Characterization of a 50kW Inductively Coupled Plasma Torch for Testing of Ablative Thermal Protection Material

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 Presented By: Benton Greene
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  - Noel Clemens

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Research Motivation

- **Atmospheric entry**
  - Typical lunar return reentry velocity: 11 km/s
  - ~10 metric ton reentry vehicle
  - 500 GJ of kinetic energy
  - 15 min from entry to landing

- **Thermal protection**
  - Ablative heat shields
    - Rely on pyrolysis and mass loss
    - Non-reusable
  - Thermal soak
    - Heat absorbed into TPS material
    - Must be either cooled or ejected
Research Motivation

- **Ground testing**
  - Replicate Mach number, heat flux, pressure, and surface velocity gradient
  - Understand chemistry of pyrolysis
  - Develop computer models of heat shield mass loss and thermal soak

- **Difficult to replicate all parameters**

- **Use different facilities to replicate specific features**

- **Combine data in computational models**
High-Enthalpy Flow Facilities

- **Impulse facilities**
  - Gun tunnels, shock tubes, expansion tubes, Ludwieg tubes
  - Use unsteady shock motion to generate high-enthalpy, high-velocity flow
  - Run time on order of milliseconds

- **Arcjet**
  - Use high-voltage discharge to superheat flow
  - Run time virtually unlimited
  - Metal electrodes contaminate flow

- **Inductively Coupled Plasma (ICP) Torch**
  - Use fluctuating magnetic fields to superheat flow
  - Run time virtually unlimited
  - No metal electrodes in contact with flow
  - Typically run at lower pressures than arcjets
What is an ICP

- Induction coils fed with high-voltage MHz AC power
- Fluctuating magnetic field generates electric field necessary for gas breakdown
- Gas injected into cooled quartz tube inside coil
- Swirling motion of air keeps plasma ball away from walls
- Superheated air forced through water cooled nozzle

![Diagram of an ICP](image)
Current Facility

COMPONENTS AND CAPABILITIES
Current Facility

- Control/Instrumentation Cabinet
- Plexiglas-Enclosed Fume Hood
- Water-Cooled Insertion Arm
- Torch Head
Video of Startup
Torch

- Developed by Applied Plasma Technologies
- Up to 50kW inductively coupled plasma
- Coil voltage between 9 kV and 12 kV at 6 MHz
- Plasma chamber
  - Water-cooled quartz tube
  - 250 mm in length
  - 30 mm exit nozzle
- Torch head tethered to power supply with flexible cable
Traverse Table

- 3-Axis translation with 1 ton capacity
- Move torch with respect to a fixed optical diagnostic setup
  - Resolution: 0.5 mm
  - Travel: 150 mm
- Allows optical diagnostics to probe arbitrary locations in plume with no readjustment of optics
Insertion Mechanism

- Developed by NASA collaborators
- Two water-cooled arms
- Adjustable height above torch
  - 0 to 150 mm
- Motorized insertion
  - Fast: 45° per second
  - Slow scan: 1 mm resolution through plume diameter
- Adapters for mounting instruments and test articles
Testing Results

FLOW CHARACTERIZATION
Operational Envelope

Maximum Operating Voltage for Power Supply Components

- Anode Voltage (kV)
- High Coolant Temp

Stable Plume with Clean Flow

Minimum Voltage to Sustain Breakdown

Mass Flow Rate of Air (SLPM)

Operational Envelope

Test Points
Bulk Enthalpy

- \( P_{\text{plasma}} = V_a I_a - \dot{m}_{H_2O} c_p \Delta T \)
- Use \( P_{\text{plasma}} \) to calculate bulk enthalpy of gas
- \( P_{\text{plasma}} \approx \text{constant} \) for given voltage
  - Increased flow rate for given voltage decreases bulk enthalpy of gas
Heat Flux

- Medtherm gardon gauge heat flux sensor
  - Consists of a constantan foil thermocouple junction
  - Water cooled
  - Outputs a voltage proportional to the incident heat flux

- Slug calorimeter heat flux sensor
  - Type K thermocouple embedded in copper slug
  - One face of copper slug exposed to flow
  - Heat flux related to slope of temperature rise
    - \[ q = \frac{mc_p}{A} \dot{T} \]
Heat Flux (Gardon Gauge)

Heat flux drops by ~0.9 W/cm² every mm of axial distance
Heat flux peaks between 30 and 45 slpm flow rate.
Competing effects of velocity increase and bulk enthalpy decrease with flow rate.
Heat flux peaks between 30 and 45 slpm flow rate
Heat Flux (Slug Calorimeter)

![Graph showing heat flux vs air mass flow for different air masses and temperatures.]

