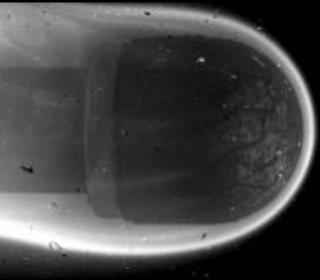


Methodology for ablation investigations in the VKI Plasmatron facility: Preliminary results with a carbon fiber preform

5th Ablation Workshop, Lexington (KY), Februrary 27th - March 01st 2012

Bernd Helber[1,2], Olivier Chazot[1], Annick Hubin[2] and Thierry Magin[1]

[1]Aeronautics and Aerospace Department, von Karman Institute for Fluid Dynamics, Belgium

[2]Department of Electrochemical and Surface Engineering, Vrije Universiteit Brussel

Outline

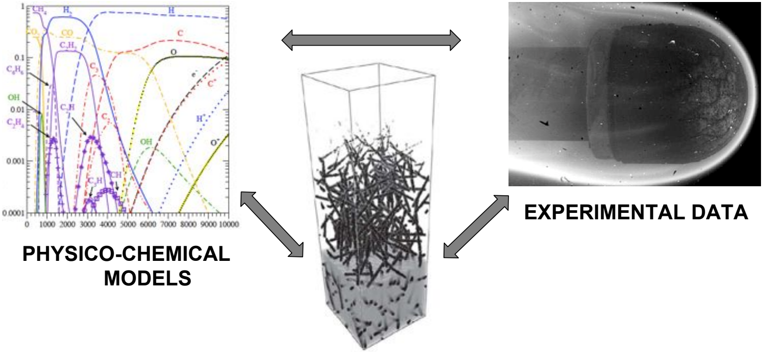
1. Introduction
2. Ground testing in Plasmatron facility
3. Numerical tools development
4. Results with a carbon fiber preform (preliminary)
5. Conclusions and perspective

Outline

1. Introduction
   - Background
   - Overview of ablation test campaigns at VKI
   - Research goals
2. Ground testing in Plasmatron facility
3. Numerical tools development
4. Results with a carbon fiber preform (preliminary)
5. Conclusions and perspective

Background: VKI

Ablation investigations for high enthalpy plasma flows and hypersonic applications



PHYSICO-CHEMICAL MODELS

EXPERIMENTAL DATA

COMPUTATIONAL METHODS

Basic ingredients for prediction in aerospace science

Overview of ablation test campaigns at VKI

2002-2009	**Graphite**	Material used for basic research (Vancrayenest, Fletcher)
2009-2011	**Cork composites (P50, AMORIM)**	Advanced TPM (cork/phenol compound) (Norcoat-Liege, ARD back-shell)
2009-2010	**Monolythic carbon composite (MonA)**	More advanced, low density TPM (AMOD program)
2011-2012	**Carbon fiber preform**	Similar to precursor for European ablator (Mersen Scotland, Ltd.)
⇒ 2012	**PICA-like materials**	ASTERM tests scheduled for 2012 (EADS Astrium)

Research goals

Definition of a methodology to characterize material response and gas-gas / gas-surface interaction of innovative ablators in the VKI Plasmatron facility

Ablation modelling framework for development of material response models for carbon / resin composites and coupling with in-house codes

Model validation

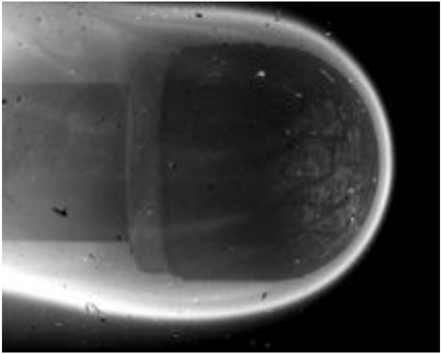
Flight extrapolation

Outline

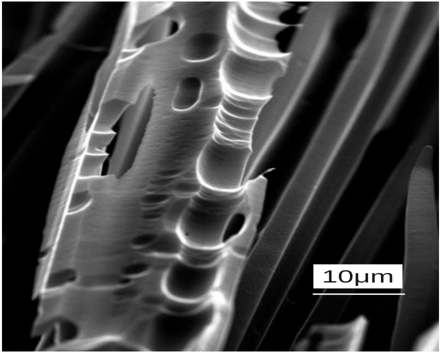
1. Introduction
2. Ground testing in Plasmatron facility
    - Plasmatron facility
    - Recession Analysis
    - Emission Spectroscopy
3. Numerical tools development
4. Results with a carbon fiber preform (preliminary)
5. Conclusions and perspective

