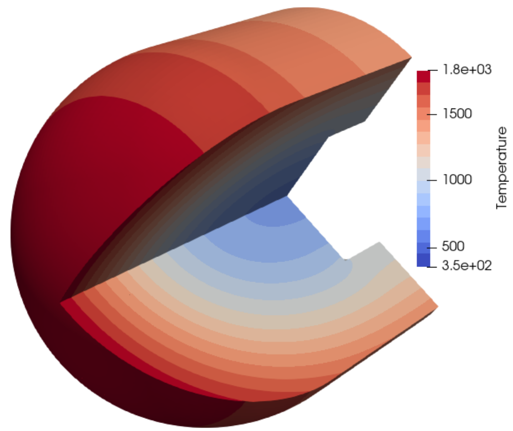
Argo material solver

GSMH python script to remesh

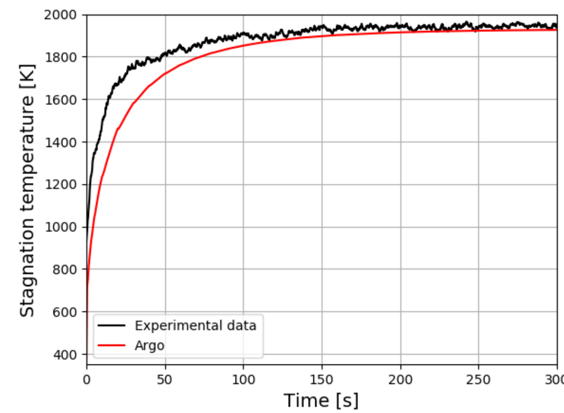
Gmsh

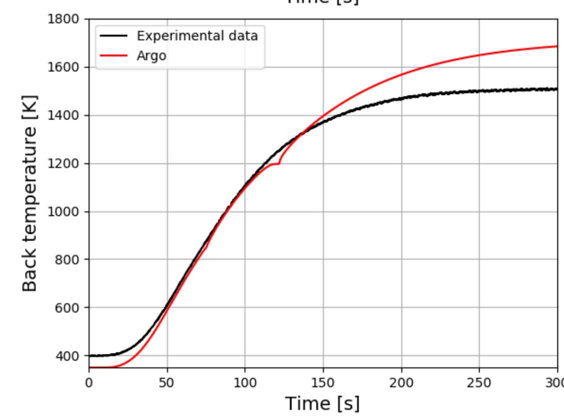
Bash script to ensure coupling and exchange of solutions

Reproduction of Titanium (G2/G5), Quartz and Zerodur materials in Plasmatron conditions



30 mm diameter Quartz response to Plasmatron low heat flux setup





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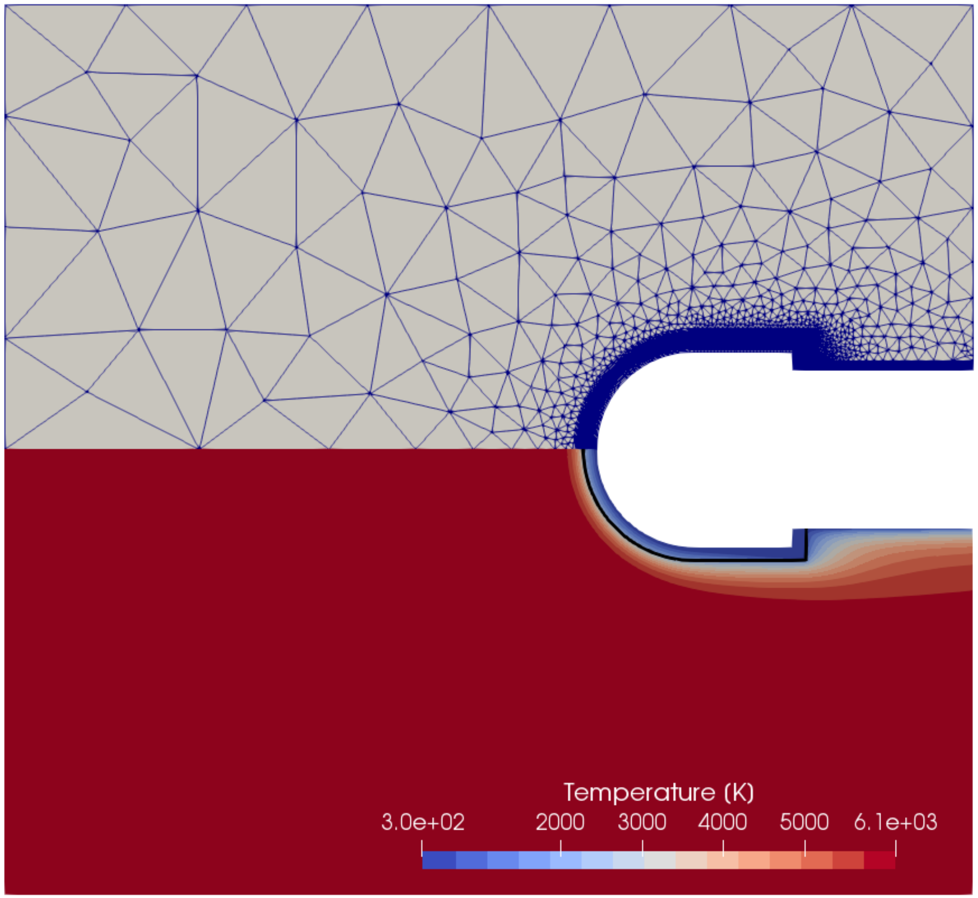
Strong coupling approach to model flow and porous medium in the same domain of computation



