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)
Gas Surface Interaction Phenomena

Catalycity

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

\[ \gamma = 0 \quad \text{Non-catalytic wall} \]

\[ \gamma = 1 \quad \text{Fully-catalytic wall} \]

Oxidation

PASSIVE: formation of protective silica layer

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

ACTIVE: formation of gaseous silicon products

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

Emissivity

\[ \varepsilon = \frac{M}{M_0} \]

100 % increase!

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
The VKI Plasmatron Facility

Exhaust

1050 kW air-water cooler

Heat exchanger  Test model  Gas supply

Test chamber  ICP torch

Characteristics

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

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)
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 SiO$_2$ Feature with P and T

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

- SiO$_2$ thickness increases with pressure and temperature up to 1800 K
- At 1800 K and low pressure SiO$_2$ starts to volatilize
- At 2000 K only few SiO$_2$ at high pressure

Passive ox. (formation of glassy silica): high P, low T
Active ox. (volatilization of silica): low P, high T
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

[Balat and Bêche., ASS. 256 (2010) 4906–4914]
Si emission appears during C/SiC testing
Si at 252 and 288 nm observed by several authors
Si as indicator of PAT (SiO₂ 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 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:
Emissivity Measurement Techniques

In-situ measurements

![Image showing in-situ measurements equipment]

Infrared broadband radiometer (radiance)

KRS5 window

quartz window

2-color pyrometer (temperature)

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

Room temperature measurements*

\[ r(\lambda) \] is measured by:

- MIR spectrometer (2.1 µm – 40 µm)
- UV/VIS/NIR spectrometer (0.25 µm – 2.5 µm)

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

*performed at ESA ESTEC, Noordwijk, The Netherlands

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

Catalycity Determination Procedure

Experimental conditions

Geometry

Plasmatron

Measurements

Tests

ICP Code

Rebuilding Code

q_w^{(n)} = q_w^{(exp)}

H_e^{(n+1)}

Heat flux abacus

Catalycity

Reacting Boundary Layer Solver

Flight conditions

Yes

H_e, U_e

No

q_w

T_w

P_s

R

P_d

q_{cw}

m

P_s

S_w

P_{W\text{(plasma)}}

Δ

v_1

v_2

U_e

U_{e5}
Catalycity Determination Procedure, contd.
We Determine an Effective, Apparent Catalycity

Effective catalycity:

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

where:

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

Energy accommodation coefficient

Apparent catalycity:

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

where:

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

Roughness

\[ \gamma_{intrinsic} \]

True catalycity
Boundary Layer Rebuilding

Edge mass fractions

Stagnation line species at 3000 Pa
Extrapolation to Flight

LHTS is valid if:

\[ H_e^f = H_e^t \rightarrow h_{\infty}^f + \frac{1}{2} V_{\infty}^f 2 = H_e^t \]

\[ p_e^f = p_e^t \rightarrow p_{\infty}^f + \rho_{\infty} V_{\infty}^f 2 = p_e^t \]

\[ \beta_e^f = \beta_e^t \rightarrow \frac{1}{R} \sqrt{\frac{2(p_e - p_{\infty})}{\rho_e}} = \beta_e^t \]
Extrapolation to Flight, contd.

Graph showing the relationship between pressure, enthalpy, and velocity gradient as a function of temperature. The graph includes data points for different temperatures: 1200 K, 1400 K, 1600 K, 1800 K, and 2000 K. The x-axis represents enthalpy in J/kg, the y-axis represents pressure in Pa, and the 3rd axis represents velocity gradient in s\(^{-1}\).
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

The diagram shows the spectral emission of various species under high heat flux conditions. The intensity is plotted on the y-axis against wavelength on the x-axis. Key peaks and transitions are labeled, including Si 251, Si 288, Si 299, SiO₂(?) 423, CN violet, B²Σ⁺-X²Σ⁺, Si 391, Na 589, and O 777. The transitions are indicated with Δv values for each peak.