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)
- 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

\[ S_{\text{LIF}}(\lambda) = N_1 \cdot E_p^2 \cdot \tau_{\text{eff}} \cdot g(\lambda; \lambda_0, \Delta \lambda) \cdot \text{[calibration constant]} \]
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**
Experiment configuration requirements – v.3.5

- **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

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

To arc jet test chamber

Arc jet (relative) pulse energy sensor

Variable attenuator

1/2 waveplate

Polarizing partial beam splitter

Collimating telescope

13
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
- Fiber optic bundle
- LIF collection telescope
- Beam director
- Collimating telescope
- Beam from laser lab
- PMT
- Spectral and ND filters
- TALIF detector (N, O, Kr, Xe)
- Kr, Xe calibration flow cell
- Arc jet pulse energy sensor
- System alignment and density calibration only

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IHF LIF configuration

- Beam from laser lab
- Laser entrance window
- Beam focusing telescope
- 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
Arc jet Kr, Xe calibration source

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

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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

Linear density dependence
### 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>
</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
- \( V = 3737 \pm 524 \text{ m/s} \)
- \( T = 1166 \pm 333 \text{ K} \)

**Oxygen**
- Excitation scan
- \( V = 3693 \pm 170 \text{ m/s} \)
- \( T = 1319 \pm 176 \text{ K} \)

**Fluorescence pulse**
- \( \tau_{eff} = 23.7 \text{ ns} \)
- \( \tau_{eff} = 15.2 \text{ ns} \)

**Fluorescence pulse**
- \( \tau_{eff} = 24.9 \text{ ns} \)
- \( \tau_{eff} = 19.6 \text{ ns} \)

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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>
</tr>
</thead>
<tbody>
<tr>
<td>3571</td>
<td>137</td>
<td>165</td>
<td>27.1</td>
</tr>
</tbody>
</table>

**Nitrogen**

- Flow reactor
- Curve Fit
- Arc jet
- Curve Fit

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

**Oxygen**

- Flow reactor
- Curve Fit
- Arc jet
- Curve Fit

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

**Excitation scan**

**Fluorescence pulse**

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

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