Material response characterization of new-class ablators in view of numerical model calibration

6th Ablation Workshop
April 10, 2014
Urbana Champaign, Illinois

B. Helber 1,2, A. Turchi 1, T. E. Magin 1

1 Aeronautics and Aerospace Department, von Karman Institute for Fluid Dynamics, Belgium
2 Research Group Electrochemical and Surface Engineering, Vrije Universiteit Brussel
Missions
Sample return, ISS serving (Dragon, ARV, ...), MPCV
- Atm. reentry speeds > 10km/s
- Ablative materials
  - Mass loss and surface recession
  - Prediction of material response required
  - High margins decrease payload

New materials (1990’s)
- Phenolic impregnated carbon fiber preform
- Very porous low density ablators
Complex Multiphysics - Multiscale problem
Coupled phenomena

Gas-Surface Interaction

Material

Radiation

C$_{248}$
NH (A–X)
CH (A–X)
CN violet (B–X)
OH (A–X)
C$_2$ Swan
Na
H$_\beta$
H$_\alpha$
N
O$_{777}$
N lines

Air plasma
Nitrogen plasma

50 µm
We aim at improvement of

Experimental Methods
(VKI)

TPS Design / Material
(VUB, Astrium, ESA)

Material Response Modeling & Validation
(VKI, collaborations)

Calibration (AIAA G-077-1998)

The process of adjusting numerical or physical modeling parameters in the computational model for the purpose of improving agreement with experimental data.
In the following:

(1) Materials and Methods for Ablation Characterization

(2) Gas-phase ⇔ BL emission & temp

(3) Surface ⇔ Char blowing rates

(4) Material ⇔ Pyrolysis outgassing
Approach for ablation modeling (Kendall et al.[1])

VKI: 1D Stagnation line description w/ surface ablation
(A. Munafo[2] / A. Turchi, VKI)

Surface Energy Balance (SEB)
- convective flux
- enthalpy by diffusion
- radiation
- re-radiation
- convected enthalpy

Surface Mass Balance (SMB)
- mass blowing
- species diffusion

Boundary condition from experiments & plasma free-stream
Experimental data for validation

GOAL: Coupling 1-D SL-code & material code (P. Schrooyen)
Materials of Investigation

**Carbon fiber preform, non-pyrolyzing (Mersen Scotland Holytown Ltd.)**

**AQ61, carbon-phenolic (AIRBUS DS)**
1.2-MW Inductively Coupled Plasmatron

Gas: Air, N₂, CO₂, Ar

Power: 1.2-MW

Heat Flux: > 12 MW/m²

Pressure: 10 mbar - 1 atm
Techniques for In-Situ Ablation Characterization

Our interest

Surface temperature
Emissivity
Internal Temperature
In-situ recession analysis
Volumetric recession
Chemical composition
Temperature estimation

(AIAA 2013-2770)
Boundary Layer Radiation Profiles

Experimental: Spatial CN violet emission

CN Production:
gas phase: \( \text{CO} + \text{N} \rightleftharpoons \text{CN} + \text{O} \)

wall: \( \text{C}_w + \text{N}_w \rightarrow \text{CN} \)
Boundary Layer Radiation Profiles

Numerical: Simplified approach using Specair slab

Simulate line-of-sight measurement

Perspective:
Radiation Coupling (J.B. Scoggins)
Comparison of Boundary Layer Radiation Profiles

Very preliminary approach but promising comparison

T = 2020K, $p_s = 200$ mbar

T = 2848K, $p_s = 15$ mbar

T = 2783K, $p_s = 200$ mbar

- Locations of maxima
- BL thickness
- Order of magnitude
Non-thermal vibrational level distribution at low pressure (AIAA 2013-2770)

- Thermal non-equilibrium?
- Deviation from Boltzmann distribution?
Boundary Layer Temperature Profile
Non-equilibrium at the wall?

$p_s = 15\text{mbar}, T_S = 2130\text{K}$

$p_s = 100\text{mbar}, T_S = 2097\text{K}$
In-situ Recession Analysis (HSC)

**Preform**

- 1724K, 15mbar
- 2180K, 15mbar
- 2020K, 200mbar
- 2848K, 15mbar
- 2783K, 200mbar

**AQ61**

- 2167K, 15mbar
- 1890K, 200mbar
- 2884K, 15mbar
- 2906K, 200mbar

![Graphs showing recession analysis for Preform and AQ61 with different temperatures and pressures.](image-url)
Ablation Regimes of Preform and AQ61

- **diffusion limited ablation and sublimation regime**
- recession not much influenced by pressure!
Surface temperature driven by catalytic reactions:

\[ \text{N} + \text{N} \rightarrow \text{N}_2 \]

- Modeling of tests in nitrogen
- 15mbar: good agreement, possibly misleading measurement? (AIAA 2012-2876)
Pyrolysis-Gas Blowing Rate Determination

Non-pyrolyzing carbon-preform

\[ m_{pg} + m_c = (\rho V)_{w} \]

\[ m_{pg} = m_{pg} - \frac{(V_{abl} \cdot \rho_c)}{t_{exp}} \]

**Carbon Preform (non-pyrol.):**

\[ \Rightarrow m_c = m_{tot} = V_{abl} \cdot \rho_c \]

**Pyrolyzing Ablators:**

\[ \Rightarrow \text{char density required} \]
Pyrolysis-Gas Blowing Rate Determination

Non-pyrolyzing carbon-preform

- discrepancy:
  - water
  - initial density
  - damage by deinstallation

<table>
<thead>
<tr>
<th>Test case, #</th>
<th>Total mass loss, g</th>
<th>weighed</th>
<th>estim. HSC</th>
<th>Uncertainty HSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Pyrolysis-Gas Blowing Rate Determination
Thermogravimetric Analysis (TGA)

Argon (20-200 ml/min), 10 K/min, 1 atm

charred AQ61: $\rho_c = 80-85\% \rho_v$
**Pyrolysis-Gas Blowing Rate Determination**

Carbon - phenolic: AQ61

\[ m_{pg} + m_c = (\rho V)_w \]

\[ m_{pg} = m_{pg} - \frac{(V_{abl} \cdot \rho_c)}{t_{exp}} \]

**AQ61 (carbon-phenolic):**

\[ m_{meas} = 4.03 \text{ g} \]

\[ m_{c,HSC} = 2.26 \pm 0.4 \text{ g} \]

\[ \Rightarrow m_{pg} = 1.77 \text{ g} \pm 0.4 \text{ g} \]

**Main challenges:**

Side-wall outgassing, non-1D effects, too-long test times
Ongoing Work
Rebuilding of ablation tests in nitrogen plasmas $\rightarrow \gamma_N$

Nitridation negligible for recession

$\Rightarrow$ Match of $T_s$ for $\gamma_N$
Conclusions

(1) Materials and Methods
- hemispherical samples
- HSC imaging
- coupled w/ 3 Spectrometers

(2) BL emission
- steady ablation process
- preliminary comparison num/exp radiation profiles

(3) Char blowing rates
- diffusion limited ablation and sublimation
- deviation from num. model

(4) Pyrolysis outgassing
- Vol. ablation + TGA $\rightarrow \dot{m}_{pg}$

Which chemical and physical phenomena matter?
ACKNOWLEDGEMENTS

Funding and materials supply:

In particular:

- Jean-Marc Bouilly & Gregory Pinaud (Airbus Defence & Space)
- N.N. Mansour (NASA ARC), J. Lachaud (UC Santa Cruz), F. Panerai (University of Kentucky) for informative support
- VKI Plasmatron & Ablation Team
- VUB SURF research team