Flow Characterization and MHD Tests in High Enthalpy Argon Flow

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Outline

I. Introduction

II. Flow Characterization
   1. High Enthalpy Facility L2K
   2. Flow Characterization Methods
   3. Flow Characterization Results

III. MHD Experiments

IV. Conclusions
I. Introduction
Magnetohydrodynamics (MHD)

Utilizing MHD effects for reentry vehicles

- Heat flux mitigation
- Communication blackout mitigation
- Flow control

Source terms

- Momentum (Lorentz force):
  \[ \vec{f} = \vec{j} \times \vec{B} \]
- Energy conversion \( EM \rightarrow \text{Internal} \):
  \[ \vec{j} \cdot \vec{E} \]
- Energy conversion \( \text{kinetic} \rightarrow \text{Internal} \):
  \[ \vec{j} \cdot (\vec{v} \times \vec{B}) \]

Currents are characterized by:

- Conductivity \( \sigma \)
- Hall parameter \( \beta \)

Characteristic parameter for MHD interaction

- Magnetic interaction parameter
  \[ Q = \frac{\sigma_0 B_0^2 L}{\rho_0 v_0} \]
II. Flow Characterization
Arc Heated Facility L2K

For MHD tests:
- Weakly ionized hypersonic Argon flow
- 100 mm nozzle exit diameter for small stagnation point models
- 200 mm nozzle exit diameter for larger stagnation point models and flat plate models
Flow State Definitions

States used for small stagnation point models with **100 mm nozzle exit diameter**

<table>
<thead>
<tr>
<th>mass flow</th>
<th>m</th>
<th>3 g/s</th>
<th>8 g/s</th>
<th>20 g/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>reservoire pressure</td>
<td>p</td>
<td>70 hPa</td>
<td>160 hPa</td>
<td>375 hPa</td>
</tr>
<tr>
<td>spec. enthalpy</td>
<td>h</td>
<td>3.1 MJ/kg</td>
<td>2.4 MJ/kg</td>
<td>2.0 MJ/kg</td>
</tr>
<tr>
<td>temperature</td>
<td>T</td>
<td>6010 K</td>
<td>4532 K</td>
<td>3886 K</td>
</tr>
</tbody>
</table>

States used for larger stagnation point or flat plate models with **200 mm nozzle exit diameter**

<table>
<thead>
<tr>
<th>mass flow</th>
<th>m</th>
<th>20 g/s</th>
<th>20 g/s</th>
<th>20 g/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>reservoire pressure</td>
<td>p</td>
<td>325 hPa</td>
<td>350 hPa</td>
<td>375 hPa</td>
</tr>
<tr>
<td>spec. enthalpy</td>
<td>h</td>
<td>1.5 MJ/kg</td>
<td>1.8 MJ/kg</td>
<td>2.0 MJ/kg</td>
</tr>
<tr>
<td>temperature</td>
<td>T</td>
<td>2919 K</td>
<td>3385 K</td>
<td>3886 K</td>
</tr>
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</table>
Flow Characterization Methods

- Coriolis gas mass flow meter
- Reservoir pressure transducer
- Pitot probe

Emission spectroscopy
  - Species spectra

LIF – Laser Induced Fluorescence on NO molecules
  - Rotational temperature
  - Concentration

DLAS – Diode Laser Absorption Spectroscopy on CO molecules
  - Velocity
  - Translational temperature

- Microwave interferometry
  - Electron density
  - Velocity

- Electrostatic probes
  - Electron density and temperature

- Microwave transmission spectroscopy
  - Electron density

- VIS camera
  - Flow topology

- IR camera
  - Surface temperatures
Flow Characterization Methods

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• VIS camera
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• IR camera
  - Surface temperatures
Microwave Interferometry (MWI)

- Determination of **electron density** by measuring the decreased optical path length
- Two interferometers are used to determine the **flow velocity**
Microwave Plasma Transmission Spectroscopy

Estimation of $f_{pl}$ by linear regression allows estimation of $n_e$

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$
Electrostatic Probes

Measurement types
• Plasma potential measurements
• Langmuir probe measurements
  • Single
  • Double
  • Triple

Measurements behind bow shock
• 70 mm diameter cylindrical model

Wire arrangement
• 2 mm distance
• 8 mm length
• 0.5 mm diameter
Electrostatic Probes

Single probe measurements
- I-V curve measurement
- probe steady on flow axis

\[
T_e = 11,594 \frac{K}{V} \cdot \frac{d \ln (j_e/j_0)}{dV}
\]

\[
I_{e,s} = \frac{1}{4}en_e v_e,th A_{probe}
\]

(1) Principles of Plasma Discharges and Material Processing, M. Lieberman, A. Lichtenberg
Electrostatic Probes

Single probe measurements
- I-V curve measurement
- probe steady on flow axis

weakly ionized argon flow

L2K test chamber (grounded)

voltmeter

Electron current $I_e$ vs. $V$ [V]

$T_e = 2705 \pm 291$ K
Electrostatic Probes

Double probe measurements
- I-V curve measurement
- probe steady on flow axis

\[ T_e = 11,594 \frac{K}{V} \cdot \frac{I_{11}I_{12}}{I_{11}+I_{12}} \cdot \left( \frac{dI}{dU} \right)_{U=0} \]

