Combustion and Emissions Study using a 7-point Lean Direct Injector Array
Focus on Flame Stability

Yolanda R. Hicks, Tyler G. Capil, Kathleen M. Tacina,
Robert C. Anderson

Canberra, Australia 22 – 28 September 2019
Objectives

- Parametric study to help guide injector design for Low-NOx emissions for aircraft gas turbine engines.
- Study fuel-air mixing and combustion using Lean Direct Injection (LDI) as platform. LDI strategy is to inject and mix the fuel and air quickly for uniform distribution to avoid near-stoichiometric burning that would lead to high NOx concentrations.
- One goal for the 7-point LDI experiments is to determine the effect of air swirl angle on recirculation, fuel-air mixing, combustion emissions and flame tube combustor operability.
Specific Objectives-Flame Stability

With respect to flame tube combustor operability for a given swirler configuration, key considerations are:

• Sustaining the flame generally, at moderate T3:
  • minimizing overall equivalence ratio
  • Highest sustainable cold flow reference velocity (air flow rate) through the combustor

• Lean blow out characteristics (typically near idle): an important figure of merit for alternative fuels and combustor design
Presentation Outline

- Describe facility hardware—fuel injector and data acquisition
- Describe flow attributes through single swirler—cold flow PIV
- Compare most viable configurations
  - Non-combusting (cold flow) PIV results
  - Present standard matrix combusting results with respect to stability
- Present LBO tests and results
- Summary
Facility Setup

• Circular cross-section
• Diameter of 7.62-cm (3-in)
• Flow is downward. Dome at z = 0
• Combustor section has 3 windows, each 5.8-cm × 6.1-cm (2.3-in × 2.4-in)

7-point Lean Direct Injection Hardware

• Axial Swirler, 6 helical vanes
• simplex atomizer
• converging-diverging venturi

Swirlers: 45°, 52°, 60°
Swirl #s: 0.59, 0.77, 1.02
Optical Diagnostics Layout

Flame Chemiluminescence Imaging and Particle Image Velocimetry

ICCD: 33-Hz, 270 x 341 spx
Filters:
- 315-nm OH* 100-µs
- 430-nm CH* 100-µs
- 515-nm C2* 100-µs
- Open 1-µs

HSIC: 8-kHz, 896 x 848 pixels
Filters and exposure times:
- OH* 315-nm, 1 – 12 µs
- CH* 430-nm, 1 - 12 µs

HSC: 40-kHz, typical, 320 x 368 px
exposure, 1/frame rate or faster
Filters and max exposure times:
- 430-nm CH* 25-µs
- 515-nm C2* 25-µs
- Open 25-µs

PIV: 15-Hz, Interline CCD
1200 x 1600 px
Δt ~ 10µs, typical

* Filters:
FWHM ~ 10-nm
Reviewing Single Point LDI Cold Flow Results for Swirl Angle On Central Recirculation Zone (CRZ) Development

Top: oil-seeded air—50 ft/s, 45 psia, 300°F—\((V_z \leq 0 \text{ colored } \downarrow\text{ for } 52° \& 45°)\)
Bottom: water seeding through fuel nozzle—50 ft/s, 75 psia, 800°F

60°: wide angle ~90°, large CRZ, lowest downstream velocity
52°: small angle ~35°, no CRZ, high downstream velocity
45°: smallest angle ~20°, no CRZ, highest downstream velocity
Down-selecting 7-pt LDI configurations

Previous 7-pt LDI tests included—all 60°, all 52°, 60° center w/45° or 52°outers
-- Given the wide 60° air flow patterns, expected interactions between adjacent swirlers
• 45° swirlers: highest downstream velocities, less swirler-swirler interaction, isolates center 60° swirler, least stable flames
• 52° swirlers: helps isolate center 60° swirler; with all 52° swirlers, fairly stable, flame farther downstream than with all 60° swirlers
• 60° swirler: most stable flames

Final configurations tested considered the effects of co- and counter-swirl and center swirler offset on recirculation zone strength (cold flow) and flame stability, compared to the baseline configuration: all co-swirling 60° without center swirler offset

<table>
<thead>
<tr>
<th>Designation</th>
<th>Center Swirler</th>
<th>Outer Swirlers</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH60all</td>
<td>RH 60°</td>
<td>RH 60°</td>
</tr>
<tr>
<td>LH60all</td>
<td>LH 60°</td>
<td>LH 60°</td>
</tr>
<tr>
<td>RH60c_RH52o</td>
<td>RH 60°</td>
<td>RH 52°</td>
</tr>
<tr>
<td>LH60c_RH52o</td>
<td>LH 60°</td>
<td>RH 52°</td>
</tr>
<tr>
<td>RH60coff_RH52o</td>
<td>RH 60°</td>
<td>RH 52°</td>
</tr>
<tr>
<td>LH60coff_RH52o</td>
<td>LH60°</td>
<td>RH 52°</td>
</tr>
</tbody>
</table>
7-point cold flow results
Comparing Central Recirculation Zones using PIV

