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

Glenn Research Center

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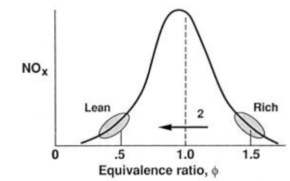
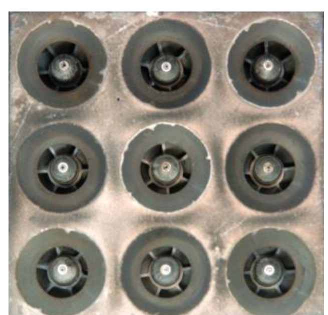
Objectives

- 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

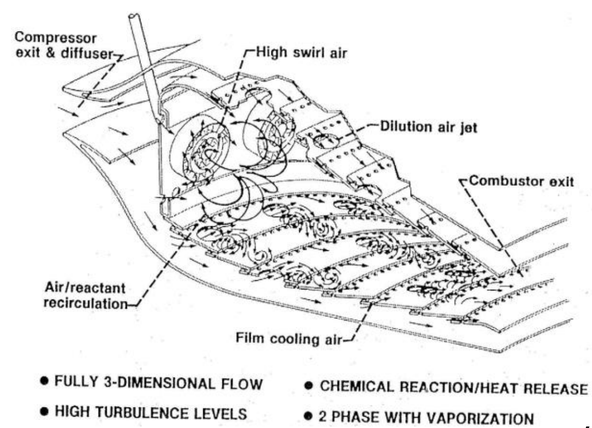


- One goal for the 7-point LDI experiments is to determine the effect of air swirl angle on recirculation, fuel-air mixing, combustion emissions and flame tube combustor operability

7-pt



9-pt



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

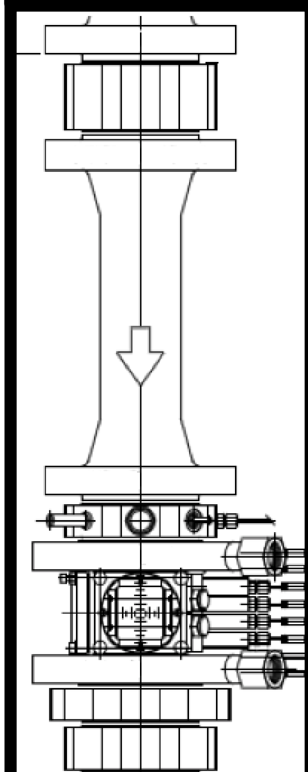
Presentation Outline

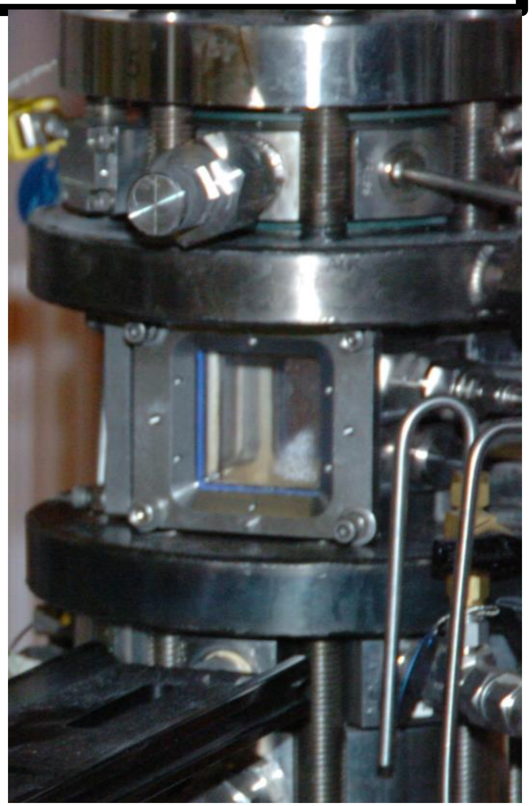
- Describe facility hardware—fuel injector and data acquisition
- Describe flow attributes through single swirler—cold flow PIV
- Compare most viable configurations
  - Non-combusting (cold flow) PIV results
  - Present standard matrix combusting results with respect to stability
- Present LBO tests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

Combustion and Dynamics Facility, LDI Hardware

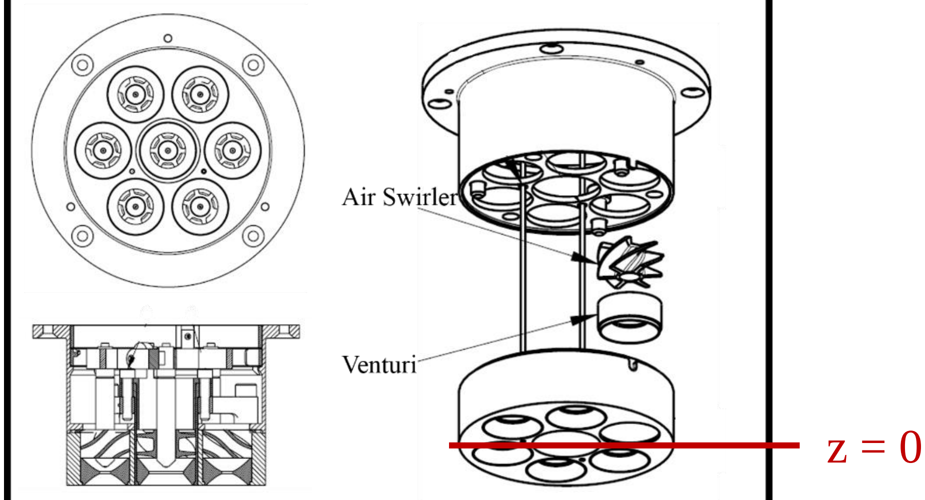
Facility Setup

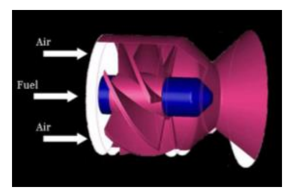
- Circular cross-section
- Diameter of 7.62-cm (3-in)
- Flow is downward. Dome at z = 0
- Combustor section has 3 windows, each 5.8-cm × 6.1-cm (2.3-in × 2.4-in)



