Advances in Boundary Layer Investigations and Heat Flux Measurements in 1.2 MW VKI Plasmatron

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  - Experimental Results
  - Comparison with ICP Code
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  - Conclusions
Introduction

Start of space flight

Today

**Ablative**

(“Space Race”, inter-cont. missiles, lunar program)

$U_\infty > 10 \text{km/s}$

**Reusable**

(Space Shuttle, Buran, X-38)

$U_\infty \sim 7 \text{km/s}$

$H_0 = h_s + \frac{U_\infty^2}{2}$

**Ablative**

(pushing forward to outer space, interplanetary)

$U_\infty > 12 \text{km/s}$

We need facilities capable to simulate very high heat fluxes for extraplanetary re-entry missions
VKI 1.2 MW PLASMA TRON

Test Chamber Torch

water cooling system

$T \approx 10000 \, K$

ICP Inductive Coupled Plasma

Primary: HF-current through coil

Secondary: current loops in plasma

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State-of-the-Art at VKI

Freestream characterization
Experimental:
- A. Cipullo
- D. Lequang
- Y. Babou
Numerical: ICP code

Boundary layer (non-intrusive)
Experimental:
- B. Helber
- D. Guariglia
Numerical: BL code Barbante et al

Supersonic High Heat Flux Measurements
Experimental: D. Guariglia
Numerical: V. Van der Hagen

Gas/Surface Interaction
Experimental:
- F. Panerai
- B. Helber
- I. Sakraker
Numerical: BL code Barbante et al

Plasmatron

Experimental:
- LTE central injection
- Annular injection
- Discharge region
- Plasma jet
- M << 1
State-of-the-Art at VKI

Heat-Flux [MW/m²]

- Recent measurements in supersonic regime
- Recent measurements in subsonic regime
- Design operation envelope in 1999
- Requirements for extraplanetary re-entry missions

Stagnation Pressure [hPa]

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Research Strategy

- Pushing the limits of the Plasmatron facility
- Exploring new methodologies for measurements in HHF

Surface: Heat Flux
- Garden Gauge
- Water Cooled Calorim.

Transient Flow Field: High Speed Camera
- Plasma fluctuations
- Estimation of the thermal BL thickness

Radiation Field (Chemistry): Emission Spectroscopy
- Thermal BL temperature profile
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Experimental Setup  M<1

- Subsonic conturred nozzle AR = 4
- Non-LTE probe shape ø = 3.5 cm
- Gardon Gauge Calorimeter
- High Speed Camera
- 3 spectrometers Ocean Optics HR4000

Courtesy of B.Helber
High Speed Camera

Test conditions

Pressure = 100 mbar
Power = 700 KW

High Speed Camera Parameters

Acquisition frequency = 7905 hz
Image Dimensions = 704 x 400 px
Exposure = 19 μs
Number of frames = 2480
Typical resolution = 0.25 mm/px
Diafragm aperture = 16 ÷ 32
BL Measurements

Test conditions

Pressure = 100 mbar
Power = 700 KW

What kind of boundary layer? Radiation Boundary Layer (RBL)

Typ. freestream light intensity profile

Typ. light intensity profile with probe

Typ. light intensity profile with probe

Confidence level

Average profile

BL thickness estimation

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RBL Thickness

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Plasma Frequency Content

High Speed Camera Imaging

- Images processing
- Collecting light intensities along a line (e.g., stagnation line)
- Performing an FFT of the signal to retrieve the plasma frequency content (experimental data with the nozzle were still missing)
Plasma Frequency Content

Distance from the probe

- d = 50 mm
- d = 25 mm
- d = 0.25 mm

Pressure = 100 mbar  
Power = 200 KW

**600 hz: Power Generator**

**Frequencies due to the flow**

**Power Generator harmonics**

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Plasma Frequency Content

<table>
<thead>
<tr>
<th>Distance from the probe</th>
<th>Pressure = 200 mbar</th>
<th>Power = 300 KW</th>
</tr>
</thead>
<tbody>
<tr>
<td>d = 50 mm</td>
<td><img src="image1" alt="Graph" /></td>
<td>100 hz harmonics of the Generator</td>
</tr>
<tr>
<td>d = 25 mm</td>
<td><img src="image2" alt="Graph" /></td>
<td>Damping of the fluctuations</td>
</tr>
<tr>
<td>d = 0.25 mm</td>
<td><img src="image3" alt="Graph" /></td>
<td></td>
</tr>
</tbody>
</table>

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Emission Spectroscopy

Spectral range = 195 ÷ 1123 nm
Spectral resolution = 1 nm
Spot size ≈ 0.2 mm

N, O

CN, NO, N₂⁺

N, O

CN, NO, N₂⁺

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Emission Spectroscopy

- Assessment of local thermal equilibrium with the Boltzmann Plot method
- Estimation of the temperature using the ratio between two atomic line intensities

Power = 300 KW  p = 100 mbar  m = 6 g/s

Power = 450 KW  p = 200 mbar  m = 6 g/s
Experimental Setup M<<1

*Test Campaign at low heat flux conditions in collaboration with RM Student J.P.S.P. Leite*

- Standard probe shape Ø = 5 cm
- Water Cooled Calorimeter
- Copper Slug Calorimeter
- Gardon Gauge Calorimeter
- High Speed Camera
- 1 spectrometers Ocean Optics HR4000

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RBL Thickness

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The BL code has been developed by Barbante et al, but experimental comparison was still missing

- $p = 50$ mbar  HF = 900 KW/m$^2$
- $p = 100$ mbar  HF = 900 KW/m$^2$
Abel Inversion of the images

In image analysis, the forward Abel transform is used to project an optically thin, axially symmetric emission function onto a plane, and the reverse Abel transform is used to calculate the emission function given a projection (i.e. a scan or a photograph) of that emission function.

