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
TPM for Atmospheric Reentry

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

Air plasma
Nitrogen plasma

Material:
- Air plasma
- Nitrogen plasma
- C$_{248}$
- OH (A–X)
- CH (A–X)
- C$_2$ Swan
- Na
- H$_\beta$
- O$_{777}$
- N lines

Gas-Surface Interaction:
- C$_2$48
- OH (A–X)
- CN violet (B–X)

Radiation:
- N lines
We aim at improvement of

Experimental Methods
(VKI)

Material Response Modeling & Validation
(VKI, collaborations)

TPS Design / Material
(VUB, Astrium, ESA)

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 $\leftrightarrow$ BL emission & temp
3. Surface $\leftrightarrow$ Char blowing rates
4. Material $\leftrightarrow$ Pyrolysis outgassing
Approach for ablation modeling (Kendall et al.\cite{1})

VKI: 1D Stagnation line description w/ surface ablation
(A. Munafo\cite{2} / A. Turchi, VKI)

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

**GOAL:** Coupling 1-D SL-code & material code (P. Schrooyen)

\[\text{Surface Energy Balance (SEB)}\]
- convective flux
- enthalpy by diffusion
- HOT GAS radiation
- re-radiation
- convected enthalpy

\[\text{Surface Mass Balance (SMB)}\]
- mass blowing
- HOT GAS species diffusion

\[\text{MATERIAL}\]
-enthalpy char mass loss
- material conduction

\[\text{CONTROL VOLUME}\]
-chem. active surface

---

\[\text{[1] Kendall et al., NASA CR 1060 (1968)}\]
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
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:** $\text{C}_\text{w} + \text{N}_\text{w} \rightarrow \text{CN}$

**Graphs:**
- **Graph 1:**
  - $I$, W/(m$^2$.sr.nm)
  - $\lambda$, nm
  - dist. surf., mm
- **Graph 2:**
  - $I_{\lambda}^2$, [W/(m$^2$.sr)]
  - Distance from surface, mm
- **Legend:**
  - Exp. data
  - Polynomial fit
  - 95% Conf. bnd

**Conditions:**
- $T = 2180\text{K}$, $p_s = 15\text{mbar}$
Boundary Layer Radiation Profiles
Numerical: Simplified approach using Specair slab

Simulate line-of-sight measurement

stagn. line solution \( \chi_i, T_i, p_i \)

slab width \( \Delta y_i \) at \( x_i \)

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

Very preliminary approach but promising comparison

- Locations of maxima
- BL thickness
- Order of magnitude

$T = 2020K, p_s = 200\text{mbar}$

$T = 2783K, p_s = 200\text{mbar}$

$T = 2848K, p_s = 15\text{mbar}$
CN Radiation Simulation for Temperature Estimation

Non-equilibrium?

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?

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

$p_s = 100\text{mbar}, \ T_S = 2097K$
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 different materials and conditions.*
Ablation Regimes of Preform and AQ61

Diffusion limited ablation and sublimation regime

Recession not much influenced by pressure!
Diffusion Limited Ablation and Code Comparison

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-pyroly.):**

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

**Pyrolyzing Ablators:**

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

discrepancy:
- water
- initial density
- damage by deinstallation

![Bar chart showing total mass loss for different test cases with weighed and estim. HSC values.](chart.png)
Pyrolysis-Gas Blowing Rate Determination

Thermogravimetric Analysis (TGA)

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

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

Carbon - phenolic: AQ61

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

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

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