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
Planetary entry aeroheating and thermal protection systems

- 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
• 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)
- 2015: IHF v.3.5 (N, O)

JSC Test Position 2 (TP-2)
- 2008: IHF v.3 (N, O)
- 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**

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

**Integrated signal magnitude**

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

- **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 532 nm

Dye laser

Harmonic generators

612-690 nm

2x

3x

Harmonic separator

204-230 nm

Lab pulse energy sensor

Microwave-driven flow reactor calibration source

Laser dyes

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

Arc jet (relative) pulse energy sensor

Variable attenuator

Polarizing partial beam splitter

1/2 waveplate

Collimating telescope

Spectral and ND filters

PMT

TALIF detector (N, O, Kr, Xe)

To arc jet test chamber
Laboratory flow reactor calibration source

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

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

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

Arc jet nozzle

Beam director

Collimating telescope

Beam from laser lab

LIF collection telescope

Fiber optic bundle

PMT

Spectral and ND filters

TALIF detector (N, O, Kr, Xe)

Arc jet pulse energy sensor

Kr, Xe calibration flow cell

to collection telescope

System alignment and density calibration only

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AHF LIF configuration

Beam from laser lab

Laser entrance window

Beam director

Arc jet flow axis

Feedthrough for fiber bundle

Fiber optic bundle

Collection telescope

Beam focusing telescope

To Detector

Beam from laser lab

Laser entrance window

Beam director

Arc jet flow axis

Feedthrough for fiber bundle

Fiber optic bundle

Collection telescope

Beam focusing telescope

To Detector

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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
• 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

PMT, preamp, HV power supply, optical filters, comm link to lab

Fiber bundle feedthrough
Arc jet Kr, Xe calibration source

- Glass tube flow cell with optical access windows
- Programmable mixtures of Kr or Xe ($\sim 10^{14} - 10^{16} \text{ cm}^{-3}$)
Example validation experiment results

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

**Quadratic pulse energy dependence**

![Graph showing quadratic pulse energy dependence](image)

**Linear density dependence**

![Graph showing linear density dependence](image)
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&quot; 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
- $V = 3737 \pm 524$ m/s
- $T = 1166 \pm 333$ K

### Oxygen

- Excitation scan
- $V = 3693 \pm 170$ m/s
- $T = 1319 \pm 176$ K

### Fluorescence pulse

- $\tau_{eff} = 23.7$ ns
- $\tau_{eff} = 15.2$ ns

- $\tau_{eff} = 24.9$ ns
- $\tau_{eff} = 19.6$ ns

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Demonstration test results – IHF

**IHF**
- 6” dia. nozzle
- Z = 4.0”

<table>
<thead>
<tr>
<th></th>
<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>Nitrogen</td>
<td>3571</td>
<td>137</td>
<td>165</td>
<td>27.1</td>
</tr>
<tr>
<td>Oxygen</td>
<td>4182 ± 148 m/s</td>
<td>1596 ± 112 K</td>
<td>4071 ± 148 m/s</td>
<td>1999 ± 307 K</td>
</tr>
<tr>
<td>t_{eff}</td>
<td>21.2 ns</td>
<td>9.7 ns</td>
<td>23.7 ns</td>
<td>13.8 ns</td>
</tr>
</tbody>
</table>

**Excitation scan**

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

**Fluorescence pulse**

\[ \tau_{eff} = 21.2 \text{ ns} \]
\[ \tau_{eff} = 9.7 \text{ ns} \]

**Fluorescence pulse**

\[ \tau_{eff} = 23.7 \text{ ns} \]
\[ \tau_{eff} = 13.8 \text{ ns} \]

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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