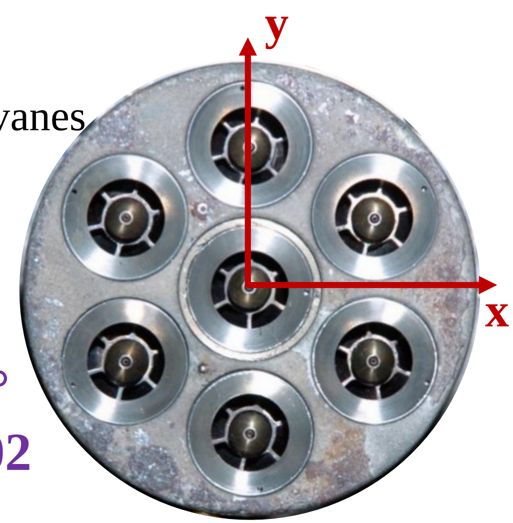


7-point Lean Direct Injection Hardware





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

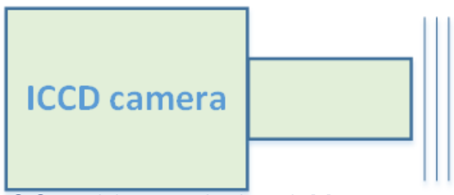


Swirlers: 45°, 52°, 60°

Swirl #s: 0.59, 0.77, 1.02

Optical Diagnostics Layout

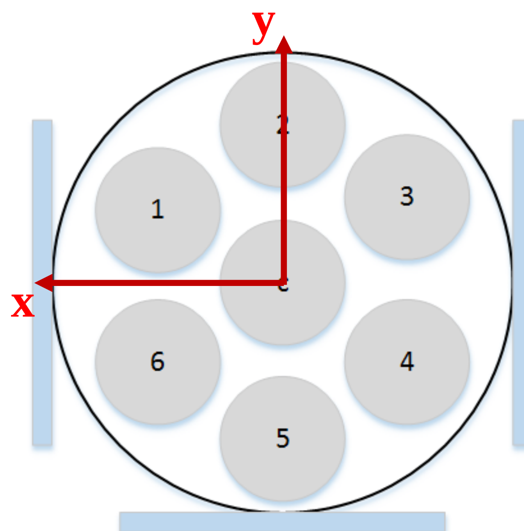
Flame Chemiluminescence Imaging and Particle Image Velocimetry

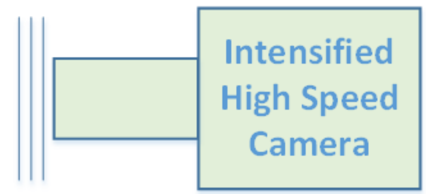


ICCD: 33-Hz, 270 x 341 spx

Filters:

- 315-nm OH* 100-μs
- 430-nm CH* 100-μs
- 515-nm C2* 100-μs
- Open 1-μs



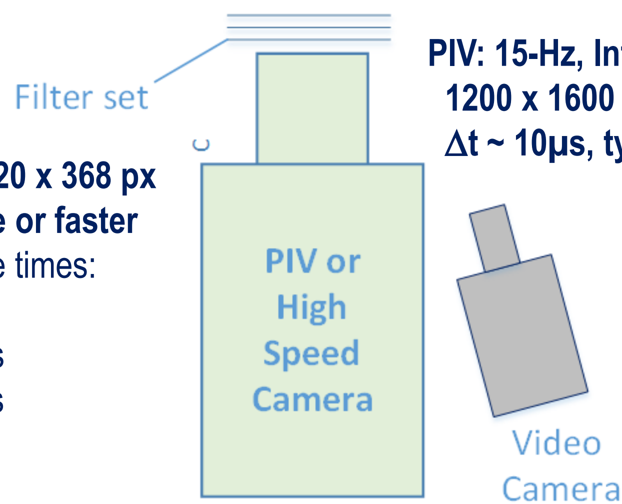


HSIC: 8-kHz, 896 x 848 pixels

Filters and exposure times:

OH* 315-nm, *1 – 12 μs*

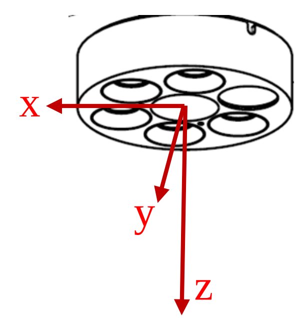
CH* 430-nm, *1 - 12 μs*



PIV: 15-Hz, Interline CCD

1200 x 1600 px

Δt ~ 10μs, typical



HSC: 40-kHz, typical, 320 x 368 px

exposure, 1/frame rate or faster

Filters and max exposure times:

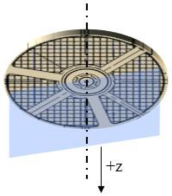
- 430-nm CH* 25-μs
- 515-nm C2* 25-μs
- Open 25-μs

* Filters:

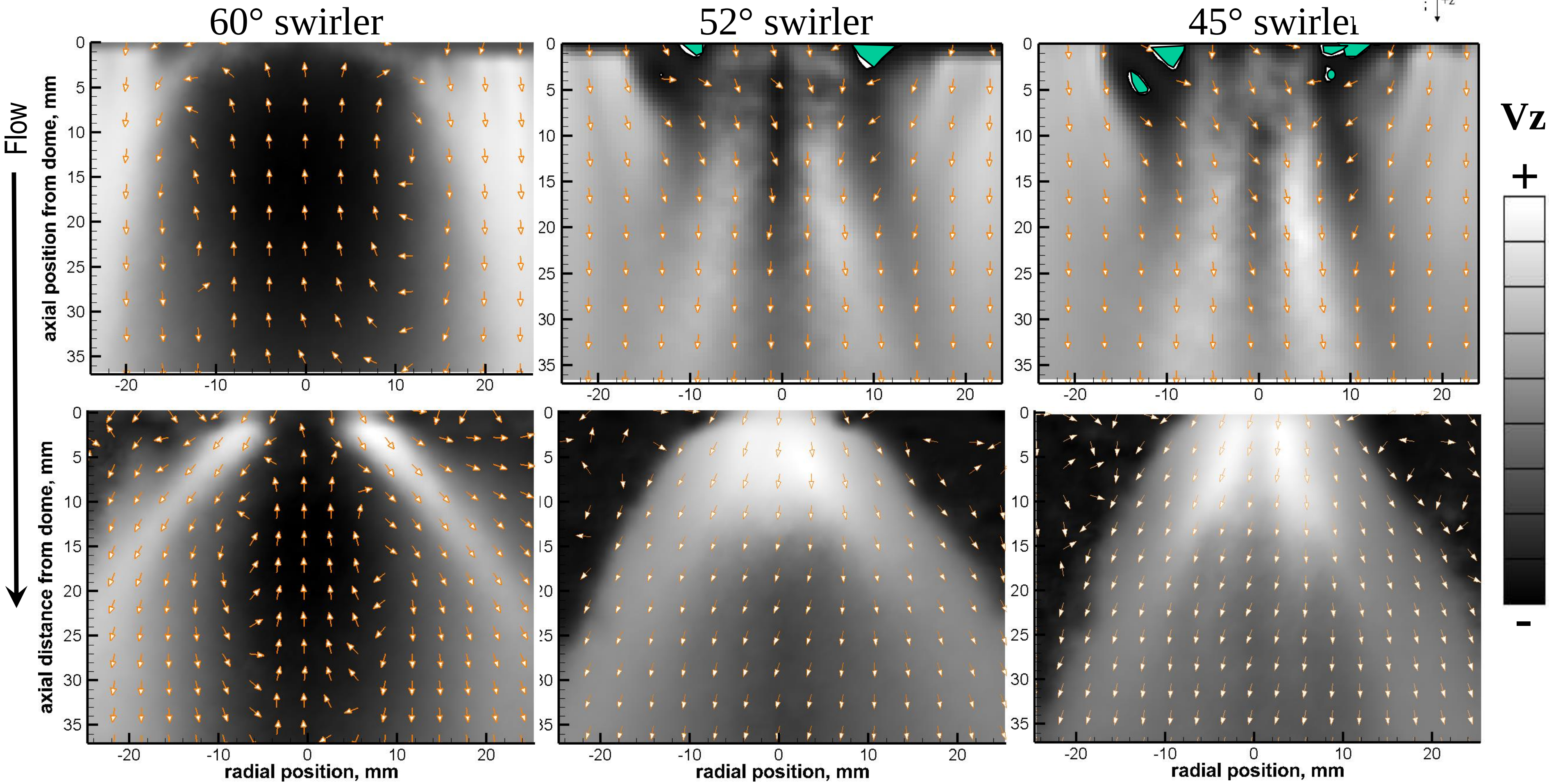
FWHM ~ 10-nm

Reviewing Single Point LDI Cold Flow Results for Swirl Angle

On Central Recirculation Zone (CRZ) Development



Top: oil-seeded air—50ft/s, 45psia, 300°F— (Vz ≤ 0 colored ◆ for 52°&45°)
Bottom: water seeding through fuel nozzle—50 ft/s, 75psia, 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

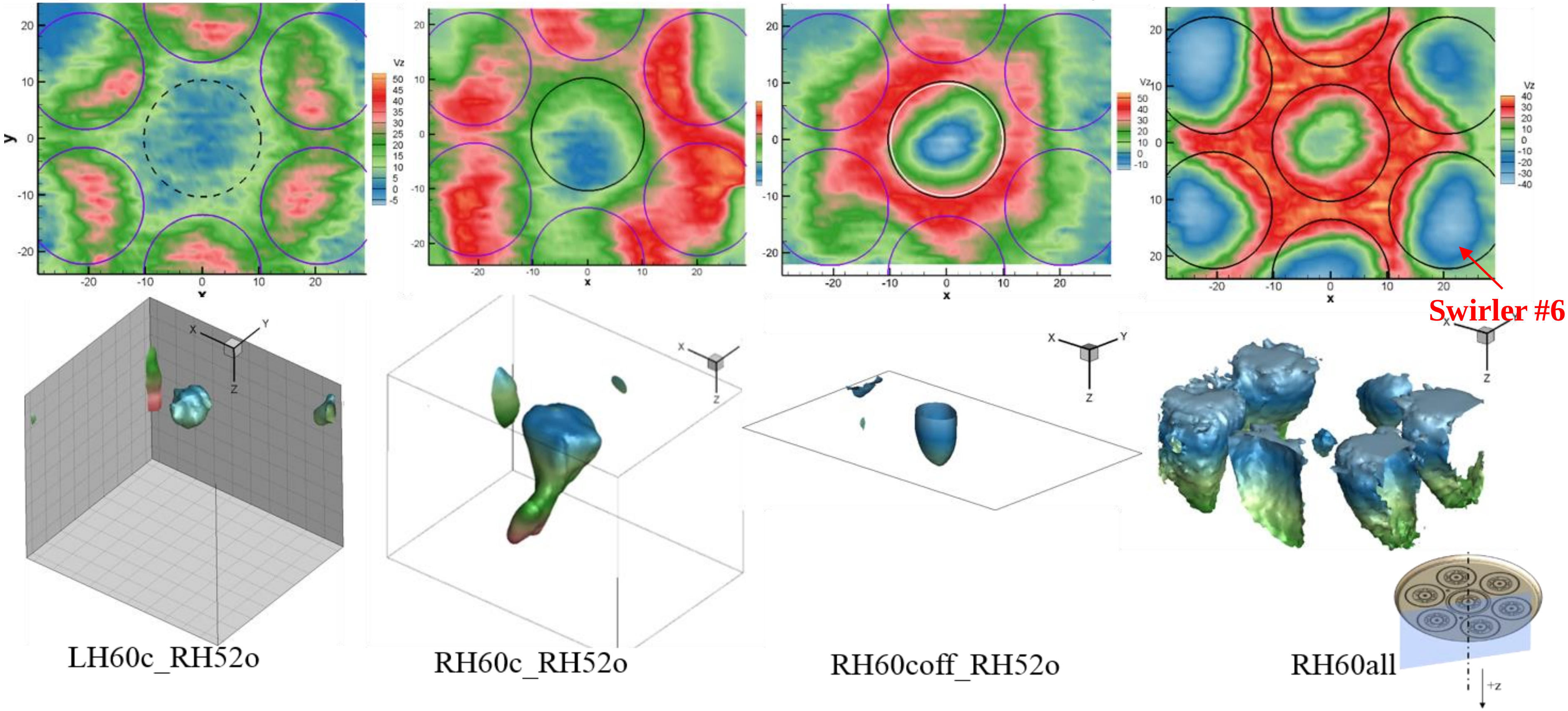
Final configurations tested considered the effects of co- and counter-swirl and center swirler offset on recirculation zone strength (cold flow) and flame stability, compared to the baseline configuration: all co-swirling 60° without center swirler offset

Designation	Center Swirler	Outer Swirlers
RH60all *baseline*	RH 60°	RH 60°
LH60all *baseline*	LH 60°	LH 60°
RH60c_RH52o: "co-swirling"	RH 60°	RH 52°
LH60c_RH52o: "counter-swirling"	LH 60°	RH 52°
RH60coff_RH52o "offset co-swirling"	RH 60°	RH 52°
LH60coff_RH52o "offset counter-swirling"	LH60°	RH 52°

Center Offset w/Outer Swirlers

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.

