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

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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
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 $\rightarrow$ BL emission & temp

(3) Surface $\rightarrow$ Char blowing rates

(4) Material $\rightarrow$ 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)

Surface Mass Balance (SMB)

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, N$_2$, CO$_2$, Ar
Power: 1.2-MW
Heat Flux: > 12 MW/m$^2$
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: $\text{C}_w + \text{N}_w \rightarrow \text{CN}$

$T = 2180\text{K}, p_s = 15\text{mbar}$

I, $[\text{W/(m}^2\cdot\text{sr}\cdot\text{nm})]$
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

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

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

\[ T = 2848K, p_s = 15\text{mbar} \]

- 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

AQ61

Recession, mm

0 1 2 3 4 5

Time, s

0 20 40 60 80

Recession, mm

0 1 2 3 4 5

Time, s

0 20 40 60 80

Recession, mm

0 1 2 3 4

Time, s

0 5 10 15 20

Recession, mm

0 1 2 3 4

Time, s

0 5 10 15 20

Preform:

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

AQ61:

- 2167K, 15mbar
- 2180K, 15mbar
- 1890K, 200mbar
- 2884K, 15mbar
- 2906K, 200mbar

1724K, 15mbar
2180K, 15mbar
2020K, 200mbar
2848K, 15mbar
2783K, 200mbar
2167K, 15mbar
1890K, 200mbar
2884K, 15mbar
2906K, 200mbar
Ablation Regimes of Preform and AQ61

- **Diffusion limited ablation and sublimation regime**

- Recession not much influenced by pressure!

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**Diagram:**

- **Preform:** 15 and 200 mbar
- **AQ61:** 15 and 200 mbar

**Axes:**
- **Recession rate, mm/s**
- **Temperature, K**

**Notes:**

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

\[ N + N \rightarrow N_2 \]

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

Test case, #

Total mass loss, g

- weighed
- estim. HSC
- Uncertainty HSC

discrepancy:
- water
- initial density
- damage by deinstallation
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

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

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

\text{AQ61 (carbon-phenolic):}
\[ m_{meas} = 4.03 \text{ g} \]
\[ m_{c,HSC} = 2.26 \pm 0.4 \text{ g} \]
\[ \implies m_{pg} = 1.77 \text{ g} \pm 0.4 \text{ g} \]

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

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 → \( \dot{m}_{pg} \)

Which chemical and physical phenomena matter?
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