Mass :

- *Gas*

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

- *Solid (fibers + char + resin)*

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

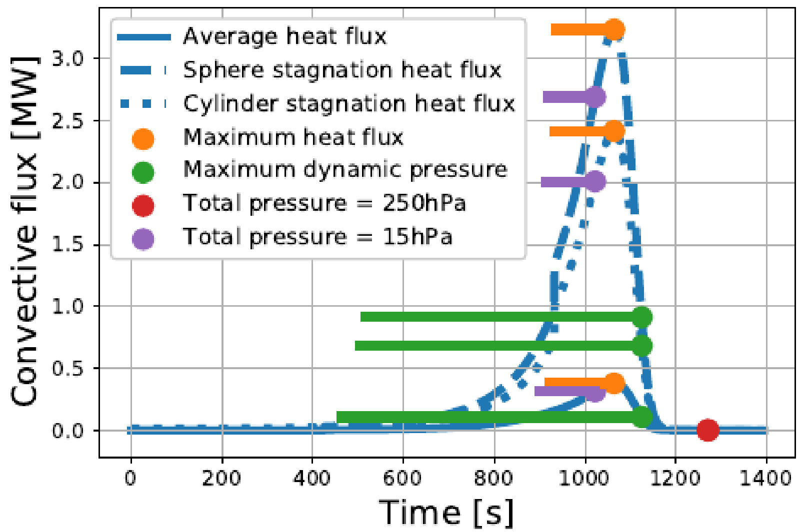
Momentum :

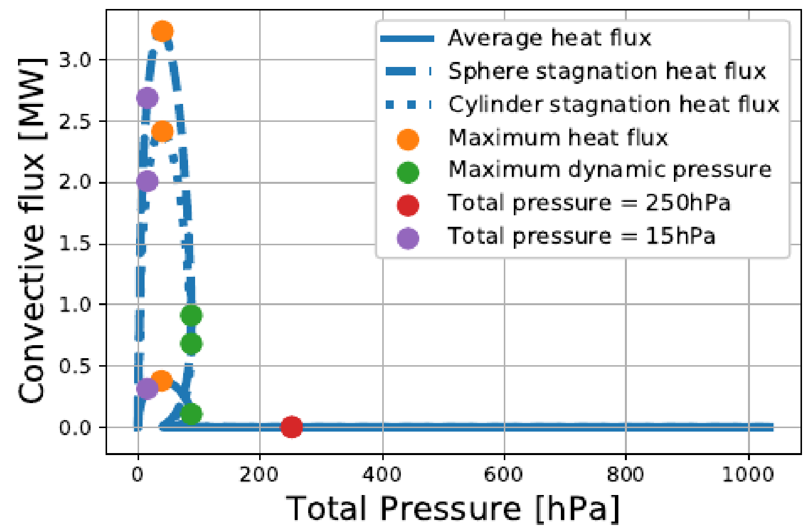
$$\frac{\partial (\epsilon_g \langle \rho u \rangle_g)}{\partial t} + \nabla \cdot (\epsilon_g \langle \rho \rangle_g \langle u \rangle_g \langle u \rangle_g) = -\epsilon_g \nabla \langle P \rangle_g + \nabla \cdot \langle \tau \rangle + F$$

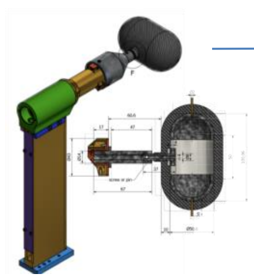
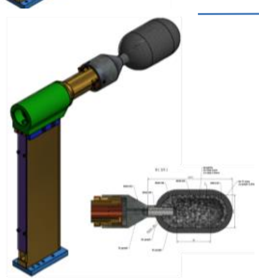
Energy :

