The Plasmatron. A unique experimental facility able to duplicate pressure and heat flux for low earth orbit re-entry

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Outline

1. Introduction

2. Re-entry flight and Plasmatron testing

3. Local Heat Transfer Simulation methodology

4. Gas surface Interaction in dissociated BL

5. Conclusion
Hypersonic testing strategies

- Pressure field: hypersonic similarity parameter, $M_\infty \tau$  (Blow down facilities)
- Viscid-inviscid interaction: $Ma - Re$  (Shock tunnels)
- High Temperature phenomena: Binary Scaling, $\rho L$  (High enthalpy facilities)
- Gas-Surface Interaction: LHTS  (Plasma wind tunnels)
Reentry Environment details (GSI)

Wall Chemistry

Gas-Surface Interaction:
- Catalysis
- Oxidation
- Ablation

Gas
- Surface
Interaction:
- Catalysis
- Oxidation
- Ablation

Aerospace vehicle nose

M>>1

Upstream flow

Shock layer

Reacting boundary layer

Relaxation zone

Intermediate zone (LTE)

Bow shock

B.L. edge

Gas Chemistry

Thermal Chemical NEQ
Plasmatron facilities offer suitable conditions for aerothermochemistry ground testing
ESA requirements for Hermes Reentry

Graph showing static pressure [mbar] vs. heat flux [kW/m²] for different sizes (193 mm, 347 mm, 447 mm, 1110 mm). The graph includes data points and lines indicating ESA specs.
Theory of Hypersonic stagnation point heat transfer (Fay & Riddell, 1958)

Fay and Riddell formula:

\[
Q_w = 0.76 \Pr^{-0.6} \left( \rho_e \mu_e \right)^{0.4} \rho_w \mu_w^{0.1} \beta_e \left( H_e - h_w \right) \left[ 1 + (Le^\alpha - 1) \frac{h_{D,e}}{H_e} \right]
\]


Goulard formula: (introduce catalycity)

\[
Q_w = 0.664 \Pr^{-2/3} \left( \beta_e \rho_e \mu_e \right)^{0.5} H_e \left[ 1 + (Le^{2/3} \varphi - 1) \frac{h_{D,e} y_e}{H_e} \right]
\]
The boundary layer problem can be considered experimentally apart from the inviscid flow field and Reynolds Number simulation does not have to be achieved.

The boundary layer on a model in the shock tube under the same stagnation conditions as in hypersonic flight will be an exact geometric scale reproduction of the flight case if the two situations are chemically similar.

(...) is that the stagnation enthalpy and the atom diffusion process through the boundary layer are correctly duplicated in the experiment. The only other variable which must be determined to complete the simulation principle is the velocity gradient at the stagnation point or pressure distribution.

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Fig. 1. Schemes of hypersonic flow around a blunt body and the stagnation point heat transfer simulation in subsonic high enthalpy flow in plasmatron.

Kolesnikov, Fluid Dynamics 28 (1) (1993) 131-137
Local Heat Transfer Simulation at VKI

Locally similar BL equations

\[
(ff')' + f'' + \frac{2s}{u_e} \frac{\partial u_e}{\partial s} \left( \frac{\rho_e}{\rho} - f'^2 \right) = 0
\]

\[
f_g' + \left( \frac{l}{Pr} \frac{l'}{g} \right) + \frac{\mu_e^2}{2h_{se}} \left( 2l(1 - \frac{1}{Pr}) f'f'' \right) + \left( \frac{l}{Pr} Le(1 - \frac{1}{Le}) \sum \frac{c_{se}}{h_{se}} h_e z' e \right) = 0
\]

\[
f_z' + \left( \frac{1}{Sc} z' \right)' - 2 \left( \frac{du_e}{dx} \right)^{-1} \frac{\alpha_i}{\rho c_{is}} = 0
\]

Real flight situation

\[H_e, P_e, \beta_e = du/dx, \ (LTE)\]

Ground test simulation

Experimental validation

\[ Q_w = 0.67 \left( \frac{\rho_e \mu_e}{\rho_w \mu_w} \right)^{0.4} \sqrt{\rho_w \mu_w \frac{du_e}{dx}} \left( He - h_w \right) / Pr \]  
(Fay & Riddell, Equilibrium)

Normalized Heat-Flux

\[ Q_w \sqrt{\frac{R_{\text{eff},H}}{P_s}} = K_h (He - h_w) \]

Effective radius

\[ \beta = \frac{1}{R_{\text{eff},H}} \sqrt{\frac{2p_t}{\rho_t} \left( 1 - \frac{p_\infty}{p_t} \right)} \]

\[ R_{\text{eff},S} = \frac{R_m}{u_{1e}} \left( 1 + \frac{v_e}{u_{1y}} \frac{u_{1y}}{u_{1e}} \right)^{1/2} \]

\( u_{1e}, u_{1y}, v_e \) are non-dim numbers characteristic from the finite thickness BL  
Barbante 2001, Chazot et al. ICMAR 2004
Hypersonic vs Subsonic testing

