Aerothermal Characterization of Silicon Carbide-Based TPS in High Enthalpy Airflow

F. Panerai    O. Chazot

von Karman Institute for Fluid Dynamics, Belgium
Atmospheric Reentry and Gas-Surface Interaction

Gas-surface interaction is characterized by highly exothermic chemistry which impose the use of a Thermal Protection System.

For reusable TPS we need to account for:

1. recombination reactions (catalysis)
2. oxidation
3. radiative heat transfer

Intermediate eXperimental Vehicle (IXV)
Aerothermal Characterization of Silicon Carbide-Based TPS in High Enthalpy Airflow

Gas Surface Interaction Phenomena

**Catalycity**

\[ \gamma = \frac{\dot{m}_r}{\dot{m}} \]

\[ \gamma = 0 \] Non-catalytic wall

\[ \gamma = 1 \] Fully-catalytic wall

**Oxidation**

PASSIVE: formation of protective silica layer

\[ \text{SiC}_\text{(s)} + 3/2\text{O}_2\text{(g)} \rightarrow \text{SiO}_2\text{(s)} + \text{CO}_\text{(g)} \]

ACTIVE: formation of gaseous silicon products

\[ \text{SiC}_\text{(s)} + \text{O}_2\text{(g)} \rightarrow \text{SiO}_\text{(g)} + \text{CO}_2\text{(g)} \]

**Emissivity**

\[ \varepsilon = \frac{M}{M^0} \]

\( \varepsilon = 0.2 \) 100 % decrease!
Background and Objectives

ESA project for a LEO lifting reentry demonstrator
Main mission objectives are:

- advancement on TPS technologies
- study aerothermodynamic phenomena during the reentry

Our Goal
Contribute, through ground testing, to the Aerothermal Database of the IXV mission proving assessment of the oxidative, catalytic and radiative behavior of the CMC Thermal Protection System
Outline

- The VKI Plasmatron facility
- Methodology and Instrumentation
- Test overview and operating conditions
- Results:
  - In-situ emissivity measurements
  - Room temperature reflectivity measurements
  - Oxidation assessment
  - Catalycity determination
  - Gas phase radiative signature
- Summary and outlook
Aerothermal Characterization of Silicon Carbide-Based TPS in High Enthalpy Airflow

The VKI Plasmatron Facility

**Characteristics**

- ICP generation
- Gas: Air, CO2, Ar
- Power: 1.2 MW
- Heat flux: 0.1 - 10 MW/m²
- Pressure: 10 mbar - 200 mbar

Exhaust

1050 kW air-water cooler

Heat exchanger

Test model

Gas supply

Test chamber

ICP torch

Roots vacuum pump

HP water pumps

By-pass valve

Water tanks

Rotating vanes vacuum pumps

200 V dc

1.2 MW 400 kHz MOS inverter

12-pulse thyristor rectifier

1700 kVA Transformer

11 kV

von Karman Institute – F. Panerai: panerai@vki.ac.be

The VKI Plasmatron Facility, contd.

How it works: electromagnetic induction

Local Heat Transfer Simulation (LHTS):

\[ H_e^f = H_e^t \quad p_e^f = p_e^t \quad \beta_e^f = \beta_e^t \]

under thermochemical equilibrium

Kolesnikov, Fluid Dynamics 28 (1) (1993) 131-137
Instrumentation
Aerothermal Characterization of Silicon Carbide-Based TPS in High Enthalpy Airflow

Plasmatron Experiments Overview

25 SPS C/SiC and 6 MTA C/SiC samples tested at different temperatures and pressures

Procedures:
- Sample exposure to plasma stream at target steady state conditions
- Sample ejection and flow calibration (heat flux and dynamic pressure measurements)
Aerothermal Characterization of Silicon Carbide-Based TPS in High Enthalpy Airflow

Test Conditions

Target conditions:
- Static pressure: 1300 – 5000 Pa
- Wall temperature: 1200 – 2000 K
- Test time: 300 sec at steady state

Flow Measurements:
- Cold wall heat flux: 160 – 1600 kW/m²
- Dynamics pressure: 25 – 300 Pa

Rebuilding (BL edge conditions):
- Enthalpy: 5 – 35 MJ/kg
- Temperature: 3000 – 6000 K
**In-situ Emissivity Measurements**

- Good radiative behavior ($\varepsilon > 0.7$)
- Emissivity increases up to $T_w=1600$ K and decreases at higher $T$
- Good comparison with literature data

[Alfano et al., JECS, 29 (2009) 2045-2051]
Room Temperature Reflectivity Measurements

- Virgin specimens follow SiC global behavior
- SiO$_2$ features appear on the tested samples

Observed for SiC based UHTC [Marschall et al., JTHT 23 (2009) 267-278]

Relative strengths of the SiO$_2$ and SiC spectral features can be used as markers for passive/active oxidation of ceramics

[Marschall and Fletcher, JECS 30 (2010) 2323-2336]
Variation of the 9 µm SiO₂ Feature with P and T

The 9 µm feature correlates the predicted oxidation behavior of a SiC surface:

- SiO₂ thickness increases with pressure and temperature up to 1800 K
- At 1800 K and low pressure SiO₂ starts to volatilize
- At 2000 K only few SiO₂ at high pressure

Passive ox. (formation of glassy silica): high P, low T
Active ox. (volatilization of silica): low P, high T
Variation of the 9 µm SiO₂ Feature with P and T

The 9 µm feature correlates the predicted oxidation behavior of a SiC surface:

- SiO₂ thickness increases with pressure and temperature up to 1800 K
- At 1800 K and low pressure SiO₂ starts to volatilize
- At 2000 K only few SiO₂ at high pressure

Passive ox. (formation of glassy silica): high P, low T
Active ox. (volatilization of silica): low P, high T
Variation of the 9 µm SiO$_2$ Feature with T and P, contd.