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

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

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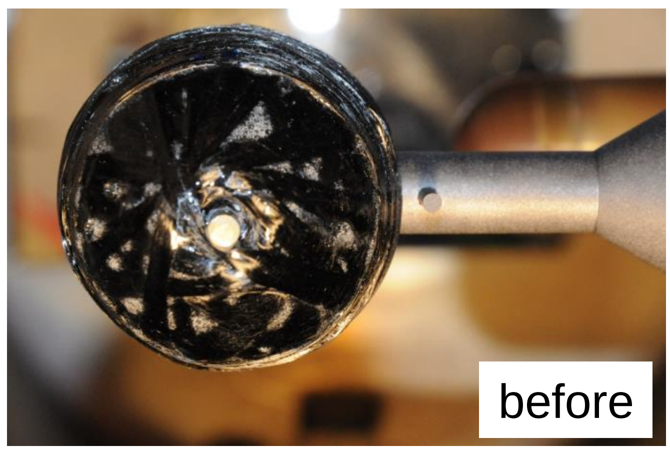
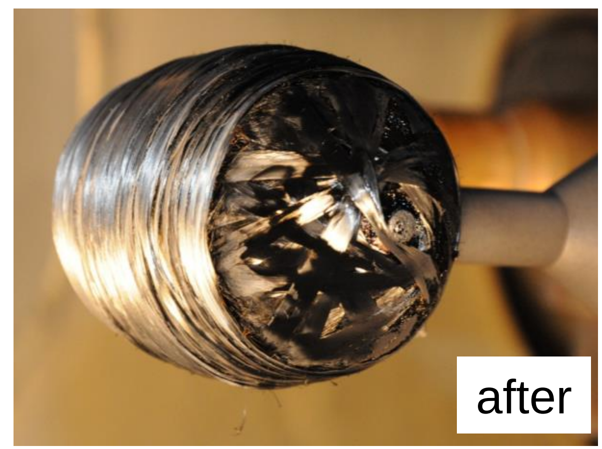
Demise of scaled sample (cylinder configuration) in Plasmatron conditions accounting for tumbling motion

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

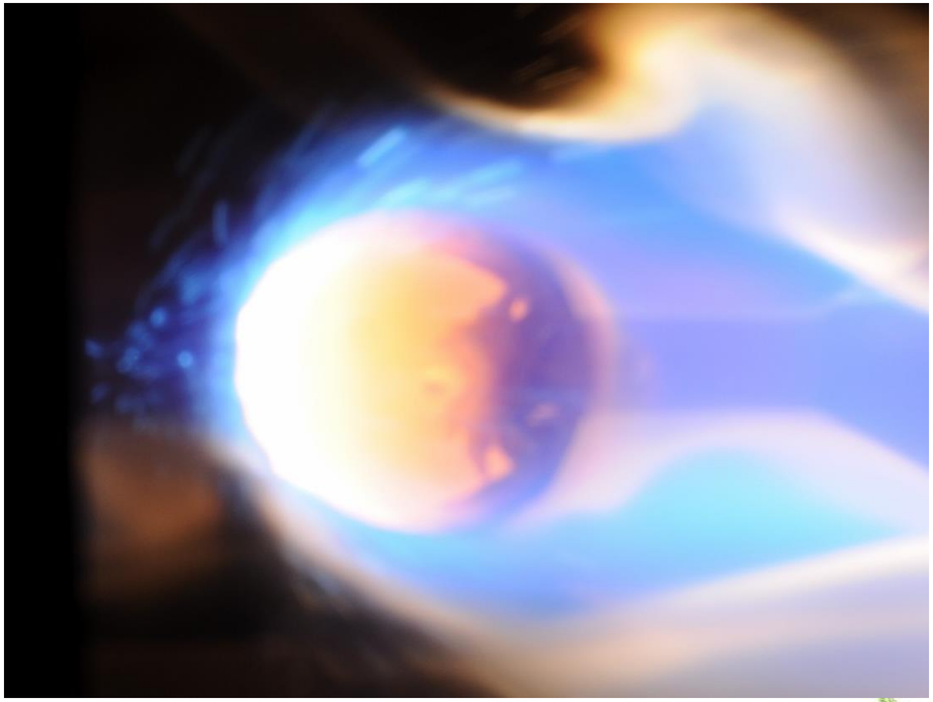




Demise of scaled sample (cylinder configuration) in Plasmatron conditions accounting for tumbling motion