Chazot et al., ICMAR 2004.
Plasmatron Testing instrumentation

Wind tunnel characteristics:
- 1.2 MW ICP generator
- Gas: Air, N2, CO2, Ar
- Heat-flux: 90 kW/m² - 16 MW/m²
- Pressure: 10 mbar - 800 mbar
Catalycity determination

Radiative equilibrium condition

\[- \lambda \frac{\partial T}{\partial n} + \sum_{i} h_i \cdot \vec{J}_i \cdot \vec{n} = \sigma \varepsilon T_w^4 \]

\[ J_i = \gamma m_i \]

\( \gamma \): catalycity, recombination coeff.
Ablation testing

Measurements:
- Surface temperature
- Surface recession
- Char layer
- Pyrolisis gas
- Species volatilization
LHTS and Ablation phenomena

SOLVING THE SURFACE ENERGY BALANCE

\[ k_w \frac{\partial T}{\partial y} \bigg|_w + \sum_{i}^{N} \left( h_i \rho_i v_i^d \right)_w + \dot{m}(h_{Sw} - h_w) = \sigma \varepsilon_{Sw} T_w^4 + \dot{q}_{cond}^{ss} \]


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LHTS and GSI

\[ Nu = \frac{\dot{q}_w}{\lambda (T_{\infty} - T_w)/\delta} \]

- Gouard
- Fay & Riddell
IXV Re-entry flight physics

- Bow shock
- Viscous interaction
- Shock layer radiation
- Dissociation and Ionization
- Surface recombination
- Boundary layer transition
- SW/BL interaction

Boundary layer
Shock wave
Off-Stagnation point testing methodology

**Real flight situation**

\[ M \gg 1 \]

**Ground test simulation**

\[ M \ll 1 \]

Off-Stagnation point:
Full profile with edge conditions to be reproduced

\[ E_c = \frac{(U_e^2)}{E_{\text{chem}}} \ll 1, \text{ one could disregards the duplication of } U_e \text{ for heat-flux considerations.} \]

For ground testing some parameters can be adapted:

\[ H_t \rightarrow H_s, \quad U_e \rightarrow U \rightarrow \frac{U_{\text{flight}}}{L_{\text{flight}}} = \frac{U_{\text{test}}}{L_{\text{test}}} \rightarrow \text{Testing on scaled model} \]
Off stagnation point testing methodology

\[ L_{FP} = \frac{\varepsilon_{IXV}}{\rho \delta \mu \delta u_\delta} \]

\[ u_\delta, h_\delta, P \]

\[ \varepsilon_{IXV} = \varepsilon_{FP} \]

\[ L_{Sub} = \frac{L_{FP}}{U_\infty / u_\delta} \]

\[ E_{ck} = \frac{u_\delta^2}{h_\delta} \ll 1 \]
Off Stagnation point testing in Plasmatron facility

Assessment of Off-Stagnation point testing methodology

2 Heat-Flux distributions are compared respecting:

- Static enthalpy
- Pressure
- X/Ue

=> Scaling Flight conditions to Ground testing
Plasmatron testing for demisable materials

- Test sample
- Plasma torch
- Exhaust & heat exchanger
- Heat flux and Pitot probes (ejected)
- CMOS video camera
- CCD camera (PCO Pixelfly)
- Pulse generator / trigger
- 2-color pyrometer (Marathon Série MR1SB)
- Light collection system
- Spectrometer (Ocean Optics HR4000)
- 71 sec. after injection
- spectra chart

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Instrumented sample holder

Specific testing methodology for demisable materials

(1) Sample

(2) Back insulation

(3) Cover

(4) water-cooled holder

High-T ceramic adhesive

Aged cork composite for moderate and high heat flux

Virgin ceramic composite for low heat flux

Preferred material: SiC

Alternative at high heat flux
Graphite w/ controlled air gap between cover and sample

316L, Al2099, AL7075 and GLARE

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Aluminium alloy Al7075 (Al-Zn)

Constant heat flux of 260kW/m²

- Complete demise at 260kW/m² (and at 100kW/m²)
- Quasi 1D heat transfer before changes in the surface structure ($\Delta t=20$ sec.)
- Detection of several species in the OES data: first, Fe+ and Al+ and then, Zn+, Si, Cr and Cu

**Evolution of the back and front temperature of a virgin Al7075 sample**

- After test: $T_c2 = T_c3$
- Change in the structure of the exposed surface
- "Wavy" superficial layer of molten Al

**Typical results from material demise tests**
VKI Plasmatron performance envelope

Heat-Flux [MW/m²]

Measurements in supersonic regime

Measurements in subsonic regime

Earlier measurements in subsonic regime for high pressure

Stagnation Pressure [hPa]

Design operation envelope in 1999

New Plasmatron Testing capabilities

ESA requirements for future missions
Conclusions

- VKI Plasmatron has been adapted for LHTS testing
- It is specifically suitable for GSI and Aerothermochemistry
- Catalycity determination
- Passive/Active Oxydation
- Temperature jump phenomena
- Ablation studies with coupling interaction
- Off stagnation point investigation
- Demisable material characterization
- ...