Consolidated laser-induced fluorescence diagnostic systems for the NASA Ames arc jet facilities

Jay Grinstead and Michael Wilder
Aerothermodynamics Branch

Barry Porter
Experimental Aero-physics Branch

Jeff Brown
Entry Systems and Vehicle Development Branch

Dickson Yeung
Thermo-physics Facilities Branch

Steve Battazzo
Engineering Systems Division

Tim Brubaker
Department of Electrical Engineering, Penn State University

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Outline

- Atmospheric entry, thermal protection, and arc jet testing
- Two photon LIF as an arc jet diagnostic
- Short history of arc jet LIF at NASA
- LIF systems redevelopment at NASA Ames
- Example results
- Current status and future work
• Spacecraft kinetic energy is converted to thermal energy during atmospheric entry deceleration
• Part of that thermal energy reaches spacecraft through convective and radiative heat transfer
• Thermal protection system (TPS) mitigates heat transfer to substructure
• TPS materials are developed and validated with **arc jet testing**
Arc jet facilities and TPS testing

- Atmospheric entry aeroheating environments for TPS materials testing
  - Heat flux, heat load, pressure, shear
- Nonequilibrium free stream
  - Highly dissociated – conditions not encountered in flight
  - TPS material response can be sensitive to the degree of nonequilibrium

- TPS testing methodology relies on facility characterization and simulation
  - High fidelity CFD simulations validated with facility performance data
  - Boundary conditions for TPS material response modeling
Two photon absorption LIF (TALIF) of atomic N and O

- Non-intrusive, species-selective diagnostic for combustion and plasma flows
- Tunable UV laser excitation, near-infrared fluorescence
Arc jet flow property measurement with LIF

- Laser excitation scan over absorption transition reveals three important flow properties
  - **Velocity** from Doppler shift
  - **Temperature** from line shape width
  - **Species density** from integrated signal magnitude

- LIF-measured flow properties and facility data are used to compute **total and modal enthalpy** of arc jet free stream
TALIF in NASA arc jet facilities – timeline

**ARC Aerodynamic Heating Facility (AHF)**
- 1995: AHF v.1 (O)
- 1998: AHF v.1 (N)
- 2002: AHF v.2 (N, radial profile)
- 2016: AHF v.3.5 (N, O)

**ARC Interaction Heating Facility (IHF)**
- 2008: IHF v.3 (N, O)
- 2015: IHF v.3.5 (N, O)

**JSC Test Position 2 (TP-2)**
- 2010: TP-2 v.3 (N,O)

Q3 2013
- Critical review and redevelopment
- Rebuild AHF system

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**TALIF process**

- **Rate equation analysis:** Accounts for state population dynamics
- **Magnitude of fluorescence signal:** function of spectroscopic and experimental parameters
- **Proportional to four factors and a calibration constant**

\[
S_{LIF}(\lambda) = N_1 \cdot E_p^2 \cdot \tau_{eff} \cdot g(\lambda: \lambda_0, \Delta \lambda) \cdot \text{[calibration constant]}
\]
TALIF signal interpretation

Excitation line shape

\[ S_{\text{LIF}}(\lambda) \propto g(\lambda: \lambda_0, \Delta\lambda_D) \]

Integrated signal magnitude

\[ \frac{\overline{S}_{\text{LIF}}}{E_p^2 \cdot \tau_{\text{eff}}} = \left[ \text{calibration constant} \right] \cdot N_1 \]

- **Velocity and Temperature**
- **Species density**

• Expressions that characterize TALIF signal response
  - Calibration and analysis to recover flow properties

• **Defines data requirements for experiment implementation**
• **Calibration methodology** – means to obtain calibration constants for measurement of absolute atomic N and O densities in arc jet

• **Validation capability** – experiments to assess conformance to TALIF theory (reveal systematic errors)
  - Quadratic pulse energy dependence
  - Linear density dependence
  - Line shape function modeling

• **Comprehensive and efficient data acquisition**
  - Optimum use of arc-on time
Calibration methodology for arc jet N and O densities

- Traceable to known absolute atomic N and O densities
  - Laboratory reference source

- Kr and Xe used as proxies of N and O
  - TALIF characteristics and experiment configurations are nearly identical

- N and O TALIF responses in the arc jet are calibrated through Kr and Xe TALIF measurements in the arc jet and lab
Implemented features for calibration and validation

• Laboratory and arc jet calibration sources
  - Target species at prescribed pressures and quantifiable densities

• Detector system
  - Dynamic range accommodation: sensitive over 3 orders of magnitude

• Laser pulse energy
  - Continuously variable and quantifiable over 1.5 orders of magnitude

• Experiment management and data acquisition program
  - Multiple independent parameter modes (laser wavelength, pulse energy, pressure, flow rate)
**LIF laboratory optical configuration – v.3.5**