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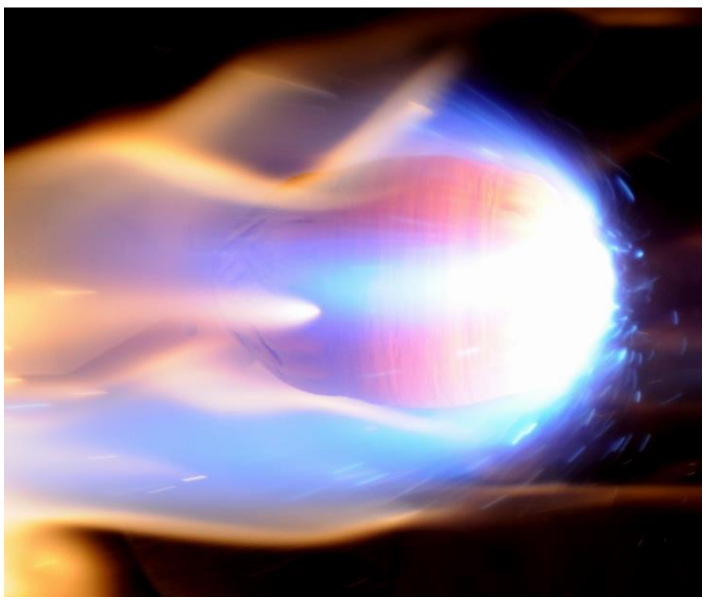
Demise of scaled sample (hemisphere configuration) in Plasmatron conditions accounting for tumbling motion



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

- Similar trend as for side way configuration
- Few delamination of the fibers until demise (mostly thermo-chemical ablation)
- Average heat flux in tumbling conditions not sufficient to ablate the material (mainly pyrolysis)
- Uniform heating but melting of the liner off stagnation point (demise after 5-6 minutes)

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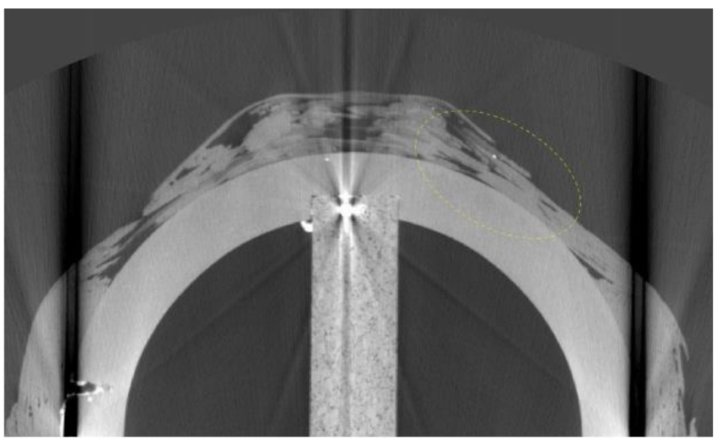
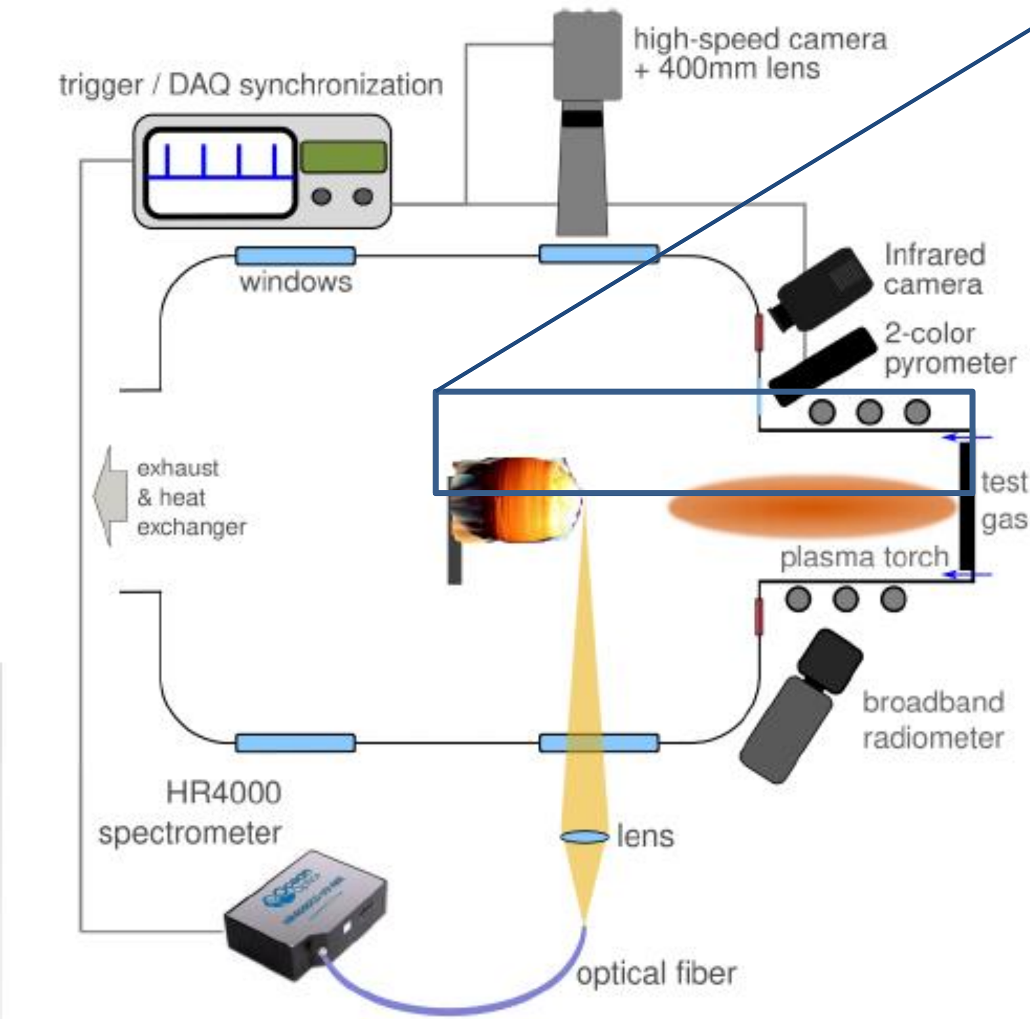
Demise of scaled sample (hemisphere configuration) in Plasmatron conditions accounting for tumbling motion