High-enthalpy tests combined with multiscale characterization

von Karman Institute:
Analysis in High-Enthalpy Plasma Flows

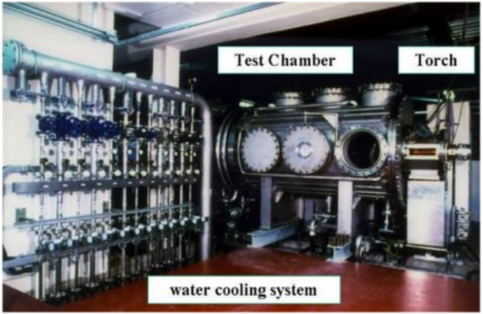


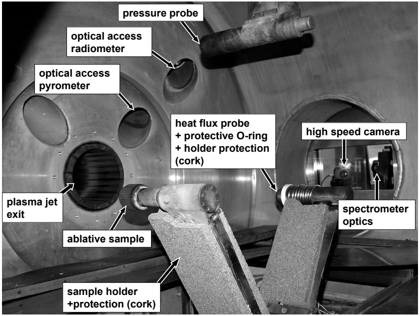
Vrije Universiteit Brussel:
Multiscale Characterization (SEM, EDX, XPS, AES)



Plasmatron facility

1.2 MW Inductively Coupled Plasmatron (ICP)

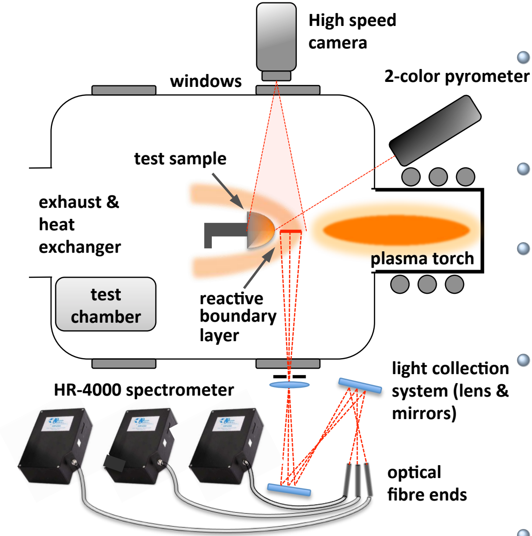




Plasmatron test chamber showing experimental setup and torch exit

- Gas: Air, N_2, CO_2, Ar
- Power: 1.2 MW
- Heat-flux: 90 $\mathrm{kW/m^2}$ - 10 $\mathrm{MW/m^2}$
- Pressure: 10 mbar - 600 mbar

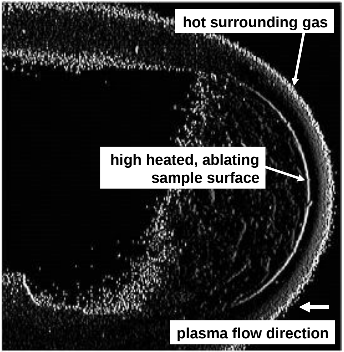
Measurement techniques development

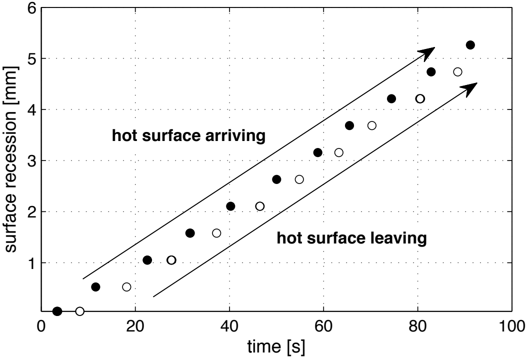


- **Radiometry**
  surface temperatures & emissivity
- **Thermocouples**
  Internal temperature histories
- **High-speed-camera**
  in-situ recession and gas-phase analysis
- **Optical emission spectroscopy**
  temporally and spatially resolved boundary layer chemistry
- **(future: recession sensors)**

MT: High Speed Camera Imaging

In-situ recession and visual gas phase studies *(AIAA 2011-2302)*



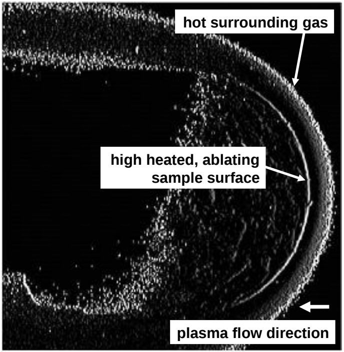


- In-situ recession analysis (linearity, dependence on outgassing)
  ⇒ Crucial data for model validation (large uncertainties)