- Z = 30 mm
- Z = 60 mm
- Z = 90 mm

Legend:
- 9.5 kV
- 10.0 kV
- 10.5 kV
- 11.0 kV
- 11.5 kV
- 11.9 kV
Heat Flux

- Calorimeter error based on temperature slope goodness of fit
- Measurements match within experimental error
- Calorimeter reads slightly higher than Gardon gauge
Heat Flux (Radial Variation)

- Radial profiles taken at $V_a = 9.5$ kV and various flow rates
- Peak heat flux much higher than that measured by calorimeter due to difference in probe shape
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- Peak heat flux much higher than that measured by calorimeter due to difference in probe shape
- Slight drift in central peak with flow rate
  - Consistent trend for both voltages

![Graph showing peak offset vs mass flow for different voltages and flow rates]
Heat Flux (Radial Variation)

- Radial profiles taken at $V_a = 9.5\text{ kV}$ and various flow rates
- Peak heat flux much higher than that measured by calorimeter due to difference in probe shape
- Slight drift in central peak with flow rate
  - Consistent trend for both voltages
- Width of peak does not change with flow rate
Emission Spectroscopy

- OceanOptics HD2000+ USB Spectrometer
  - 200nm - 1200nm
  - Calibrated with OceanOptics LS1-CAL tungsten calibration lamp

- 1mm diameter field of view

- Emission spectra taken at 2mm intervals through plume diameter

- Spectra are Abel inverted to obtain $I(\lambda; r)$
Emission Spectroscopy

- Capture spectrum from narrow beam through plume at multiple radial locations
- Fit symmetric polynomial in $x$ to intensity measurements, $I(x; \lambda)$, for every $\lambda$
- Abel invert polynomial fit to get $I(r; \lambda)$ and therefore $I(\lambda; r)$
Emission Spectroscopy
Emission Thermometry

- Use oxygen emission
- Only 777nm and 615nm lines visible and non-overlapping with N emission
- Fit line to Gaussian profile to determine intensity
- Use intensity ratio of two lines to get temperature

\[ T = \frac{\varepsilon_{u2} - \varepsilon_{u1}}{k \ln \left( \frac{I_1 A_2 \Delta \varepsilon_2 g_{u1}}{I_2 A_1 \Delta \varepsilon_1 g_{u2}} \right)} \]

- Eliminates need for absolute intensity
Emission Thermometry

![Graph showing temperature variation with radius for different voltages (V=10.0 kV, V=10.5 kV, V=11.0 kV). The graph displays a clear trend of decreasing temperature with increasing radius.]
Emission Thermometry

![Graph showing the relationship between $T/T_{max}$ and $r/R$. The graph includes multiple datasets: Laux$^2$, UT ICP 1, UT ICP 2, and UT ICP 3. The x-axis represents $r/R$, ranging from 0.0 to 0.6, while the y-axis represents $T/T_{max}$, ranging from 1.00 to 0.75.]
Comparison to Other Facilities

<table>
<thead>
<tr>
<th></th>
<th>UT-Austin</th>
<th>UVM(^4)</th>
<th>VKI Plasmatron(^6)</th>
<th>Ecole Centrale, Paris(^3,5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run time</td>
<td>1.5 hr</td>
<td>6 min</td>
<td></td>
<td>&gt;10 min</td>
</tr>
<tr>
<td>Max Heat Flux</td>
<td>225 W/cm(^2)</td>
<td>85 W/cm(^2)</td>
<td>350 W/cm(^2)</td>
<td></td>
</tr>
<tr>
<td>Operating Pressure</td>
<td>500 kPa</td>
<td>10 kPa</td>
<td>1.5 kPa - 20 kPa</td>
<td>100 kPa</td>
</tr>
<tr>
<td>Flow Regime</td>
<td>Subsonic</td>
<td>Subsonic</td>
<td>Subsonic/Supersonic</td>
<td>Subsonic</td>
</tr>
<tr>
<td>Gas Composition</td>
<td>Air, Ar</td>
<td>Ar, Air, N(_2), CO(_2)</td>
<td>Air, Ar</td>
<td>Ar, Air</td>
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<tr>
<td>Flow Rate</td>
<td>20-75 slpm</td>
<td>0 to 50 slpm</td>
<td>800 slpm</td>
<td>70 slpm</td>
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<tr>
<td>Operating Frequency</td>
<td>6 MHz</td>
<td>2.7 MHz</td>
<td>400 kHz</td>
<td>4MHz</td>
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<tr>
<td>Operating Power</td>
<td>50 kW</td>
<td>30 kW</td>
<td>1.2 MW</td>
<td>50 kW</td>
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</tbody>
</table>
Future Work

- Graphite and Teflon test articles
  - Pyrometry to measure model surface temperature
  - LIF to measure species concentration near model surface
  - Raman scattering to measure temperature and species concentration

- Measure recession rates over a simulated heating cycle
Questions?
References