Nd:YAG pump laser

Dye laser

Harmonic generators

Laboratory pulse energy sensor

Laser dyes
- N/Kr: DCM + PM597 (612 nm, 620 nm)
- O/Xe: LDS698 (676-677 nm)

Microwave-driven flow reactor calibration source

TALIF detector (N, O, Kr, Xe)

PMT

Spectral and ND filters

Collimating telescope

Arc jet (relative) pulse energy sensor

Variable attenuator

To arc jet test chamber

1/2 waveplate

Polarizing partial beam splitter

Harmonic separator

612-690 nm

532 nm

204-230 nm

2x

3x
Laboratory flow reactor calibration source

- Programmable mixtures of N, O, Kr, or Xe
- N and O densities quantified through titration

Number densities (cm$^{-3}$)
- $[N], [O] \sim 10^{13} – 10^{14}$
- $[Kr], [Xe] \sim 10^{14} – 10^{16}$

Pressure
- 0.2 – 10 torr
Arc jet LIF optical configuration – v.3.5

Arc jet nozzle

Beam director

Collimating telescope

LIF collection telescope

Fiber optic bundle

PMT

TALIF detector (N, O, Kr, Xe)

Spectral and ND filters

Arc jet pulse energy sensor

Kr, Xe calibration flow cell

to collection telescope

System alignment and density calibration only

Beam from laser lab

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IHF LIF configuration

Beam from laser lab

Beam focusing telescope

Laser entrance window

Collection telescope

Arc jet flow axis

Beam director

Fiber optic bundle

Feedthrough for fiber bundle

To Detector

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LIF collection telescope – v.3.5

- Reflective optics
- Imaged fluorescence is coupled out of facility through fiber optic bundle
- One telescope – used in both facilities
Fiber bundle and integrated LIF detector – v.3.5

- Fiber optic bundle
- Fiber bundle feedthrough
- PMT, preamp, HV power supply, optical filters, comm link to lab
• Glass tube flow cell with optical access windows
• Programmable mixtures of Kr or Xe ($\sim 10^{14} - 10^{16}$ cm$^{-3}$)
Example validation experiment results

- Ensures conformance to TALIF theory for signal interpretation
- Enables quantification of random error for uncertainty estimates

**Quadratic pulse energy dependence**

**Linear density dependence**
**Demonstration test results – AHF**

<table>
<thead>
<tr>
<th>AHF (TP-3 arc heater)</th>
<th>Arc Current (A)</th>
<th>N₂ Flow (g/s)</th>
<th>O₂ Flow (g/s)</th>
<th>Add Gas (N₂) Flow (g/s)</th>
<th>Enthalpy (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 7.5” dia. nozzle</td>
<td>1205</td>
<td>177</td>
<td>71</td>
<td>62</td>
<td>19.7</td>
</tr>
<tr>
<td>• Z = 6.0”</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Nitrogen

- Excitation scan
- $V = 3737 \pm 524 \text{ m/s}$
- $T = 1166 \pm 333 \text{ K}$
- $\tau_{\text{eff}} = 23.7 \text{ ns}$

### Oxygen

- Excitation scan
- $V = 3693 \pm 170 \text{ m/s}$
- $T = 1319 \pm 176 \text{ K}$
- $\tau_{\text{eff}} = 24.9 \text{ ns}$
- $\tau_{\text{eff}} = 19.6 \text{ ns}$
Nitrogen

Excitation scan

$V = 4182 \pm 148 \text{ m/s}$
$T = 1596 \pm 112 \text{ K}$

Fluorescence pulse

$\tau_{eff} = 21.2 \text{ ns}$

Oxygen

Excitation scan

$V = 4071 \pm 148 \text{ m/s}$
$T = 1999 \pm 307 \text{ K}$

Fluorescence pulse

$\tau_{eff} = 13.8 \text{ ns}$

### IHF

- 6" dia. nozzle
- $Z = 4.0"$

<table>
<thead>
<tr>
<th>Arc Current (A)</th>
<th>Main Air Flow (g/s)</th>
<th>Add Air Flow (g/s)</th>
<th>Enthalpy (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3571</td>
<td>137</td>
<td>165</td>
<td>27.1</td>
</tr>
</tbody>
</table>

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Summary and next steps

• Revised LIF system design for the Ames arc jet facilities
  - Critical review of measurement requirements
  - Modifications to enable validation experiments
  - New arc jet LIF receiver and detector system
  - **New experiment management software**
• Updated existing IHF LIF system
• Rebuilt AHF LIF system
  - Inactive since 2005
  - Incorporated design improvements
• Both systems have identical functionality and capabilities

• Future work
  - Operational optimization
  - Comprehensive error analysis