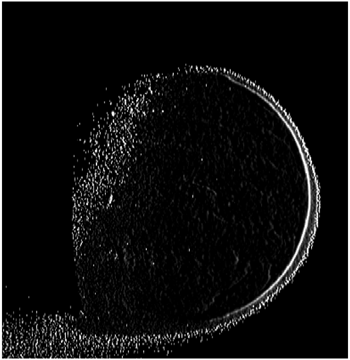
MT: High Speed Camera Imaging

In-situ recession and visual gas phase studies *(AIAA 2011-2302)*

Test start



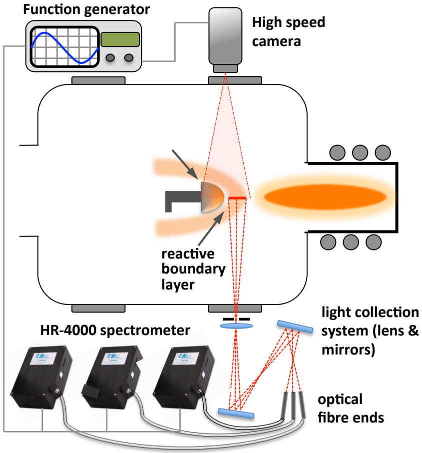
Test end



- In-situ recession analysis (linearity, dependence on outgassing)
  ⇒ Crucial data for model validation (large uncertainties)
- Gas phase observation (off-set of surrounding flame)
  ⇒ Outgassing effects

MT: Temporally & spatially resolved emission spectroscopy

Thermo-chemistry in reactive boundary layer



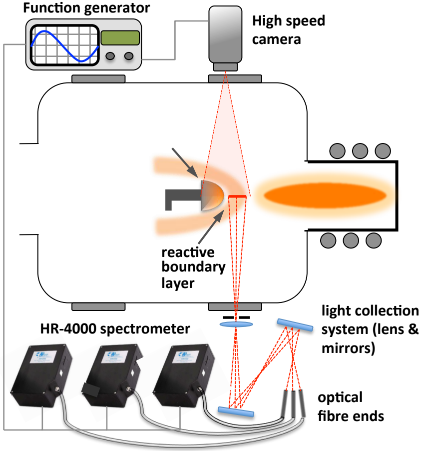
3 spectrometers with **broad wavelength range** per acquisition $(200 - 1000\,\mathrm{nm})$
$\Rightarrow$ temporal resolution (up to 5 ms)

imaging mode with **optical magnification** factor of ~ 2
$\Rightarrow$ narrow boundary layer screening (all spectrometers within $\sim$ 3mm)

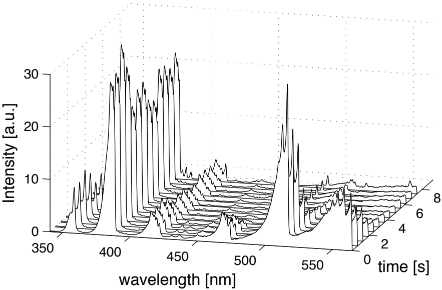
Function generator to **trigger acquisition with high-speed-camera**
$\Rightarrow$ temporally resolved distance of probing volumes from ablating surface

MT: Temporally & spatially resolved emission spectroscopy

Thermo-chemistry in reactive boundary layer (*AIAA 2011-2302*)



Temporal spectra of ablation of MonA in nitrogen plasma



→ CN violet, CN red, C_2 Swan, CH, Ca, K, Na, N, N_2, N_2^+, O

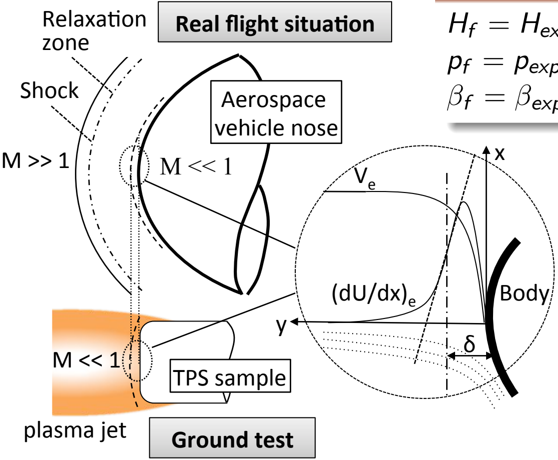
Outline

1. Introduction
2. Ground testing in Plasmatron facility
3. Numerical tools development
4. Results with a carbon fiber preform (preliminary)
5. Conclusions and perspective

Local Heat Transfer Simulation (LHTS)