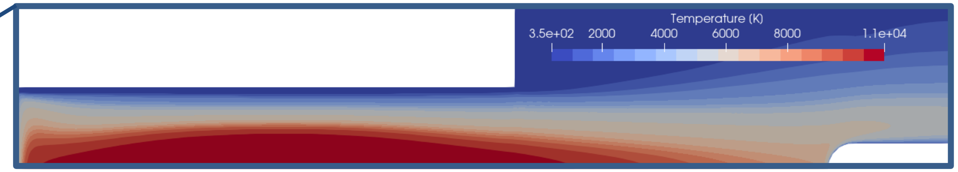


- Challenges to manufacture small scale sample with wet filament winding, hemispherical shape and thick layer of CFRP
  - Final geometry not axisymmetric
  - Non homogeneous thickness
  - Smoothness of the COPV envelope

→ **Manufacturing and test of new batch of sample**

Numerical reproduction of the experimental campaign





ICP simulation

Steady magneto-hydrodynamic flow simulation assuming chemical equilibrium (VKI ICP code)

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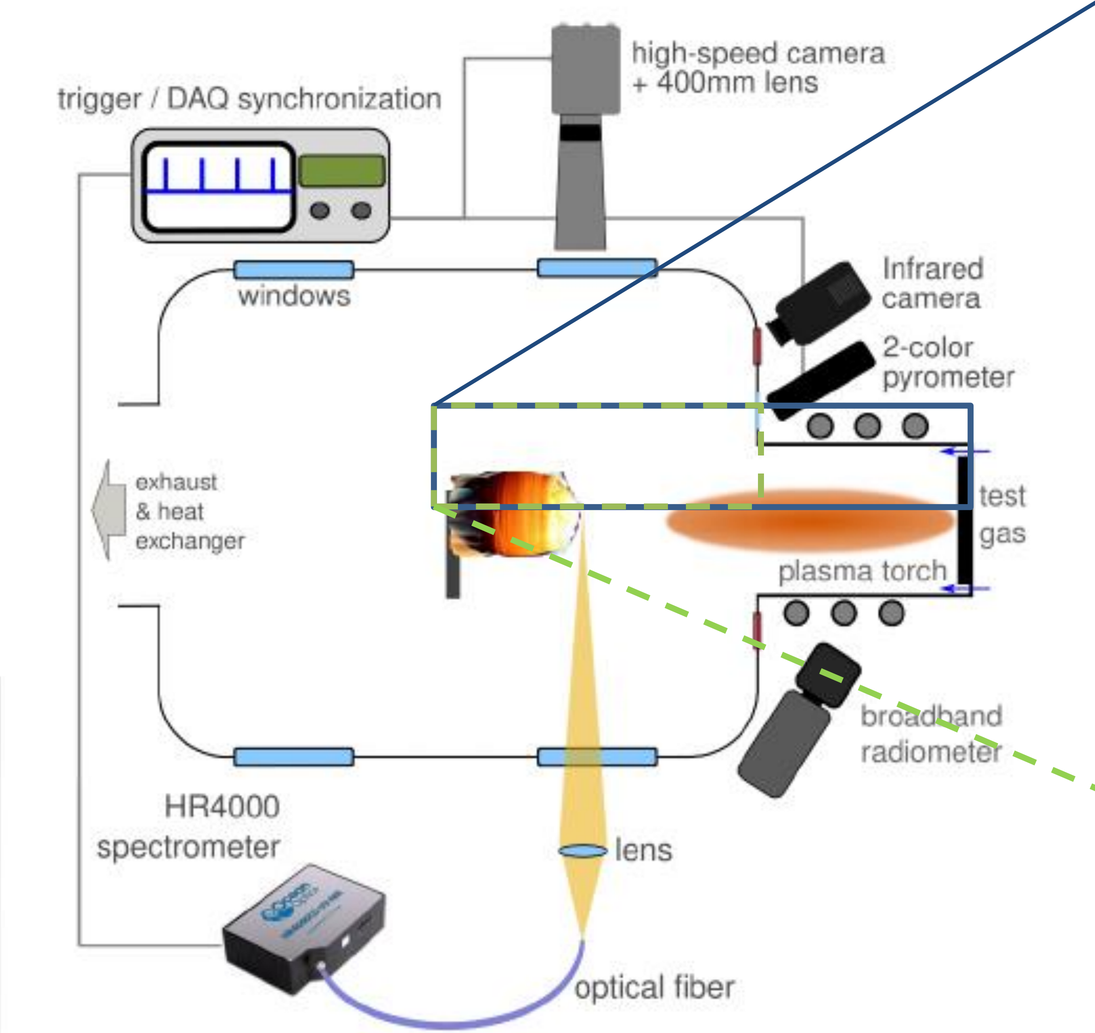
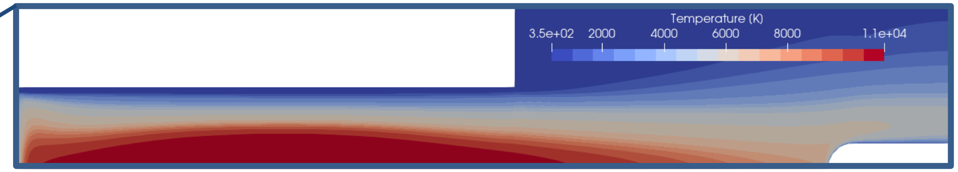
Numerical reproduction of the experimental campaign





ICP simulation

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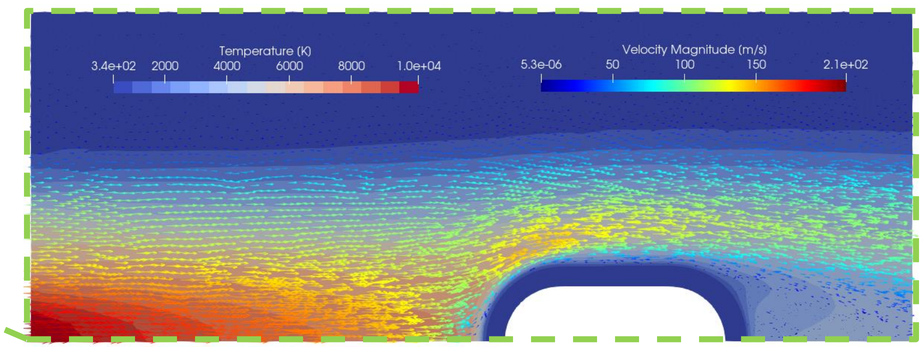

Flow and material response

Unsteady Volume Average Navier-Stokes simulation assuming chemical non-equilibrium

(Argo code)

