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

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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 \textit{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)

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

**Express lineshape**

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

**Integrated signal magnitude**

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

- **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

![Energy level diagrams for Nitrogen, Krypton, Oxygen, and Xenon]
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

612-690 nm

Harmonic generators

2x

3x

Harmonic separator

532 nm

204-230 nm

Nd:YAG pump laser

Dye laser

Harmonic generators

Lab 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
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
- Beam from laser lab
- System alignment and density calibration only

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AHF LIF configuration

Beam focusing telescope

Collection telescope

Fiber optic bundle

Feedthrough for fiber bundle

Beam from laser lab

Laser entrance window

Beam director

Arc jet flow axis

To Detector

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IHF LIF configuration

- Beam from laser lab
- Arc jet flow axis
- Beam focusing telescope
- Laser entrance window
- Collection telescope
- 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

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Arc jet Kr, Xe calibration source

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

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Example validation experiment results

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

**Quadratic pulse energy dependence**

- $S_{LIF} \sim E_p^{2.1}$

**Linear density dependence**

- $\tilde{S}_{LIF} \frac{E_p}{\tau_{eff}}$

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AHF (TP-3 arc heater)
• 7.5" dia. nozzle
• Z = 6.0"

<table>
<thead>
<tr>
<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>1205</td>
<td>177</td>
<td>71</td>
<td>62</td>
<td>19.7</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>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>

**Nitrogen**

- Excitation scan
- $V = 4182 \pm 148$ m/s
- $T = 1596 \pm 112$ K

**Oxygen**

- Excitation scan
- $V = 4071 \pm 148$ m/s
- $T = 1999 \pm 307$ K

**Fluorescence pulse**

- $\tau_{eff} = 21.2$ ns
- $\tau_{eff} = 9.7$ ns

- $\tau_{eff} = 23.7$ ns
- $\tau_{eff} = 13.8$ 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