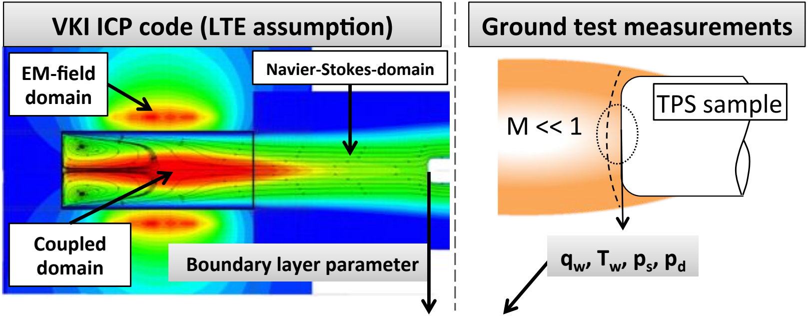
Rebuilding of freestream properties & stgn.pt. heat flux similarity:

$$H_f = H_{exp},$$
$$p_f = p_{exp},$$
$$\beta_f = \beta_{exp}, \ \beta = (dU/dx)_e$$



Kolesnikov, Fluid Dynamics, 28(1):131-137, 1993.

Combined numerical/experimental rebuilding procedure



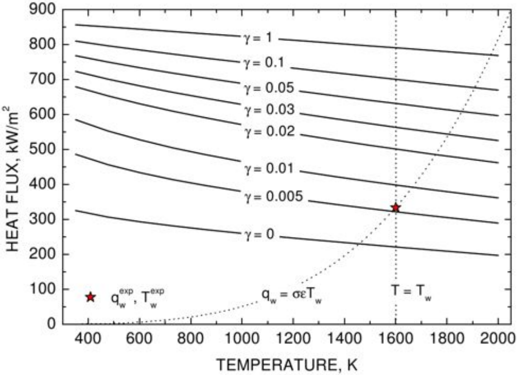
Boundary layer solver

- **Input**: Boundary layer parameter (LTE CFD computation) & measurements from experiments
- **Procedure**: Iteration on boundary layer edge temperature T_e:
  $\Rightarrow q_w^n = q_w^{(exp)} = q_w(\gamma, T_w, p_e, h_e, \beta, ...)$
- **Output**: Edge enthalpy H_e, boundary layer chemistry, (catalycity)

Stagnation point chemical environment

State-of-the-art (VKI)

Flight extrapolation & catalycity rebuilding for reusable heat shields

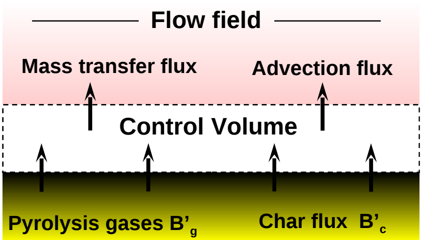


[*Panerai, F., Aerothermochemistry Testing of Thermal Protection Systems, Ph.D. thesis, VKI / University of Perugia*]

Stagnation point chemical environment

Extension to ablation

GSI models for CFD codes:
Control volume approach for B'-table generation (MUTATION)



Flow field

Mass transfer flux

Advection flux

Control Volume

Pyrolysis gases B'_g

Char flux B'_c

Assumptions:

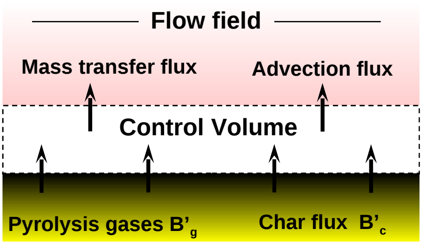
- Chemically active surface:
  → carbon char reacts with oxygen
- Chemically active species from
  → pyrolysis of decomposing material
  → edge of boundary layer (equilibrium chemistry)

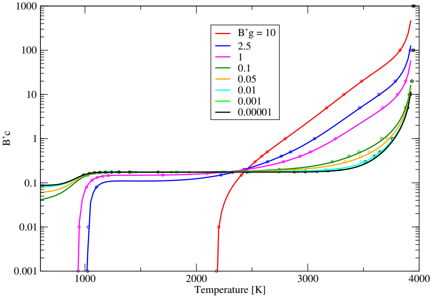
Collaboration J. de Muelenaere (VKI),
J. Lachaud & N.N. Mansour (NASA Ames) (*AIAA 2011-3616*)

Stagnation point chemical environment

Extension to ablation

GSI models for CFD codes:
Control volume approach for B'-table generation (MUTATION)





- ⇒ Coupling with stagnation line formulation
- ⇒ Development of a new approach to build B'-tables

Collaboration J. de Muelenaere (VKI),
J. Lachaud & N.N. Mansour (NASA Ames) (*AIAA 2011-3616*)

Stagnation point chemical environment

High-fidelity material response models

Boundary layer chemistry:

Damköhler number: $\tau_\mathrm{f} / \tau_\mathrm{chem}$

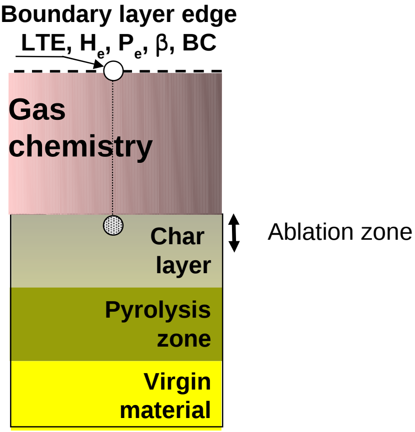
Required for ablation:

Gas-surface interaction and char layer chemistry:

⇒ **Char-Damköhler number**: Reaction vs. diffusion competition in porous media

⇒ **Thiele number**:

$$\Phi = \frac{L}{\sqrt{\mathcal{D}_i / s_f k_f}} \quad (1)$$



Stagnation point chemical environment

High-fidelity material response models

Boundary layer chemistry:

Damköhler number: τ_f / τ_{chem}

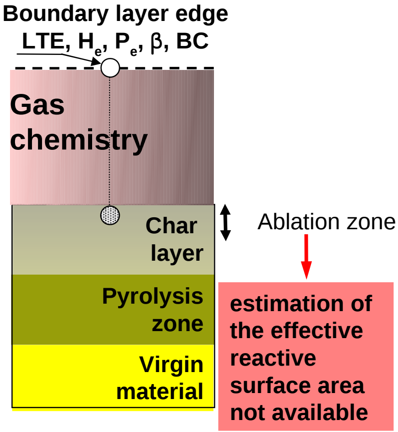
Required for ablation:

Gas-surface interaction and char layer chemistry:

⇒ **Char-Damköhler number**: Reaction vs. diffusion competition in porous media

⇒ **Thiele number**:

$$\Phi = \frac{L}{\sqrt{\mathcal{D}_i / s_f k_f}} \qquad (1)$$



estimation of the effective reactive surface area not available

→ **Experiments with microscale characterization**

Outline

1. Introduction
2. Ground testing in Plasmatron facility
3. Numerical tools development
4. Results with a carbon fiber preform (preliminary)
   - Plasma tests of carbon fiber preform
   - Scanning Electron Microscopy
5. Conclusions and perspective

Plasma tests of carbon fiber preform

Carbon fiber preform, Mersen Scotland Ltd.

- Chopped carbon fibers in phenol-resin slury, fully carbonized (1200K)
- density: $180 - 210\,\mathrm{kg/m^3}$
- specific surface area: $18\,\mathrm{m^2/g}$ (fiber volume surface: 3.24E6 $\mathrm{m^2/m^3}$)
- 2D randomly oriented carbon fibers, through-the-thickness (TTT) direction parallel to flow field in this study
- similar to precursor for European ablator ASTERM

Plasma tests of carbon fiber preform

movie loading...

Plasma tests of carbon fiber preform

movie loading...

Table: Test conditions (t=90s)

	(#1)	(#2)	(#3)
p_s [kPa]	1.5	10	20
$\dot{q}_{cw}$ [kW/m^2]	1021	946	1026

Plasma tests of carbon fiber preform

movie loading...

Table: Test conditions (t=90s)

	(#1)	(#2)	(#3)
p_s [kPa]	1.5	10	20
$\dot{q}_{cw}$ [kW/m^2]	1021	946	1026
$\dot{m}$ [g]	6.88	5.49	5.11
r [mm]	7.0	5.0	5.5

Plasma tests of carbon fiber preform

movie loading...

Table: Test conditions (t=90s)

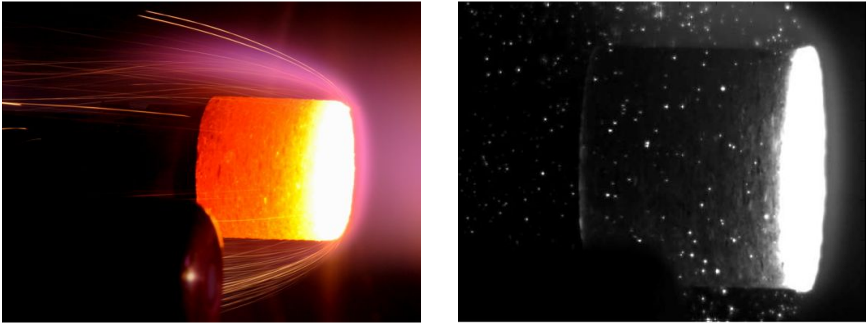
	(#1)	(#2)	(#3)
p_s [kPa]	1.5	10	20
$\dot{q}_{cw}$ [kW/m^2]	1021	946	1026
$\dot{m}$ [g]	6.88	5.49	5.11
r [mm]	7.0	5.0	5.5

→ strongest degradation at lowest static pressure
⇒ diffusion mechanisms in diffusion limited regime ($T_S > 2000K$)?
⇒ other failure modes (Spallation?)

