Laser-Based Diagnostic Measurements of Low Emissions Combustor Concepts

This presentation provides a summary of primarily laser-based measurement techniques we use at NASA Glenn Research Center to characterize fuel injection, fuel/air mixing, and combustion. The report highlights using Planar Laser-Induced Fluorescence, Particle Image Velocimetry, and Phase Doppler Interferometry to obtain fuel injector patternation, fuel and air velocities, and fuel drop sizes and turbulence intensities during combustion. We also present a brief comparison between combustors burning standard JP-8 Jet fuel and an alternative fuels. For this comparison, we used flame chemiluminescence and high speed imaging.

National Aeronautics and Space Administration

Laser-Based Diagnostic Measurements of Low Emissions Combustor Concepts

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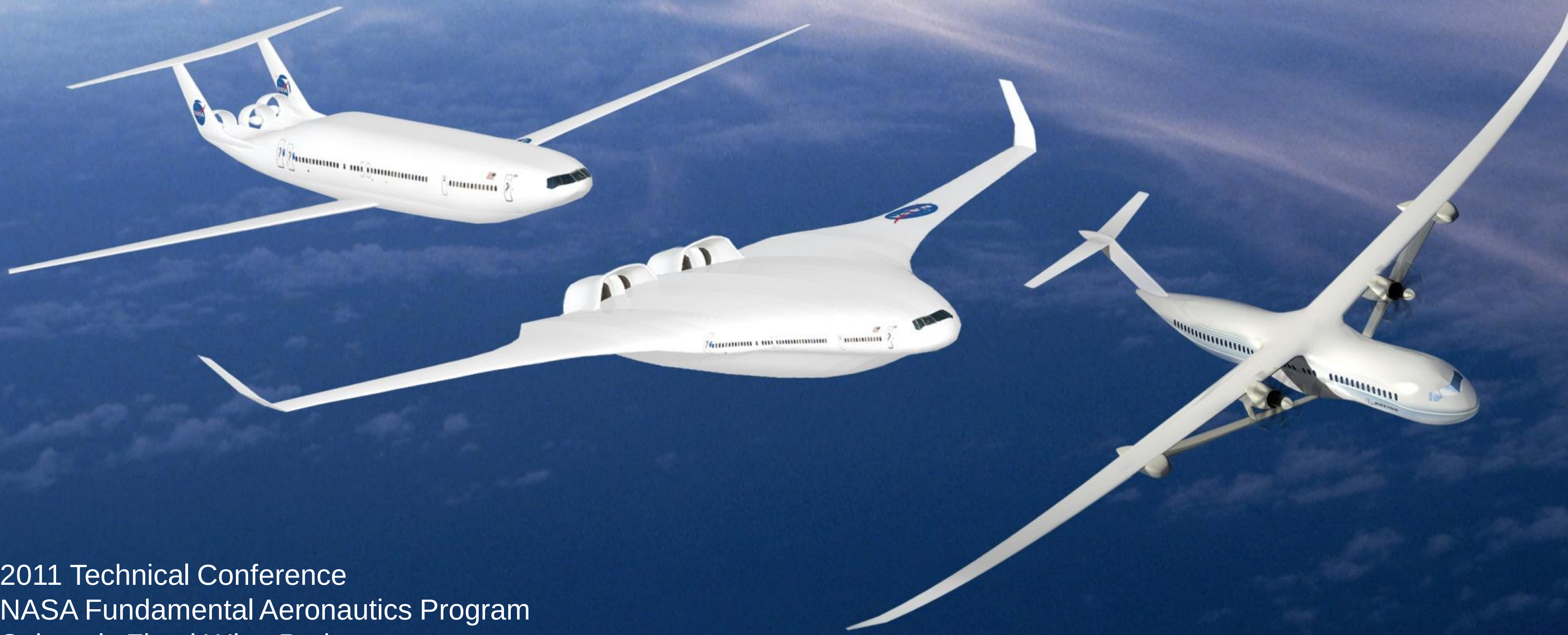

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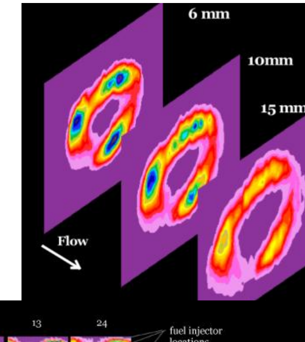
NASA Fundamental Aeronautics Program
Subsonic Fixed Wing Project
Cleveland, OH, March 15 - 17, 2011

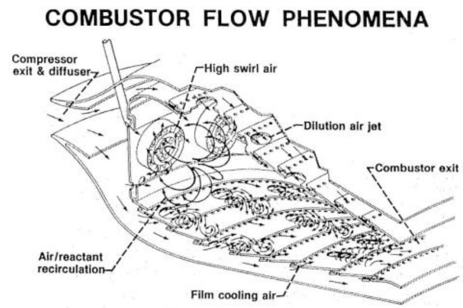
Diagnostics Objectives: Support efforts to produce next generation low emission combustor technology

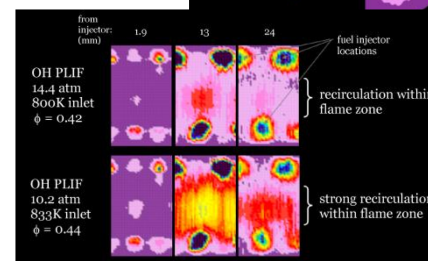
Use and develop tools to facilitate understanding of the fuel vaporization, turbulent mixing and combustion processes within aircraft combustors

