Nitric Oxide PLIF Visualization of Simulated Fuel-Air Mixing in a Dual-Mode Scramjet

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*AIAA SciTech 2015, Orlando FL, Jan 5, 2015*
Motivations

- Use Nitric Oxide (NO) Planar Laser Induced Fluorescence (PLIF) technique to evaluate fuel/air mixing in a dual mode scramjet
  - Pre-mix fuel and air to simplify the physics occurring in the combustor

- Simulation of scramjet combustion using a cold mixture:
  - Fuel surrogate (N₂-NO mixture) in place of ethylene (C₂H₄)
    - N₂-NO mixture has similar molecular weight as C₂H₄
    - Combustion back-pressure effect simulated by air-throttle

- Different configurations tested to identify the best premixed case:
  - Variations in Equivalence Ratios (ER) tested
  - Variations in shock train locations tested
Experimental Setup

Facility Flow Path

- Two rows of upstream fuel injectors at 90 degree to the free stream
- Air-throttle mechanism to simulate combustion back-pressure
- Cavity for flame holding
- Vary equivalence ratio (ER) and shock train location
Experimental Setup

Laser and Optical Setup

[Diagram of laser and optical setup]
Experimental Method

Choosing the Laser Frequency

Laser frequency was chosen to make NO LIF signal \( S_{\text{LIF}} \) proportional only to NO mole fraction \( \chi_{\text{NO}} \) and independent of temperature \( T \) and Pressure \( P \):

\[
S_{\text{LIF}} \sim K \chi_{\text{NO}}
\]

- Excitation of NO rotational transitions \( ^{P}P_{11}(27) \), \( ^{Q}Q_{22}(24) \) and \( ^{S}R_{21}(8) \)
- Line selected base on previous work* with extended range based on estimated test conditions \( T = 667-1100 \) K, \( p = 80-160 \) kPa

Experimental Method

Sensitivity to Pressure

- LIF signal proportional to mole fraction
- LIF signal pressure-independent in measurement region (blue box)
- Laser profile always overlaps the selected NO transitions
Sensitivity to Laser Detuning

- LIF signal is proportional to mole fraction
- LIF signal not sensitive to small detuning in measurement region (blue box)
Experimental Method

Dotcard

- Raw images (not cropped, not processed, not stretched, not rotated)
- X magnification: 7.75 pixel/mm, Y magnification: 12.5 pixel/mm
- Laser sheet passes right to left, skimming across the dotcard.
Experimental Method