Top row: Axial velocity contours at z ~ 10 mm; Bottom row: iso-velocity contours of Vz = 0

• Results confirm CRZ downstream of 60° swirler only
• Swirler spacing leads to interaction that reduces the center CRZ for the RH60all configuration
• If flame stability is related to CRZ volume size and strength, then RH60all configuration has 7 CRZs and should produce the most stable flame.
PIV result: 7-point Swirler CRZ Volumes and average Axial Velocities

Regarding Center Swirler CRZ:
- co-swirl produces stronger CRZ than counter-swirl
- Offsetting center swirler helps isolate it, providing for larger CRZ volume and greater upstream velocity. Vz magnitude is highest of the four configurations
- Center CRZ of baseline configuration has smallest volume

Regarding baseline RH60all:
- Despite having the smallest center swirler CRZ, the outer swirlers have large CRZs.
- Swirler #6 CRZ was fully contained within the field-of-view, and produced the largest volume and greatest upstream velocity shown on the graph

Predicting stability based on CRZ “strength”
RH60all most stable, LH60cRH52o least stable
# Combusting Tests

Test matrices to elucidate differences based on:

- **equivalence ratio**
  - $u_{ref} = 35$-ft/s

We limited the upper equivalence ratio in order to maintain integrity of the uncooled windows.

<table>
<thead>
<tr>
<th>$\phi$ overall</th>
<th>Fuel Flow/nozzle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lbm/h</td>
</tr>
<tr>
<td>0.400</td>
<td>3.73</td>
</tr>
<tr>
<td>0.430</td>
<td>4.17</td>
</tr>
<tr>
<td>0.450</td>
<td>4.37</td>
</tr>
<tr>
<td>0.480</td>
<td>4.65</td>
</tr>
<tr>
<td>0.500</td>
<td>4.85</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$U_{ref}$</th>
<th>Air flow</th>
<th>Fuel flow/nozzle</th>
</tr>
</thead>
<tbody>
<tr>
<td>ft/s</td>
<td>m/s</td>
<td>lbm/s</td>
</tr>
<tr>
<td>30</td>
<td>9.1</td>
<td>0.237</td>
</tr>
<tr>
<td>35</td>
<td>10.7</td>
<td>0.276</td>
</tr>
<tr>
<td>40</td>
<td>12.2</td>
<td>0.316</td>
</tr>
<tr>
<td>45</td>
<td>13.7</td>
<td>0.355</td>
</tr>
<tr>
<td>50</td>
<td>15.2</td>
<td>0.394</td>
</tr>
<tr>
<td>55</td>
<td>16.8</td>
<td>0.434</td>
</tr>
<tr>
<td>60</td>
<td>18.3</td>
<td>0.473</td>
</tr>
</tbody>
</table>
Results—Comparing Flame Zone Structure and Stability via OH* chemiluminescence

<table>
<thead>
<tr>
<th>U_{ref} = 35 \text{ ft/s}</th>
<th>LH60all</th>
<th>RH60c_RH52o</th>
<th>LH60c_RH52o</th>
<th>LH60_coff_RH52o</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \phi ]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.43</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.48</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Flow: Top to Bottom

- Supports Lowest $\phi$
- Closest to dome
- Shortest flame
- Very symmetric

- Very symmetric
- Longest flame zone
- Least symmetric
- Sits slightly away from dome
- Fairly symmetric

Images from High speed Intensified camera (HSIC), 8-kHz
Stability comparison based on reference velocity

- Flame zone thickens as $u_{\text{ref}}$ increases

From most to least stable:
1) baseline, co-swirling 60°
2) counter-swirl, center offset
3) co-swirl
4) counter-swirl

- This trend is similar to the CRZ “strength” seen in the cold-flow studies
- Co-swirl, center offset might be comparable to baseline configuration with respect to sustaining high reference velocity

• less symmetric as $u_{\text{ref}}$ increases
\textbf{Comparing CH* to OH*}

- CH* pattern is similar to OH*, especially at $u_{\text{ref}} \geq 40$ ft/s.
- For 30 and 35 ft/s, CH* shows that fuel is farther downstream for all but the baseline configuration, indicating that mixing and combustion are both less effective and less efficient under these conditions.
Another perspective: CH* and C₂* chemiluminescence as seen by the HSC
Configuration LH60coff_RH52o

\[ \phi = 0.45, 40 \text{ kHz}, \text{ all images self-scaled} \]

• RMS gives variation from mean, shows downstream extent of signal
• Similar to HSI camera, as \( u_{\text{ref}} \) increases, the flame becomes shorter

**Comparing CH* to C₂***
• Center integrates signal from three swirlers. Dominant C₂* signal from center swirler, with less from outer swirlers (compare CH* and C₂* at 50ft/s)