(assuming Maxwell distributed electron energies)

References:
**Electrostatic Probes**

Double probe measurements
- I-V curve measurement
- probe steady on flow axis

![Langmuir Double Probe](chart)

- $T_e=1459K, n_e=6.7 \times 10^{17} \text{ m}^{-3}$
- $T_e=1176K, n_e=5.7 \times 10^{17} \text{ m}^{-3}$
- $T_e=1581K, n_e=6.4 \times 10^{17} \text{ m}^{-3}$
Electrostatic Probes

Triple probe measurements

• voltage measurement
• probe movement across the flow
• applied voltage $U_3 = 5\, \text{V}$

\[ T_e = 16.742 \frac{K}{V} \cdot V_2 \]

\[ n_e = \frac{\sqrt{m_1 I}}{S} \cdot \frac{\exp\left(\frac{1}{2}\right)}{e\sqrt{k_B T_e}} \]

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Electrostatic Probes

Triple probe measurements
- voltage measurement
- probe movement across the flow
- applied voltage $U_3 = 5 \text{ V}$
Flow Characterization Results

<table>
<thead>
<tr>
<th>State (20 g/s)</th>
<th>MPTS</th>
<th>MWI</th>
<th>2L</th>
</tr>
</thead>
<tbody>
<tr>
<td>375 mbar</td>
<td>6.8</td>
<td>6.1</td>
<td>13.3</td>
</tr>
<tr>
<td>350 mbar</td>
<td>2.6</td>
<td>2.7 ± 0.1</td>
<td>7.0</td>
</tr>
<tr>
<td>325 mbar</td>
<td>1.4</td>
<td>1.6 ± 0.2</td>
<td>3.3</td>
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<tr>
<th>State (20 g/s)</th>
<th>1L</th>
<th>2L</th>
<th>3L</th>
</tr>
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<tbody>
<tr>
<td>375 mbar</td>
<td>3266</td>
<td>1492</td>
<td>2405</td>
</tr>
<tr>
<td>350 mbar</td>
<td>2884</td>
<td>1401</td>
<td>(-)</td>
</tr>
<tr>
<td>325 mbar</td>
<td>(-)</td>
<td>1502</td>
<td>(-)</td>
</tr>
</tbody>
</table>

**Electron Density [10^{17} / m^3]**

**Electron Temperature [K]**

MPTS: Microwave Plasma Transmission Spectroscopy  
MWI: MicroWave Interferometry  
2L: Langmuir double probe ($T_e = 180$ K)
Flow Characterization Results

200 mm nozzle exit diameter states, varying reservoir pressure

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<td>electron density (MWI)</td>
<td>n_e</td>
<td>1.6 \cdot 10^{17} 1/m^3</td>
<td>2.7 \cdot 10^{17} 1/m^3</td>
<td>6.1 \cdot 10^{17} 1/m^3</td>
</tr>
<tr>
<td>velocity (MWI)</td>
<td>v</td>
<td>1723 m/s</td>
<td>1850 m/s</td>
<td>2150 m/s</td>
</tr>
<tr>
<td>temperature (DLAS)</td>
<td>T</td>
<td>(-)</td>
<td>(-)</td>
<td>180 K</td>
</tr>
<tr>
<td>pitot pressure</td>
<td>p</td>
<td>4.5 Pa</td>
<td>4.9 Pa</td>
<td>5.6 Pa</td>
</tr>
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# Flow Characterization Results

100 mm nozzle exit diameter states, varying mass flow rate

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<tbody>
<tr>
<td>n_e</td>
<td>8.6 \times 10^{17} 1/m^3</td>
<td>1925 m/s</td>
<td>(-)</td>
<td>2.4 Pa</td>
</tr>
<tr>
<td>v</td>
<td>1945 m/s</td>
<td>(--)</td>
<td>(--)</td>
<td>4.6 Pa</td>
</tr>
<tr>
<td>T</td>
<td>(--)</td>
<td>(--)</td>
<td>360 K</td>
<td>(--)</td>
</tr>
<tr>
<td>p</td>
<td>10.0 Pa</td>
<td>(--)</td>
<td>(--)</td>
<td>(--)</td>
</tr>
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III. MHD Experiments
Flow Field Topology

Model
- 70 mm diameter cylindrical stagnation point model with quartz surface
- Electromagnet
- 0.48 T stagnation point field strength

without B

with B

3g/s

8g/s
Heat Flux Measurements

- Surface temperature measurement via IR camera
- 1D thermal conduction model to determine the heat flux
- 2D heat flux profile on model surface

Model
- 70 mm diameter cylindrical stagnation point model with quartz surface
- Permanent magnet (NdFeB)
- 0.54 T stagnation point field strength
Conclusions

Flow Characterization
• Different high enthalpy argon flow states for MHD test have been defined and characterized by various methods.
• Comparison of different methods for determination of electron density and electron temperature.

MHD Test
• Flow field topology and surface heat flux measurements for stagnation point models with axial magnetic field.
• Increased heat flux measured when applying magnetic field at the 3 g/s condition for cylindrical stagnation point model with a stagnation point magnetic field strength of 0.54 T.
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