Plasma tests of carbon fiber preform

Spalling of particles

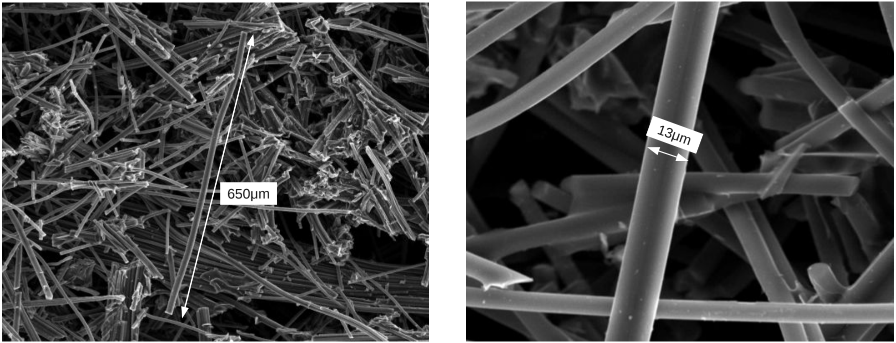
Conventional image (5ms) High-speed-camera (5µs)



⇒ Continual release of particles into the flow field, burn-off in plasma flow

SEM of carbon fiber preform

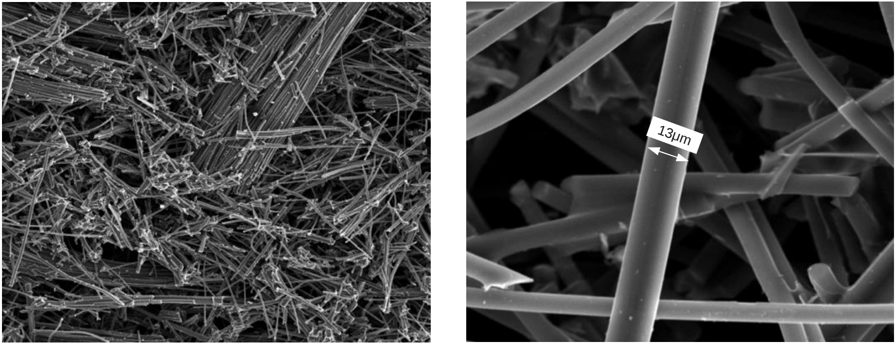
Carbon preform surface before test



- $l_f = 650\,\mu\mathrm{m}$
- doubled fiber diameter ($d_f = 6.5\,\mu\mathrm{m}$)

SEM of carbon fiber preform

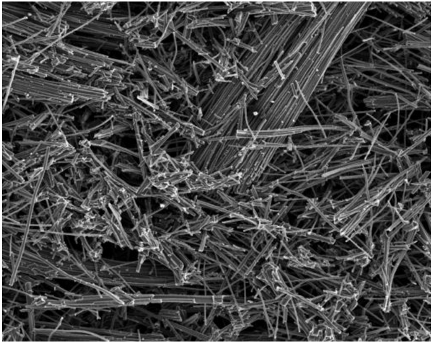
Carbon preform surface before test

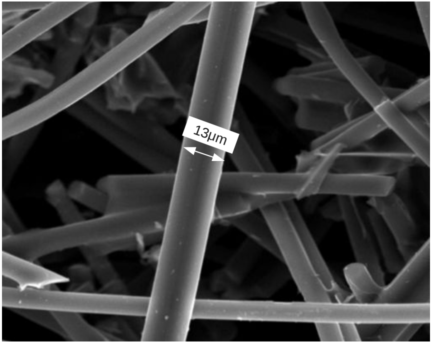


- $l_f = 650\,\mu\mathrm{m}$
- doubled fiber diameter ($d_f = 6.5\,\mu\mathrm{m}$)
- glued fibers →bundels