• CH* appears more evenly distributed between swirlers

• The differences between CH* and C₂* will provide opportunity for further exploration of chemistry and kinetics within this system
Lean Blowout Testing
### Fuels used for LBO testing

<table>
<thead>
<tr>
<th>Fuel</th>
<th>A-2</th>
<th>C-1</th>
<th>C-4</th>
<th>n-dodecane</th>
</tr>
</thead>
<tbody>
<tr>
<td>POSF No.</td>
<td>10325</td>
<td>13572</td>
<td>12489</td>
<td>13226</td>
</tr>
<tr>
<td>Composition</td>
<td>Jet A</td>
<td>GEVO ATJ, highly branched C&lt;sub&gt;12&lt;/sub&gt; and C&lt;sub&gt;16&lt;/sub&gt; iso-paraffins</td>
<td>60% Sasol IPK (highly branched C&lt;sub&gt;9&lt;/sub&gt;-C&lt;sub&gt;13&lt;/sub&gt; iso-paraffins), 40% C-1</td>
<td>Straight chain C&lt;sub&gt;12&lt;/sub&gt; paraffin</td>
</tr>
<tr>
<td>Description</td>
<td>Average/Nominal jet fuel</td>
<td>Very low cetane number with unusual boiling range</td>
<td>Low cetane number with conventional, wide-boiling range</td>
<td>High cetane number</td>
</tr>
<tr>
<td>DCN</td>
<td>49</td>
<td>16</td>
<td>28</td>
<td>73.5</td>
</tr>
<tr>
<td>Heat of combustion</td>
<td>43.1</td>
<td>43.9</td>
<td>43.8</td>
<td>44.5</td>
</tr>
<tr>
<td>(MJ/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal formula</td>
<td>C&lt;sub&gt;11.4&lt;/sub&gt;H&lt;sub&gt;22.1&lt;/sub&gt;</td>
<td>C&lt;sub&gt;12.6&lt;/sub&gt;H&lt;sub&gt;27.2&lt;/sub&gt;</td>
<td>C&lt;sub&gt;11.4&lt;/sub&gt;H&lt;sub&gt;24.8&lt;/sub&gt;</td>
<td>C&lt;sub&gt;12&lt;/sub&gt;H&lt;sub&gt;26&lt;/sub&gt;</td>
</tr>
<tr>
<td>stoichiometric f/a</td>
<td>0.068026</td>
<td>0.066637</td>
<td>0.066536</td>
<td>0.066589</td>
</tr>
</tbody>
</table>
Near-LBO (NBO, idle) Condition, Pilot (center nozzle) only:

- Air: $P_3 = 70$ psia, $T_3 = 450^\circ F$, $m_{air} = 0.300$ lbm/s
- $\phi_{center} = 1.3$, $\phi_{overall} = 0.19$

**LBO procedure:**

- Lightoff
- Go to NBO condition, hold fuel flow, air pressure, temperature steady, collect data
- Slowly increase air flow rate until LBO achieved
  - LBO detection based on sudden drop in $T_4$ over 2-3 scans, confirmed using additional variables
- 5-7 repeats were typical

---

**Example of LBO detection** (large drop in “T4” thermocouple value).

**View from ICCD camera at NBO**
Run Repeatability

**NBO repeats, C-4 fuel, ICCD camera**

- **OH**, **CH**, **C₂** have similar flame structure across runs, demonstrating repeatability at near-LBO condition.

- LBO Repeats based on $T_4$ thermocouple

Filled box represents the middle portion of data, 1st – 3rd quartiles. Top and bottom whiskers are maximum and minimum values.

- Narrow distribution of the equivalence ratio at LBO for each fuel shows repeatability of achieving LBO.
Results as a function of Derived Cetane Number

Trend of $u_{\text{ref}}$ vs DCN is similar to other results: Monotonic increase of $u_{\text{ref}}$ with DCN

Trend of $\phi$ vs DCN is different: C-4 equivalence ratio at LBO is lower than what others reported

Possible reasons for discrepancy:
- spray quality differences due to differing viscosity, surface tension, or density
- Air flow rate increased to blowout, so look also at laminar burning velocity
We considered the effects of air swirler angle, swirl direction and center swirler offset on the flow field immediately downstream from the dome and on the ensuing combustion.

- **We noted that each swirler configuration resulted in a different flame structure, as observed using OH*, CH*, and C₂* species imaging.**

We determined, by observing the fuel-lean limit and maximum reference velocity, which configurations could best sustain the flame.

- **Based on these criteria, we determined that the baseline configuration, with all co-swirling 60° swirlers, had the widest operating range.**

With regard to lean blowout:

- **we determined that n-dodecane fuel could sustain the leanest flame, followed by C-4 fuel and A-2 fuel. C-1 fuel required the highest equivalence ratio to sustain the flame.**

Further work will include a deeper exploration of the speciation observed for the configurations studied, with a focus on flame chemistry.
Acknowledgment

The NASA Transformational Tools and Technologies Project supported this work.