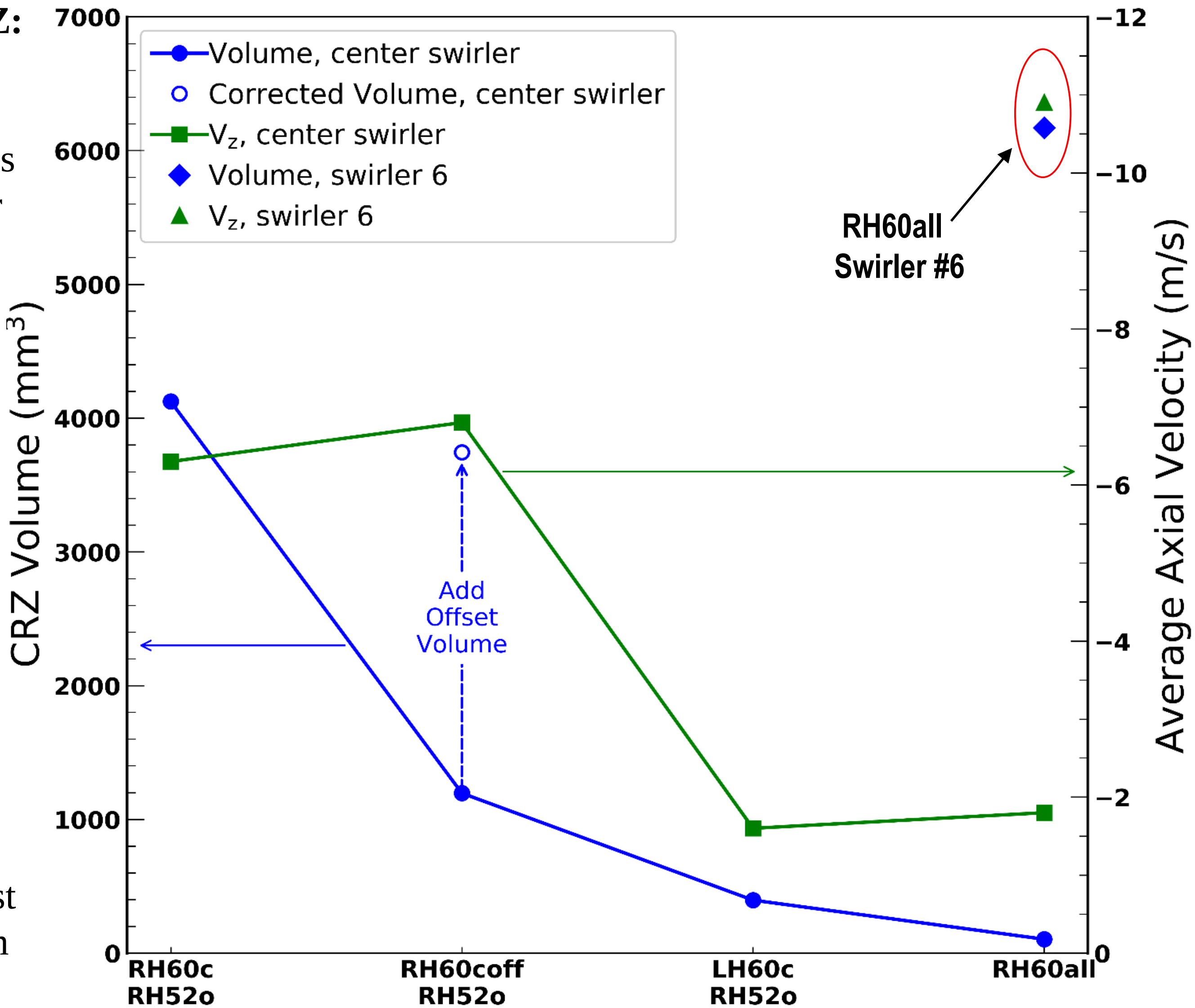
PIV result: 7-point Swirler CRZ Volumes and average Axial Velocities

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*

ϕ overall	Fuel Flow/nozzle lbm/h	Fuel Flow/nozzle kg/h
0.400	3.73	1.69
0.430	4.17	1.89
0.450	4.37	1.98
0.480	4.65	2.11
0.500	4.85	2.20