SEM of carbon fiber preform

Carbon preform surface before test



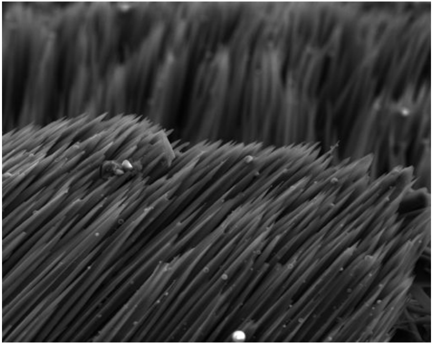


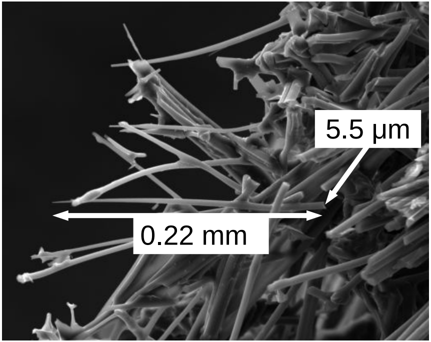
- $l_f = 650\,\mu\mathrm{m}$
- doubled fiber diameter ($d_f = 6.5\,\mu\mathrm{m}$)
- glued fibers →bundels

Does ablation of individual fibers lead to detachment of fiber bundels?

SEM of carbon fiber preform

Surface of ablated sample ($p_s = 10\text{kPa}$), stagnation region

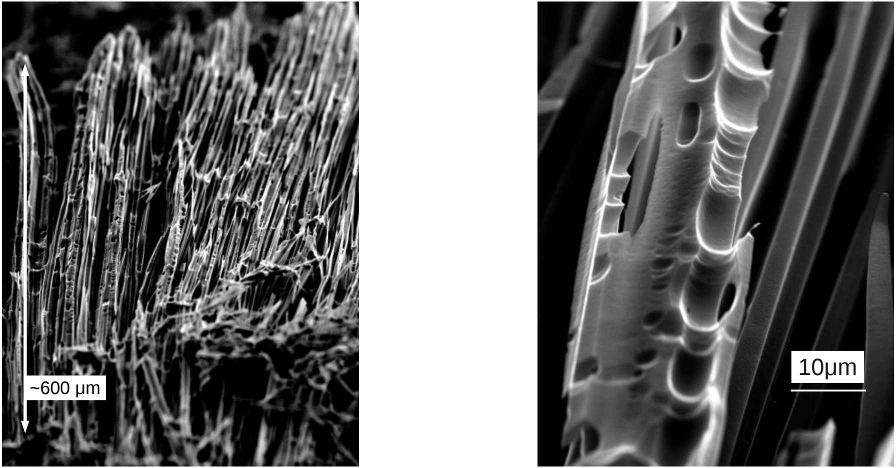




- fibers shortened to a length of $\sim 220\,\mu\mathrm{m}$
- oxidation leads to icicle shape
- diameter increasing to original fiber diameter of $d_f = 6.5\,\mu\mathrm{m}$
  $\rightarrow$ oxidation zone of $\sim 250\,\mu\mathrm{m}$?

SEM of carbon fiber preform

Surface of ablated sample ($p_s = 1.5$ kPa)



⇒ Strong degradation along whole fiber length $\sim 650\,\mu\mathrm{m}$

SEM of carbon fiber preform

Diffusion in a porous medium

species diffusion coefficients

$$\mathcal{D}_i = \frac{1 - x_i}{\sum_{j \neq i} x_j / \mathscr{D}_{i,j}}$$

binary diffusion coefficients

$$\mathscr{D}_{i,j} = \frac{3}{16} \sqrt{\frac{2\pi k_B T (m_i + m_j)}{m_i m_j}} \frac{k_B T}{p \Omega_{i,j}^{(1,1)}}$$

(*Capitelli, M., Gorse, C., Longo, S., and Giordano, D., JTHT 14 (2) (2000) 259-268.*)

Thiele number

$$\Phi = \frac{L}{\sqrt{\mathcal{D}_i / s_f k_f}}$$

SEM of carbon fiber preform

Diffusion in a porous medium

species diffusion coefficients

$$\mathcal{D}_i = \frac{1 - x_i}{\sum_{j \neq i} x_j / \mathscr{D}_{i,j}}$$

binary diffusion coefficients

$$\mathscr{D}_{i,j} = \frac{3}{16} \sqrt{\frac{2\pi k_B T (m_i + m_j)}{m_i m_j}} \frac{k_B T}{p \Omega_{i,j}^{(1,1)}}$$

(*Capitelli, M., Gorse, C., Longo, S., and Giordano, D., JTHT 14 (2) (2000) 259-268.*)

Thiele number

$$\Phi = \frac{L}{\sqrt{\mathcal{D}_i / s_f k_f}}$$

Enhanced diffusion at low pressures

Boundary layer edge

	(#1)	(#2)	(#3)
p_s [kPa]	1.5	10	20
$\rho_e \times E4$ [kg/m^3]	6	38	79

SEM of carbon fiber preform

Diffusion in a porous medium

species diffusion coefficients

$$\mathcal{D}_i = \frac{1 - x_i}{\sum_{j \neq i} x_j / \mathscr{D}_{i,j}}$$

binary diffusion coefficients

$$\mathscr{D}_{i,j} = \frac{3}{16} \sqrt{\frac{2\pi k_B T (m_i + m_j)}{m_i m_j}} \frac{k_B T}{p \Omega_{i,j}^{(1,1)}}$$

