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
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
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)
- 1995: AHF v.1 (O)
- 1998: AHF v.1 (N)
- 2002: AHF v.2 (N, radial profile)
- 2008: IHF v.3 (N, O)
- 2015: IHF v.3.5 (N, O)
- 2010: TP-2 v.3 (N,O)

JSC Test Position 2 (TP-2)
- 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

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

- Defines data requirements for experiment implementation

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

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

Velocity and Temperature

Species density
• **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

612-690 nm

2x

3x

Harmonic separator

204-230 nm

Microwave-driven flow reactor calibration source

Laser dyes

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

TALIF detector (N, O, Kr, Xe)

PMT

Spectral and ND filters

Lab pulse energy sensor

1/2 waveplate

Polarizing partial beam splitter

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
- Spectral and ND filters
- Arc jet pulse energy sensor
- TALIF detector (N, O, Kr, Xe)
- Kr, Xe calibration flow cell
- Beam from laser lab

System alignment and density calibration only

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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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• 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
Arc jet Kr, Xe calibration source

- Glass tube flow cell with optical access windows
- Programmable mixtures of Kr or Xe (~ $10^{14} - 10^{16}$ 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
Demonstration test results – AHF

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>
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<tr>
<td>1205</td>
<td>177</td>
<td>71</td>
<td>62</td>
<td>19.7</td>
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Nitrogen

Excitation scan

\[ V = 3737 \pm 524 \text{ m/s} \]
\[ T = 1166 \pm 333 \text{ K} \]

Fluorescence pulse

\[ \tau_{\text{eff}} = 23.7 \text{ ns} \]
\[ \tau_{\text{eff}} = 15.2 \text{ ns} \]

Oxygen

Excitation scan

\[ V = 3693 \pm 170 \text{ m/s} \]
\[ T = 1319 \pm 176 \text{ K} \]

Fluorescence pulse

\[ \tau_{\text{eff}} = 24.9 \text{ ns} \]
\[ \tau_{\text{eff}} = 19.6 \text{ ns} \]

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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>
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<tr>
<td>3571</td>
<td>137</td>
<td>165</td>
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**Nitrogen**
- $V = 4182 \pm 148$ m/s
- $T = 1596 \pm 112$ K
- $\tau_{eff} = 21.2$ ns

**Oxygen**
- $V = 4071 \pm 148$ m/s
- $T = 1999 \pm 307$ K
- $\tau_{eff} = 13.8$ ns

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

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**Excitation scan**
- $\delta \lambda$

**Fluorescence pulse**
- $\tau_{eff} = 21.2$ ns

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**Excitation scan**
- $\delta \lambda$

**Fluorescence pulse**
- $\tau_{eff} = 13.8$ ns

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**IHF**
- 6" dia. nozzle
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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