Dewarping

Original Dotcard

“Cleaned” Dotcard

Target Image

Dewarped Dotcard
Experimental Method

Laser Intensity Correction

Laser Sheet with mask

Dewarped Dotcard with mask

Plot profiles overlapped

Dotcard and laser sheet overlapped
Experimental Method

Image Processing

Dewarped and Laser Intensity Corrected Image

180° Rotated Image and False Colors Added

Average Image
## Results

### Cases Tested

<table>
<thead>
<tr>
<th>Date</th>
<th>Run</th>
<th>NO conc.</th>
<th>E.R.</th>
<th>Injector split cav/obs</th>
<th>Shock train [x/H]</th>
<th>Mixing Goodness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jun 13th</td>
<td>3</td>
<td>10%</td>
<td>0.42</td>
<td>0.23/0.15</td>
<td>-45</td>
<td>81%</td>
</tr>
<tr>
<td>Jun 13th</td>
<td>3b</td>
<td>10%</td>
<td>0.42</td>
<td>0.23/0.15</td>
<td>-45</td>
<td>75%</td>
</tr>
<tr>
<td>Jun 13th</td>
<td>4</td>
<td>10%</td>
<td>0.31</td>
<td>0.31/0.00</td>
<td>-15</td>
<td>30%</td>
</tr>
<tr>
<td>Jun 13th</td>
<td>5</td>
<td>10%</td>
<td>0.31</td>
<td>0.155/0.155</td>
<td>-15</td>
<td>80%</td>
</tr>
<tr>
<td>Jun 13th</td>
<td>7</td>
<td>10%</td>
<td>0.31</td>
<td>0.155/0.156</td>
<td>off</td>
<td>69%</td>
</tr>
<tr>
<td>Aug 29th</td>
<td>4</td>
<td>10%</td>
<td>0.44</td>
<td>0.22/0.22</td>
<td>-45</td>
<td>86%</td>
</tr>
<tr>
<td>Aug 29th</td>
<td>5</td>
<td>10%</td>
<td>0.36</td>
<td>0.19/0.17</td>
<td>-45</td>
<td>87%</td>
</tr>
<tr>
<td>Aug 29th</td>
<td>6</td>
<td>10%</td>
<td>0.35</td>
<td>0.18/0.17</td>
<td>-30</td>
<td>88%</td>
</tr>
<tr>
<td>Aug 29th</td>
<td>7</td>
<td>5%</td>
<td>0.44</td>
<td>0.22/0.22</td>
<td>-45</td>
<td>90%</td>
</tr>
<tr>
<td>Aug 29th</td>
<td>8a</td>
<td>10%</td>
<td>0.22</td>
<td>0.22/0.00</td>
<td>-45</td>
<td>81%</td>
</tr>
<tr>
<td>Aug 29th</td>
<td>8c</td>
<td>10%</td>
<td>0.22</td>
<td>0.22/0.00</td>
<td>off</td>
<td>24%</td>
</tr>
</tbody>
</table>

- Cases in green are presented herein
- Define “Mixing goodness”:

\[
Mixing \ goodness = \left(1 - \frac{Standard \ Deviation}{Mean}\right) \times 100
\]

- Higher mixing goodness → more uniform image

Results

Run 4 June 13\textsuperscript{th}

Selected single shots

Average

Cavity Side

Observer Side

ER = 0.31

- ER = 0.31
- Shock Train \(x/H = -15\)
- Mixing goodness = 30%
Results

Run 7 June 13\textsuperscript{th}

Selected single shots

Cavity Side

\begin{itemize}
  \item ER = 0.18
  \item ER = 0.17
\end{itemize}

Observer Side

\begin{itemize}
  \item ER = 0.35
  \item Shock Train off
  \item Mixing goodness = 69%
\end{itemize}
Results

Run 6 August 29th

Selected single shots

Average

Cavity Side

ER = 0.17
ER = 0.18

Observer Side

Results

• ER = 0.35
• Shock Train x/H = -30
• Mixing goodness = 88%

Results

Run 7 August 29th

Selected single shots

Average

Cavity Side

ER = 0.21
ER = 0.21

Observer Side

• ER = 0.42
• Shock Train x/H = -45
• Mixing goodness = 90%
Results

Laser Beam Attenuation from Absorption by NO

- Observed left-to-right attenuation of PLIF signal in images: is it fuel distribution or an artifact of the experiment?
  - Run 4 (August 29th):
    - Fuel: 10% NO – 90% N₂
    - Mixing goodness 86%
  - Run 7 (August 29th):
    - Fuel: 5% NO – 95% N₂
    - Mixing goodness 90%

- Vertical uniformity is comparable (±5%)
- Horizontal uniformity is different for different amounts of NO:
  - More NO injected → more laser absorbed → less signal on right
Conclusions

- NO PLIF system successfully integrated into existing laser cart:
  - NO PLIF, OH PLIF and WIDEARS on the same mobile system

- Excitation of NO rotational transitions $^3P_{11}(27)$, $^3Q_{22}(24)$ and $^3S_{21}(8)$ provided:
  - LIF signal proportional to NO mole fraction
  - LIF signal pressure and temperature independent
  - LIF signal insensitive to laser detuning

- Theoretical calculations extended to test conditions:
  - Temperature range 667 – 1100 K
  - Pressure range 80 – 160 kPa

- NO PLIF images successfully acquired in scramjet combustor:
  - Mixing goodness parameter introduced to compare mixing uniformity
  - Runs 6 and 7 (Aug 29th) identified as best cases
  - Best cases used for subsequent tests using ethylene fuel
Thank you for your attention

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QUESTIONS?