SiO$_2$ features grow with decreasing temperature and increasing pressure
Aerothermal Characterization of Silicon Carbide-Based TPS in High Enthalpy Airflow

Passive/Active Oxidation Assessment

[Balat, JECS 16 (1996) 55-62]

- Plasmatron data agree with Balat PA oxidation transition law for SPS C/SiC
Catalycity Coefficients

- Catalycity coefficients between $10^{-3}$ and $10^{-1}$
- ~50% reduction with respect to the fully catalytic condition
- $\gamma$ increases with increasing surface temperature and decreasing pressure

$[\text{Balat and Bêche.}, \text{ASS. 256 (2010) 4906–4914}]$
Gas Phase Radiative Signature by OES

- Si emission appears during C/SiC testing
- Si at 252 and 288 nm observed by several authors
- Si as indicator of PAT (SiO$_2$ volatilization)

[Hirsch et al., HTHP. 31 (1999) 455–465]
[Jentschke et al., RSI 70 (1999) 336–339]
[Herdrich et al., JSR, 42 (2005) 817–824.]
Si (λ=252 nm) Emission History

- Si emission correlates the passive/active oxidation behavior found by reflectivity measurements:

  - $\text{SiO}_2$ volatilization decreases with pressure and increases with temperature
Summary and Outlook

1. Characterization of the catalytic, radiative and oxidation behavior of the IXV TPS materials
2. Silica features found on the reflectivity spectra of plasma exposed specimens
3. Silica features intensity varies with P and T according to the predicted passive/active oxidation behavior for SiC
4. Si emission in front of the test specimens well correlates the predicted SiO$_2$ volatilization due to oxidation

- Extrapolation to flight…
- Uncertainty quantification…
- Very high heat fluxes…
- GSI models validation benchmark
Thanks for your attention...

... questions?

panerai@vki.ac.be

von Karman Institute for Fluid Dynamics

Thanks to:
In-situ measurements

- KRS5 window
- Quartz window
- Infrared broadband radiometer (radiance)
- 2-color pyrometer (temperature)

Emissivity Measurement Techniques

\[ \varepsilon'_{0.6-39\mu m} = \frac{\mathcal{L}'}{\mathcal{L}^0} \]

Room temperature measurements*

\[ r(\lambda) \] is measured by:
- MIR spectrometer (2.1 \(\mu m\) – 40 \(\mu m\))
- UV/VIS/NIR spectrometer (0.25 \(\mu m\) – 2.5 \(\mu m\))

\[ \varepsilon(T) = \frac{\int_{0.25\mu m}^{40\mu m} (1-r(\lambda))E(\lambda,T)d\lambda}{\int_{0.25\mu m}^{40\mu m} E(\lambda,T)d\lambda} \]

*performed at ESA ESTEC, Noordwijk, The Netherlands
Aerothermal Characterization of Silicon Carbide-Based TPS in High Enthalpy Airflow

Catalycity Determination Procedure

Experimental conditions

Geometry

Plasmatron

Measurements

Tests

ICP Code

Rebuilding Code

Flight conditions

Reacting Boundary Layer Solver

Heat flux abacus

Catalycity

von Karman Institute – F. Panerai: panerai@vki.ac.be

Catalycity Determination Procedure, contd.

\[ q_w = \sigma \varepsilon T_w \]

\[ T = T_w \]
We Determine an Effective, Apparent Catalycity

Effective catalycity:

\[ \gamma_{\text{eff}} = \gamma \beta \]

where:

\[ \beta = \frac{q_{\text{rec}}}{D} \]

Energy accommodation coefficient

\[ \gamma = \frac{M_r}{M} \downarrow \]

Recombination efficiency

Apparent catalycity:

\[ \gamma_{\text{app}} = \frac{S_{\text{wet}}}{S_{\text{geom}}} \gamma_{\text{intrinsic}} \]

where:

\[ \frac{S_{\text{wet}}}{S_{\text{geom}}} \]

Roughness

\[ \gamma_{\text{intrinsic}} \]

True catalycity
Boundary Layer Rebuilding

Edge mass fractions

Stagnation line species at 3000 Pa

von Karman Institute – F. Panerai: panerai@vki.ac.be

Extrapolation to Flight

LHTS is valid if:

\[ H_e^f = H_e^t \rightarrow h_e^f + \frac{1}{2} V_e^f \, v^2 = H_e^t \]

\[ p_e^f = p_e^t \rightarrow p_e^f + \rho_e \, V_e^f \, v^2 = p_e^t \]

\[ \beta_e^f = \beta_e^t \rightarrow \frac{1}{R} \sqrt{\frac{2(p_e - p_\infty)}{\rho_e}} = \beta_e^t \]

IXV flight trajectory
Extrapolation to Flight, contd.
Aerothermal Characterization of Silicon Carbide-Based TPS in High Enthalpy Airflow

1.8 MW/m² Heat Flux Test

"Temperature jump" ~ 2150 K

[Herdrich et al., JSR, 42 (2005) 817–824.]
1.8 MW/m² Heat Flux Test - Gas Phase Radiative Signature

INTENSITY, a.u.

WAVELENGTH, nm

CN violet, $B^2\Sigma^+-X^2\Sigma^+$

$\Delta v = 0$

$\Delta v = +1$

$\Delta v = -1$

SiO₂ (?) 423

CN red, $A^2\Pi-X^2\Sigma^+$

Na 589

O 777

N 742, 744, 746

K 766, K 770

N 818, 821, 824

O 844

N 868

von Karman Institute – F. Panerai: panerai@vki.ac.be