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

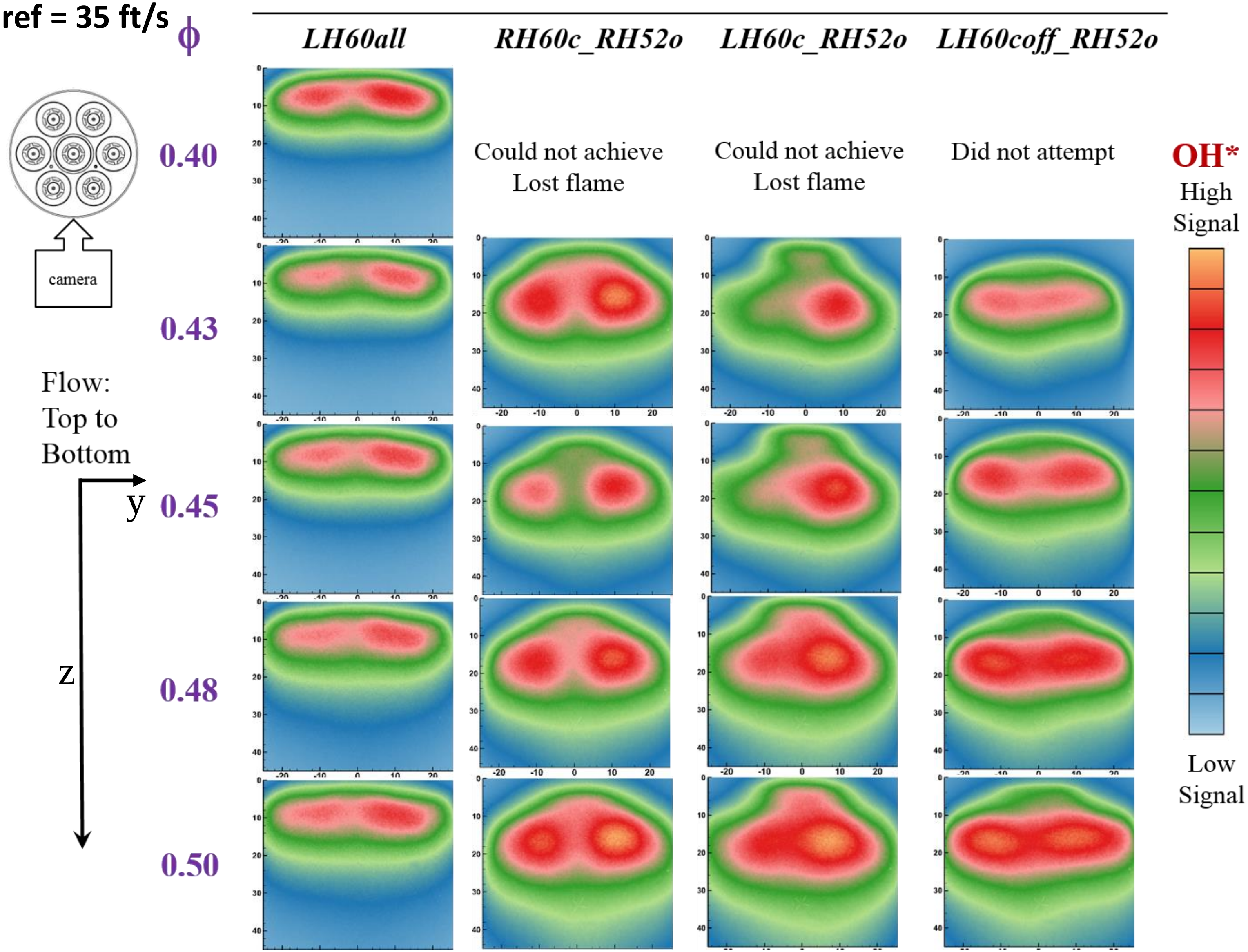
reference velocity

$\phi = 0.45$

U_{ref} ft/s	U_{ref} m/s	Air flow lb_m/s	Air flow kg/s	Fuel flow/nozzle lbm/h	Fuel flow/nozzle kg/h
30	9.1	0.237	0.107	3.73	1.69
35	10.7	0.276	0.125	4.37	1.98
40	12.2	0.316	0.143	4.98	2.26
45	13.7	0.355	0.161	5.60	2.54
50	15.2	0.394	0.179	6.22	2.82
55	16.8	0.434	0.197	6.83	3.10
60	18.3	0.473	0.215	7.36	3.34

Results—Comparing Flame Zone Structure and Stability via OH* chemiluminescence

Uref = 35 ft/s



Images from High speed Intensified camera (HSIC), 8-kHz

LH60all
- Supports Lowest ϕ
- Closest to dome
- Shortest flame
- Very symmetric

RH60c_RH52o
- Very symmetric

LH60c_RH52o
- Longest flame zone
- Least symmetric

LH60coff_RH52o
- Sits slightly away from dome
- Fairly symmetric

Stability comparison based on reference velocity

- Flame zone thickens as u_{ref} increases

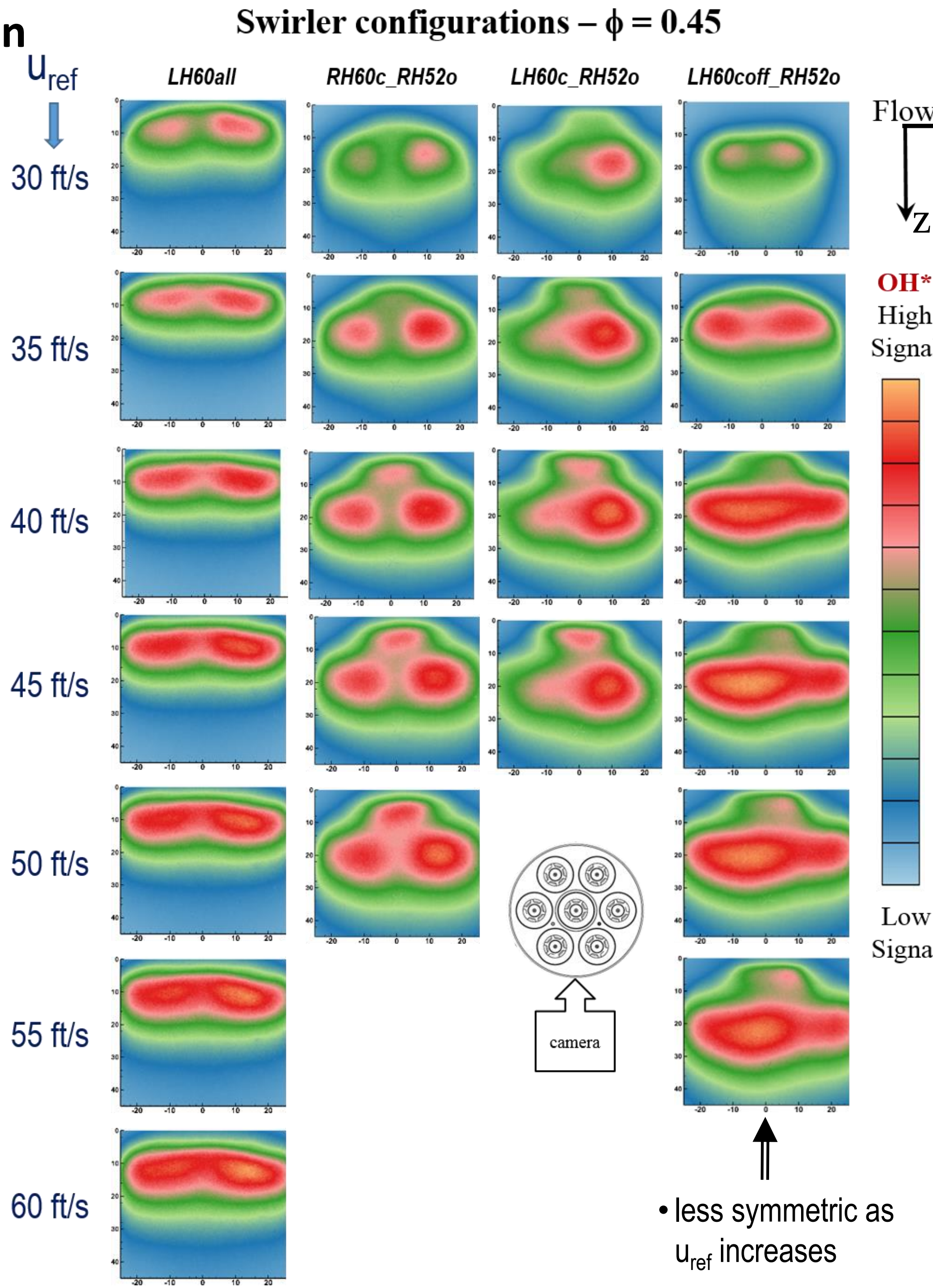
From most to least stable :

