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

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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 (N$_2$-NO mixture) in place of ethylene (C$_2$H$_4$)
    • N$_2$-NO mixture has similar molecular weight as C$_2$H$_4$
    • 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

- Coolsnap Camera (Sheet Profile Imaging)
- Scramjet Duct
- UV Grade Fused Silica Window
- Beam Block
- PIMAX2 Camera (NO Imaging)
- 226 nm Laser Beam
- 5 cm FL Cylindrical Lens
- Iris
- 30 cm FL Spherical Lens
- Beam Splitter
- Silvered Mirror
- 226 nm Blocking Filter
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 based 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
Experimental Method

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.

PI Max (PLIF Camera) Image

Photographic Camera Image
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
### 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”:

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

- Higher mixing goodness ➔ more uniform image
Run 4 June 13th

Selected single shots

Average

Cavity Side

Observer Side

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

Run 7 June 13th

Selected single shots

Average

Cavity Side

\[ ER = 0.18 \]
\[ ER = 0.17 \]

Observer Side

• ER = 0.35
• Shock Train off
• Mixing goodness = 69%

Results

Run 6 August 29\textsuperscript{th}

- 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%
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 WIDECARS on the same mobile system

• Excitation of NO rotational transitions $^3P_{11}(27)$, $^3Q_{22}(24)$ and $^3S_{R21}(8)$ 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 ?