(*Capitelli, M., Gorse, C., Longo, S., and Giordano, D., JTHT 14 (2) (2000) 259-268.*)

Thiele number

$$\Phi = \frac{L}{\sqrt{\mathcal{D}_i / s_f k_f}}$$

Enhanced diffusion at low pressures

Boundary layer edge

	(#1)	(#2)	(#3)
p_s [kPa]	1.5	10	20
$\rho_e \times E4$ [kg/m^3]	6	38	79
$c_\mathrm{O} \times E3$ [mol/m^3]	8.7	54.4	112.1
$\mathcal{D}_O$ [m^2/s]	0.52	0.09	0.04

SEM of carbon fiber preform

Diffusion in a porous medium

species diffusion coefficients

$$\mathcal{D}_i = \frac{1 - x_i}{\sum_{j \neq i} x_j / \mathscr{D}_{i,j}}$$

binary diffusion coefficients

$$\mathscr{D}_{i,j} = \frac{3}{16} \sqrt{\frac{2\pi k_B T (m_i + m_j)}{m_i m_j}} \frac{k_B T}{p \Omega_{i,j}^{(1,1)}}$$

(*Capitelli, M., Gorse, C., Longo, S., and Giordano, D., JTHT 14 (2) (2000) 259-268.*)

Thiele number

$$\Phi = \frac{L}{\sqrt{\mathcal{D}_i / s_f k_f}}$$

Enhanced diffusion at low pressures

Boundary layer edge

	(#1)	(#2)	(#3)
p_s [kPa]	1.5	10	20
$\rho_e \times E4$ [kg/m^3]	6	38	79
$c_{\mathrm{O}} \times E3$ [mol/m^3]	8.7	54.4	112.1
$\mathcal{D}_O$ [m^2/s]	0.52	0.09	0.04

⇒ valid in continuum flow regime (stagnation region →Knudsen number)

⇒ in porous media defined by mean pore diameter: $Kn = \frac{\bar{\lambda}}{d_p}$ ($Kn > 0.1$ possible)

Outline

Conclusions: Carbon fiber preform

- Enhanced diffusion effects at low pressures may cause stronger ablation in diffusion-limited regime
- Oxidation of fibers shows variation with (static) pressure
  - → Conform with theory on species diffusion
- Ablation of individual fibers may lead to detachment of fiber bundels → mechanical failure
  - → Enhanced at lower pressures

⇒ More experiments necessary to confirm trends

→ Define methodology to estimate reactive surface area

⇒ Extend to full ablator (ASTERM, AQ61)

⇒ Modelling of carbon preform ablation tests

→ Start with control volume approach suppressing pyrolysis

Perspectives for ablation studies at the VKI

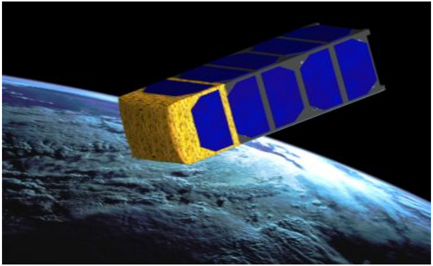
- Testing condition and boundary layer characterization
  - ⇒ Application of LHTS methodology to ablation testing
  - ⇒ Uncertainty quantification methods
- Mircoscale analysis of virgin and tested ASTERM / AQ61
  - ⇒ Comparison to preform (no phenolic impregnation)
  - ⇒ Definition of reactive surface needed, char layer depth, porosity
- Very high heat-flux testing
  - ⇒ Appropriate measurement techniques
- Reference test case definition for model validation
- Flight extrapolation methodology

Perspectives: Extend ablation framework to related studies at VKI

Converging nozzle

- Supersonic plasma flow studies at VKI
- Extension to high heat flux testing (aim: $10\,\mathrm{MW}/\mathrm{m}^2$)

QB50 / flight demonstrator



- 50 double-unit cubesats: in-situ, multipoint & long-duration measurements
- 10 triple-unit cubesats: re-entry flight demonstrator for ablation studies

Questions?

Acknowledgements

- AFOSR
- ESA
- Lockheed Martin UK (Ampthill)
- Mersen Scotland Holytown Ltd.
- EADS Astrium ST
- Agency for Innovation by Science and Technology (IWT)
- N.N. Mansour, J. Lachaud, J.-M. Bouilly

helber@vki.ac.be