1) baseline, co-swirling 60°

60° center, RH52° outer swirlers

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



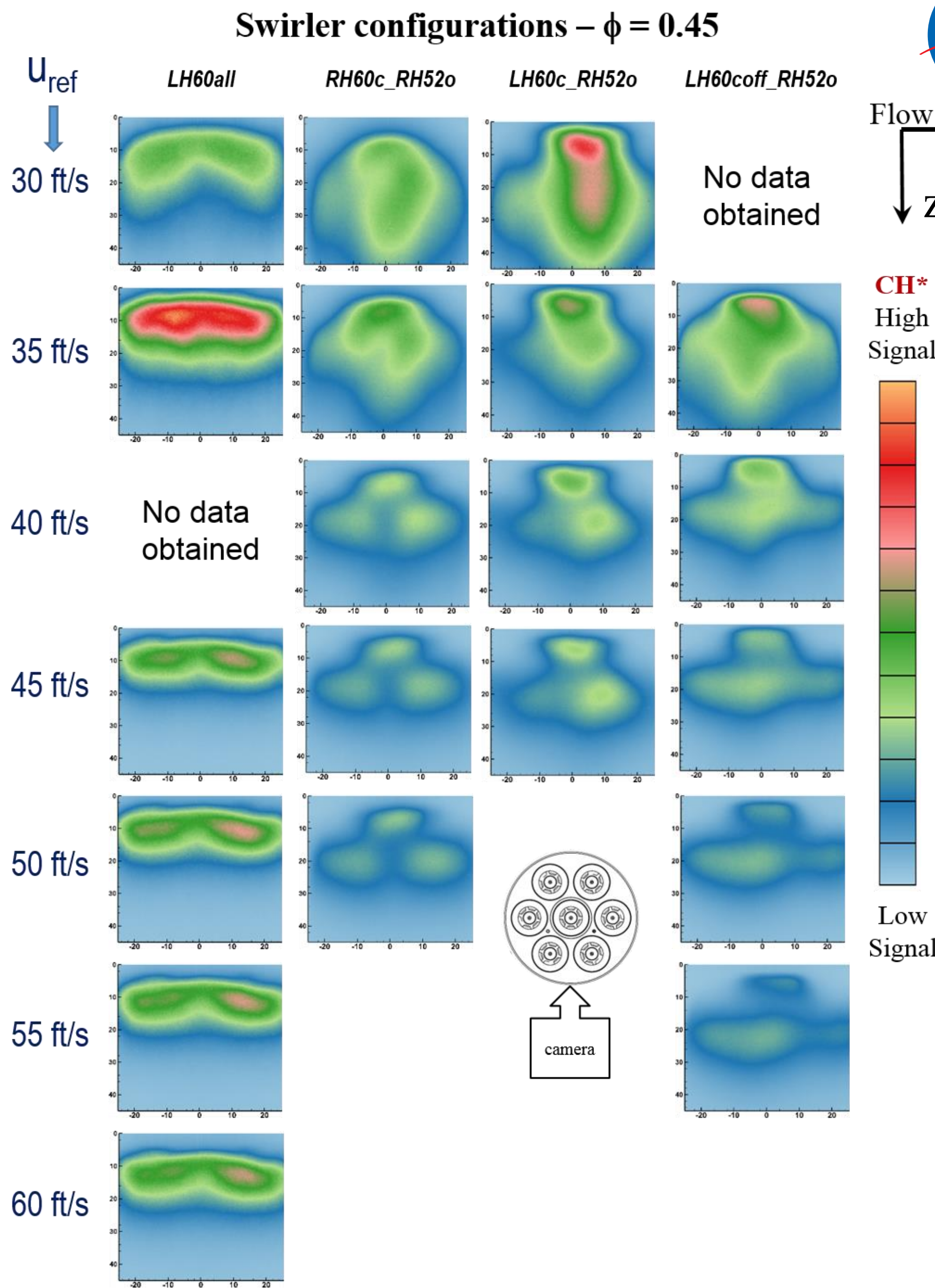
HSIC, 8-kHz

- less symmetric as u_{ref} increases

reference velocity chart, CH* chemiluminescence

Comparing CH to OH**

- CH* pattern is similar to OH*, especially at $u_{ref} \geq 40$ 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.



HSIC, 8-kHz

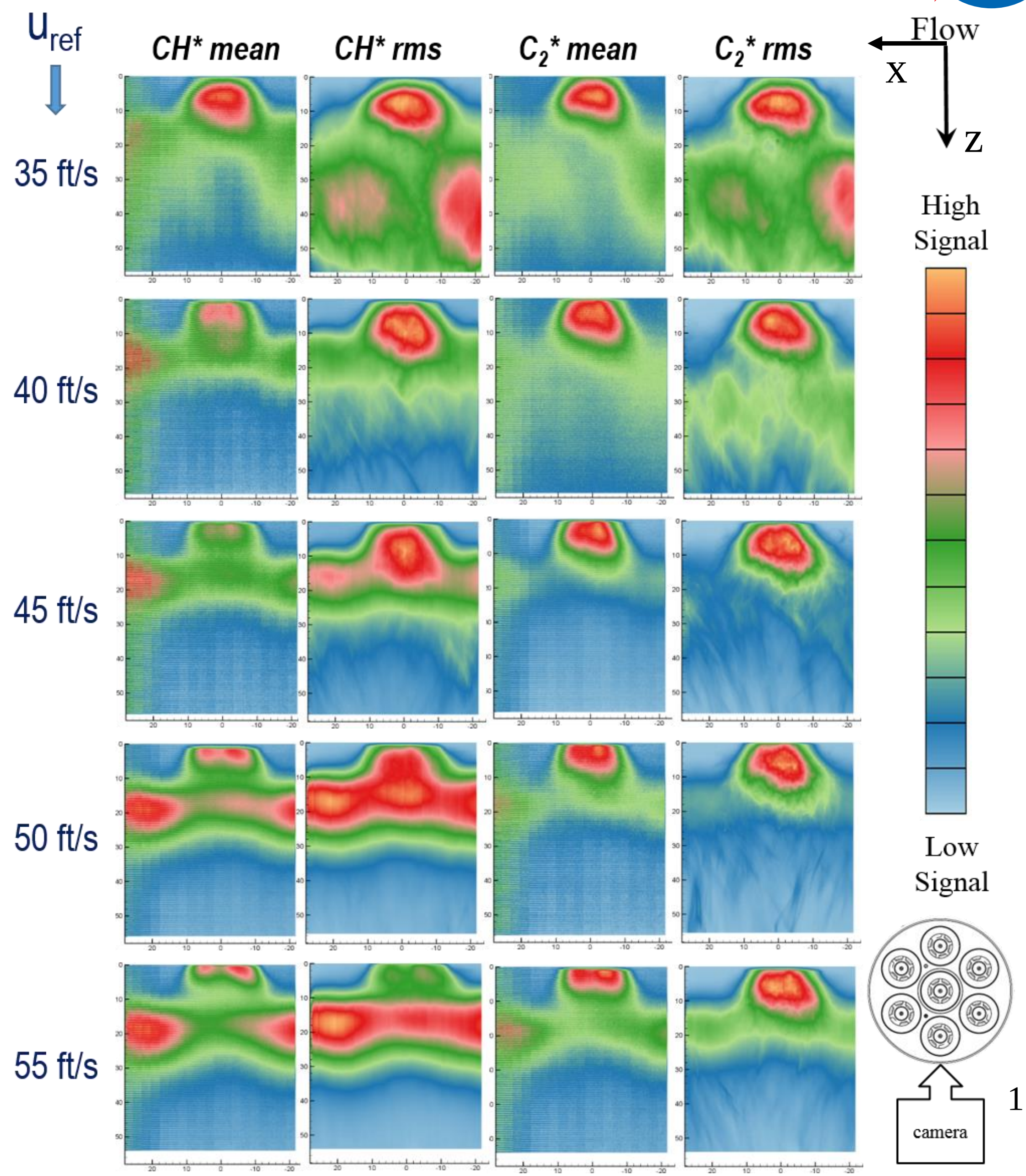
Another perspective: CH^* and C_2^* chemiluminescence as seen by the HSC