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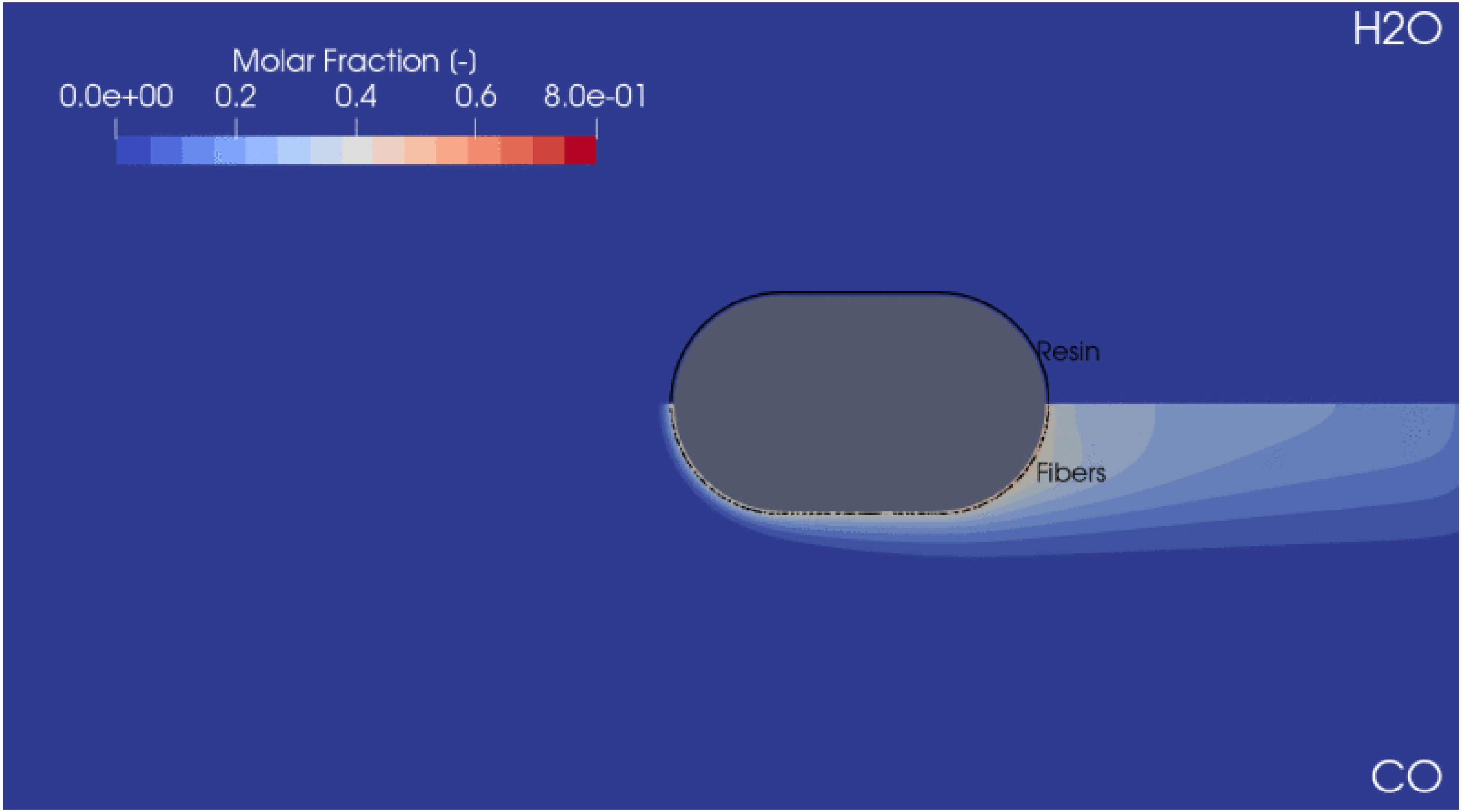
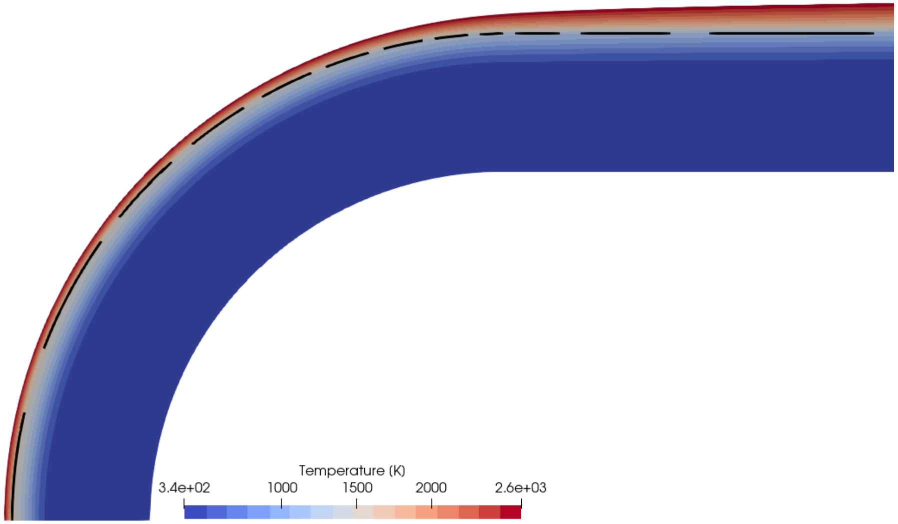
Strong gradients to be captured in unified method for dense material responses