\[
F(y) = 2 \int_{y}^{\infty} f(r) r \, dr / \sqrt{r^2 - y^2}
\]

\[
f(r) = -\frac{1}{\pi} \int_{r}^{\infty} \frac{\partial F}{\partial y} \frac{dy}{\sqrt{y^2 - r^2}}
\]
If the image is not perfectly symmetric, Abel Inversion can give different results inverting the upper half-image or the lower half-image. In practical cases, it’s impossible to have a perfectly symmetric jet.
Abel Inversion of the images

Radiation Boundary Layer profile

Scatter of the points is due to computational error, because we are close to the centerline, where the Abel function diverges and because of the poor resolution of the camera (few points to Abel invert).
Abel Inversion of the images

Radial profiles of RAW image

Here are shown the ten RAW radial intensity profiles from the free jet up to 10 mm from the probe. Is possible so see how the profiles appears almost smooth and symmetric.
Radial light profiles comparison

Radial profiles from 10 mm to 0.25 mm from the probe

- Approaching the probe, the radial intensity became parabolic.
- Very close to the probe, we see many peaks and valleys.
- The intensity of light radial profile is linear.
- Close to the probe, a plateau starts to form valleys.

* x axis in mm

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The radial intensity profile doesn’t seem to match or to be similar with the temperature nor the enthalpy radial profile.
Abel Inversion of the images
Comparison of radial profiles with the ICP code

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Abel Inversion of the images
Comparison of radial profiles with the ICP code

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Boundary Layer Conclusions

- We assessed the possibility to use Emission Spectroscopy to study the boundary layer BUT Abel Inversion is mandatory to have reliable results;
- We measured the Radiation Boundary Layer thickness on a cold probe for different static pressures and heat fluxes;
- We retrieved the plasma fluctuation frequencies in subsonic regime, with a nozzle;
- We performed an Abel inversion of the High Speed Camera images and we compared it with with the results from the IPC code, showing traces of the singular species emission in the RBL radial profile.

Future Work

- A radiation code could be used to calculate light generated by the plasma, using the results of the ICP code, and compare it with the HSC images;
- Currently experiments are ongoing, using HSC and optical filter, isolating light at oxygen wavelengths only (P. Solano).
HIGH HEAT-FLUX MEASUREMENTS
High Heat-Flux Measurements M<1

![Graph showing heat flux vs. plasmatron power](Image)

- **Heat Flux [MW/m²]**
- **Plasmatron Power [KW]**

- **Legend**
  - ○ 100 mbar 6 g/s
  - × 200 mbar 6 g/s
  - ◊ 100 mbar 8 g/s

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The reason for passing to the supersonic regime were:

• It seems we reached a limit in subsonic regime
• From the literature this limit has been overcomed testing in supersonic regime [Kolesnicov]
• The HF should increase: reducind the distance from the nozzle and increasing the stagnation pressure
Experimental Setup M>1
Preliminary test campaign

- Supersonic contoured nozzle $AR = 20.9$
- Non-Equilibrium Probe $\phi = 3 \text{ cm}$
- Gardon Gauge Calorimeter
- High Speed Camera
- 3 spectrometers Ocean Optics HR4000
- Two distances tried: 6 and 3 cm
Experimental Setup M>1

Main test campaign

- Supersonic contoured nozzle AR = 20.9
- Hemispherical Probe \( \varnothing = 5 \text{ cm} \)
- Water Cooled Calorimeter
- High Speed Camera
- Two distances tried: 3 and 2 cm

Flat faced, non-equilibrium probe

Hemispherical probe

2 cm
Experimental Setup M>1
*Preliminary test campaign*

**Preliminary Test Campaign Conditions**

- \( d = 3 \text{ cm} \)
- \( \rho_{\text{res}} = 101.5 \text{ mbar} \)
- \( \rho_{\text{stat}} = 4 \text{ mbar} \)
- \( m = 4.5 \text{ g/s} \)
- **Power** = 500 KW \( \Rightarrow \) \( HF = 9.67 \text{ MW/m}^2 \)
- **Power** = 600 KW \( \Rightarrow \) \( HF = 10.20 \text{ MW/m}^2 \)

*Courtesy of D. Le Quang*

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The RBL is too thin to be resolved by the HSC.

The presence of the shock-wave makes meaningless the point spectroscopy.

Free-stream spectrum

Spectrum after shock (Abel inversion required)
High Heat-Flux Measurements M>1

- Shock waves pattern completely different from the flat faced probe.
- For the same test conditions, the frontal shock wave is more distant from the surface compared to the flat faced probe.
Max HF measured: 16.7 MW/m² with $p_0=220$ mbar
Plasma Frequency Content M>1

\[ p_{\text{res}} = 101 \text{ mbar} \quad p_{\text{stat}} = 4 \text{ mbar} \quad m = 4.5 \text{ g/s} \quad \text{Power} = 500 \text{ KW} \]

- \( d = 30 \text{ mm} \)
- \( d = 15 \text{ mm} \)
- \( d = 0.25 \text{ mm} \)

**Single-Sided Amplitude Spectrum of y(t)**

600 hz peak is missing

Harmonics multiple of 178 hz

Other sub-harmonics

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Conclusions and future works

- We assessed the capability of the 1.2 MW VKI Plasmatron to generate high heat fluxes of 16.5 MW/m²;
- We retrieved the plasma fluctuation frequencies in supersonic regime, showing they are far different from the ones in subsonic regime. Here more studies are required to understand such phenomena;

Future Work

- The ICP code for supersonic plasma is ready for validation;
- Works are ongoing to extend the LHTS theory also in presence of shock-waves.
THANK YOU QUESTIONS?