Configuration LH60coff_RH52o *ϕ = 0.45, 40 kHz, all images self-scaled*

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

Comparing CH^* to C_2^*

- Center integrates signal from three swirlers. Dominant C_2^* signal from center swirler, with less from outer swirlers (compare CH^* and C_2^* at 50ft/s)
- CH^* appears more evenly distributed between swirlers
- The differences between CH^* and C_2^* will provide opportunity for further exploration of chemistry and kinetics within this system



Lean Blowout Testing

Fuels used for LBO testing

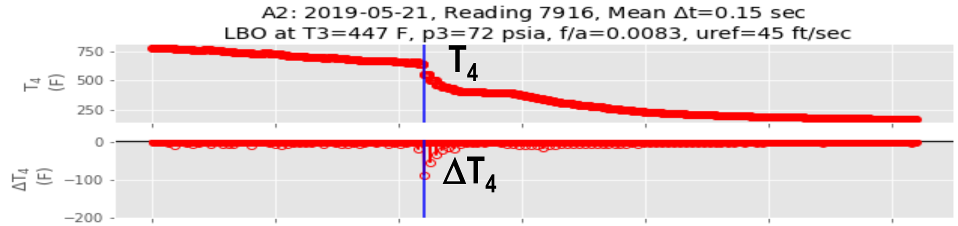
Fuel	A-2	C-1	C-4	n-dodecane
POSF No.	10325	13572	12489	13226
Composition	Jet A	GEVO ATJ, highly branched C_{12} and C_{16} iso-paraffins	60% Sasol IPK (highly branched C_9-C_{13} iso-paraffins), 40% C-1	Straight chain C_{12} paraffin
Description	Average/ Nominal jet fuel	Very low cetane number with unusual boiling range	Low cetane number with conventional, wide-boiling range	High cetane number
DCN	49	16	28	73.5
Heat of combustion (MJ/kg)	43.1	43.9	43.8	44.5
Nominal formula	$C_{11.4}H_{22.1}$	$C_{12.6}H_{27.2}$	$C_{11.4}H_{24.8}$	$C_{12}H_{26}$
stoichiometric f/a	0.068026	0.066637	0.066536	0.066589

Cetane number describes fuel propensity to ignite

LBO Test details

Near-LBO (NBO, idle) Condition, Pilot (center nozzle) only:

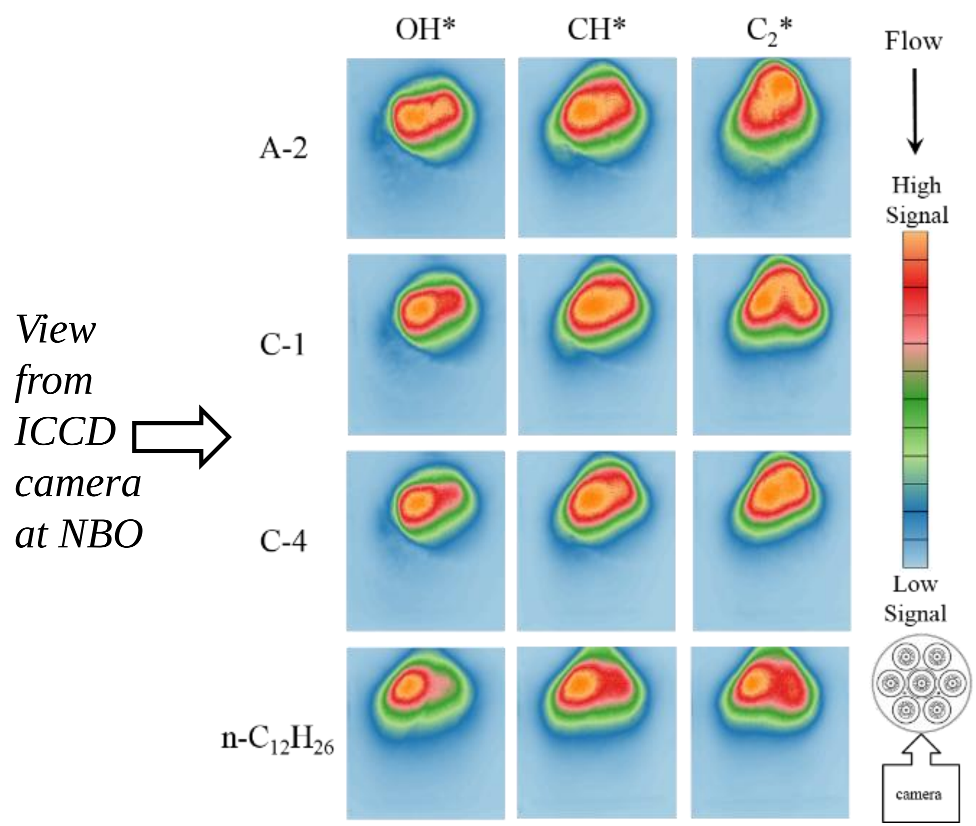
- Air: P_3 = 70 psia, T_3 = 450°F, m_{air} = 0.300 lbm/s
- ϕ_{center} = 1.3, $\phi_{overall}$ = 0.19



Example of LBO detection (large drop in "T4" thermocouple value).

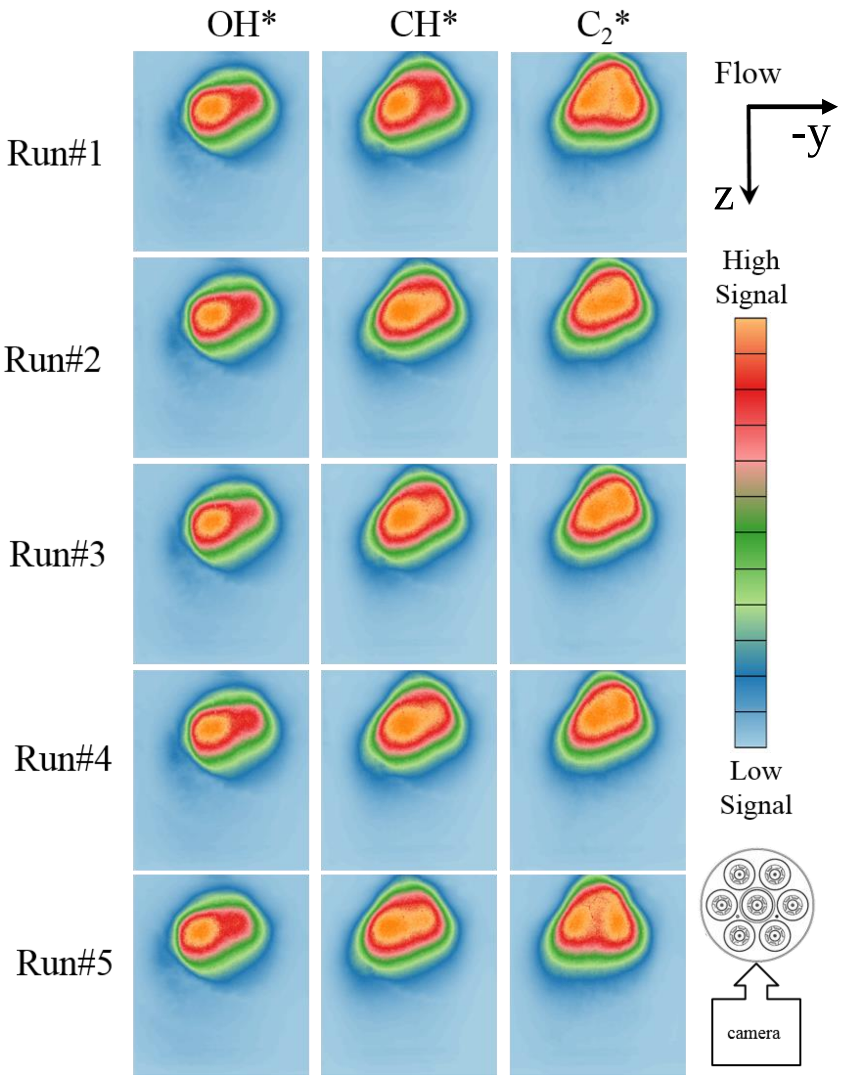
LBO procedure:

- 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



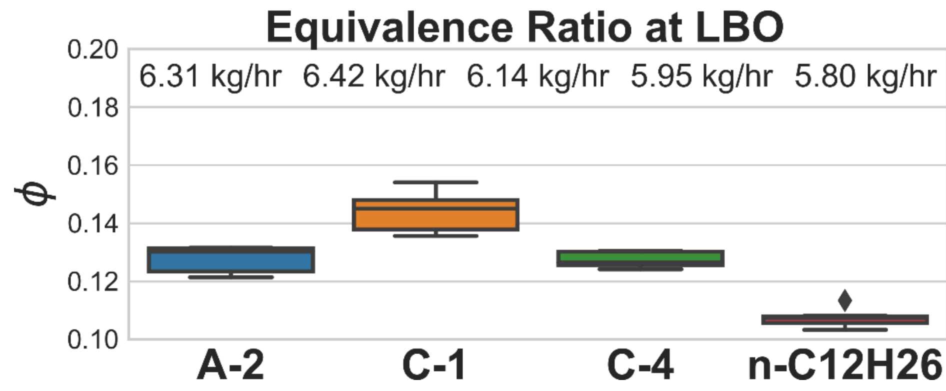
Run Repeatability

NBO repeats, C-4 fuel, ICCD camera



- **OH*, CH*, C_2* have similar flame structure across runs, demonstrating repeatability at near-LBO condition**

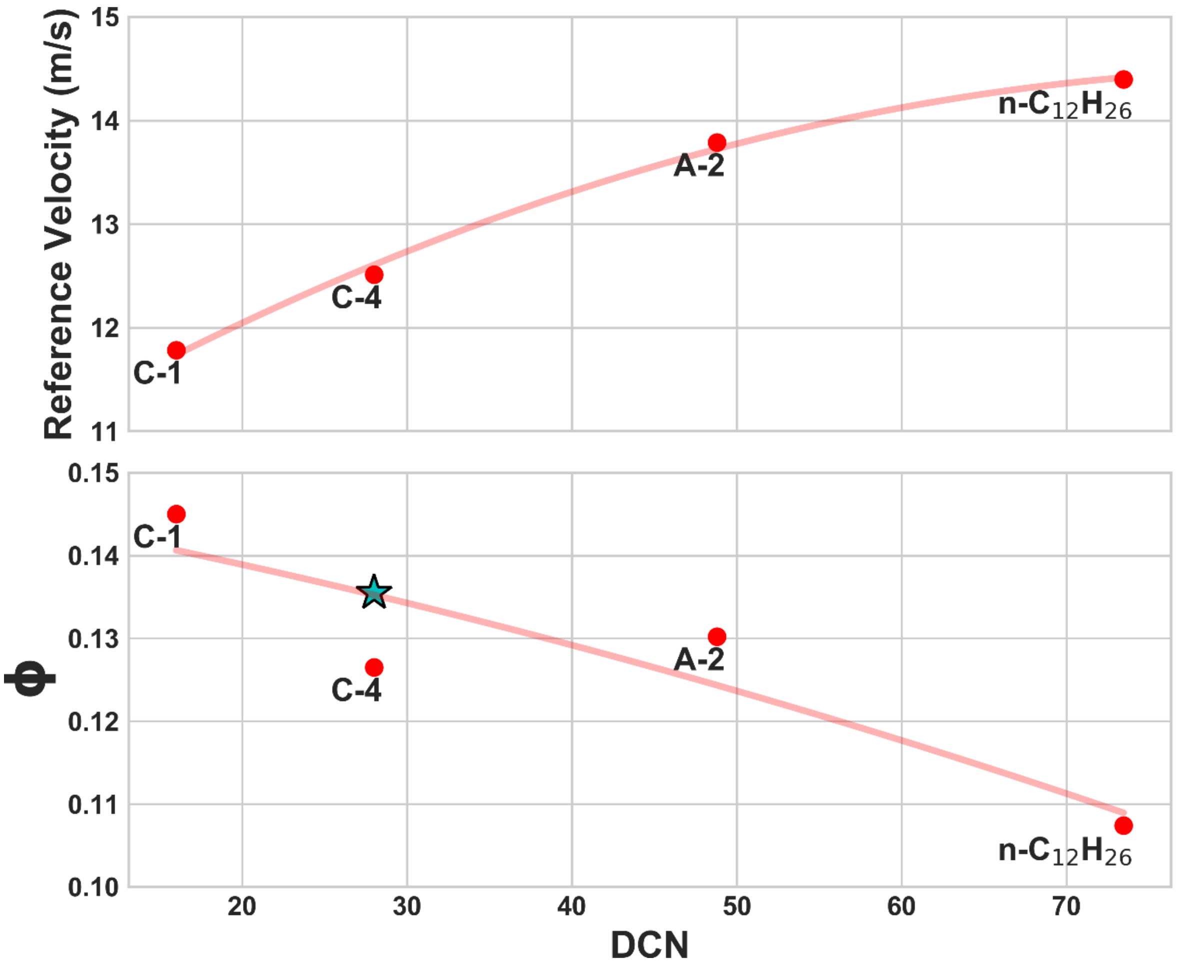
LBO Repeats based on T_4 thermocouple



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_{ref} vs DCN is similar to other results: **Monotonic increase of u_{ref} with DCN**

Trend of ϕ 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

Summary

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 C_2* 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

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