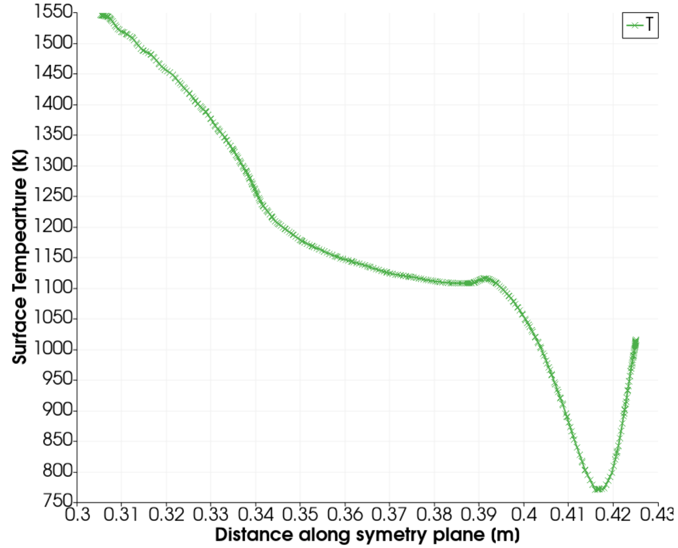
Properties	Value for CFRP (high density composite material)	Values for TACOT (low density composite material)
Virgin density [kg/m³]	1574,56	280
Virgin porosity [-]	0,04	0,8
Char density [kg/m³]	1158,76	220
Char porosity [-]	0,31	0,85
Conductivity	anisotropic	Isotropic
Initial radius of the fibers [µm]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

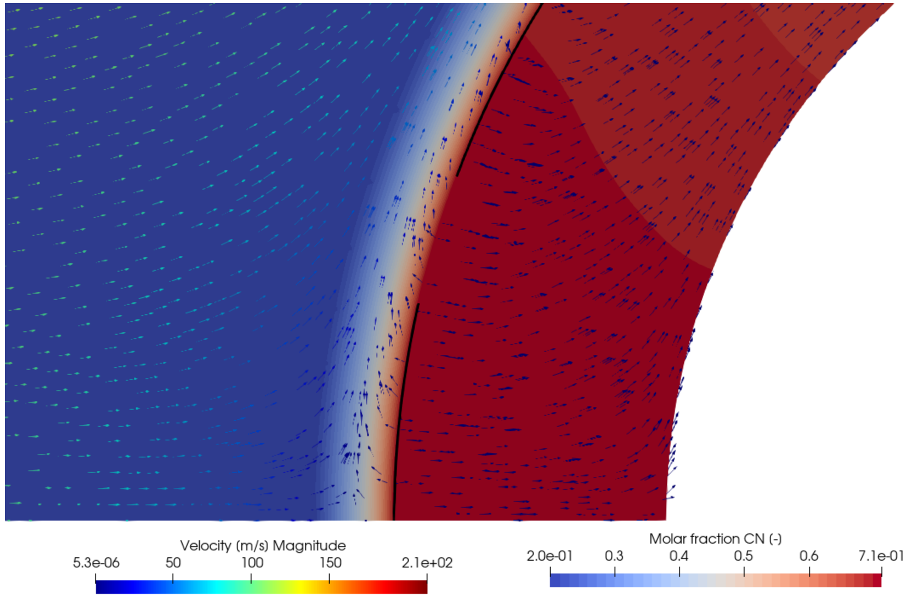
Unified solution for CFRP material response

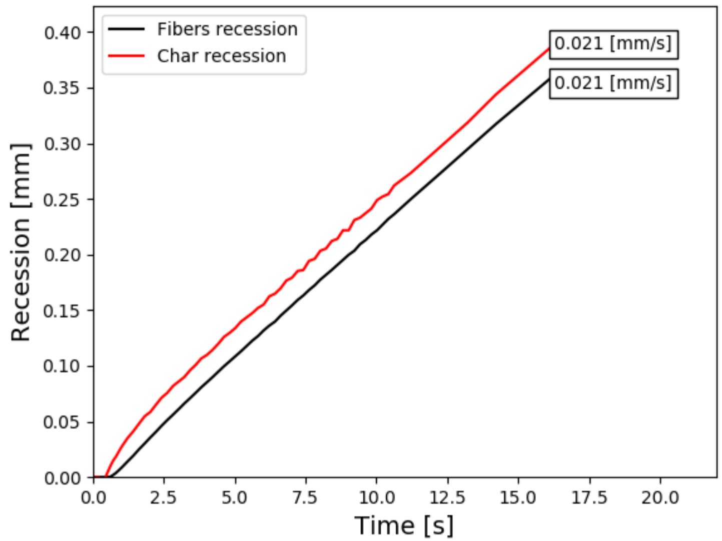


Demise of scaled sample (hemisphere configuration) in Plasmatron conditions accounting for tumbling motion









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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)