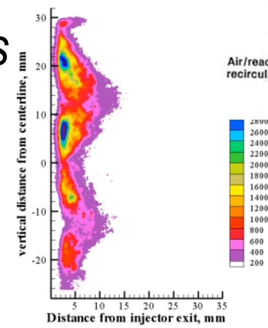


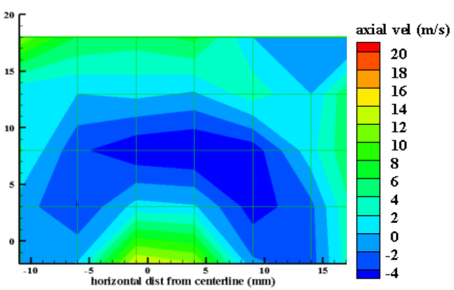
Describe overall performance:

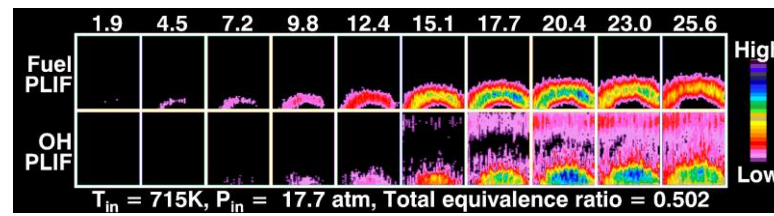
- *Characterize fuel injection-fuel/air mixing*
- *Characterize combustion*
- *Provide data to validate models*

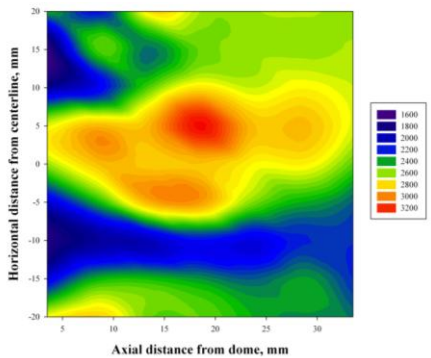


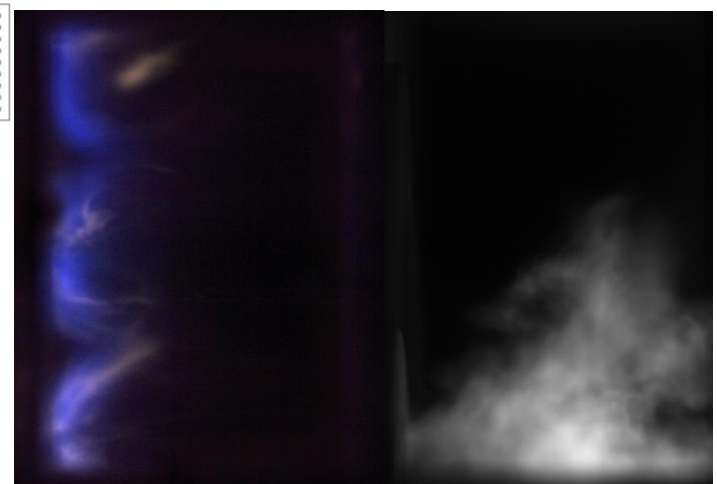


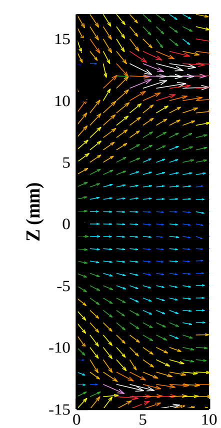












Example systems

•Complex Swirl Mixers

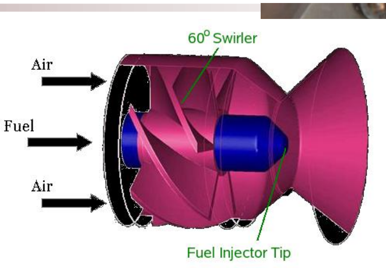
*•NASA Lean Direct Injector (**LDI**)*

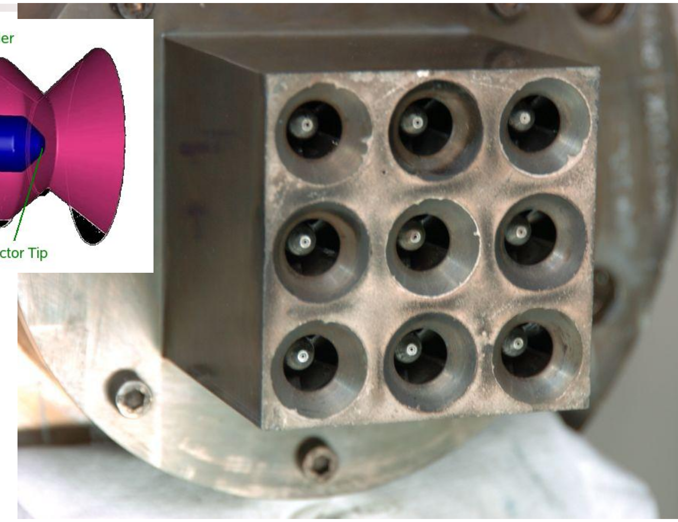
low emissions technology research injector

CE-5 Combustor Subcomponent Test Facility

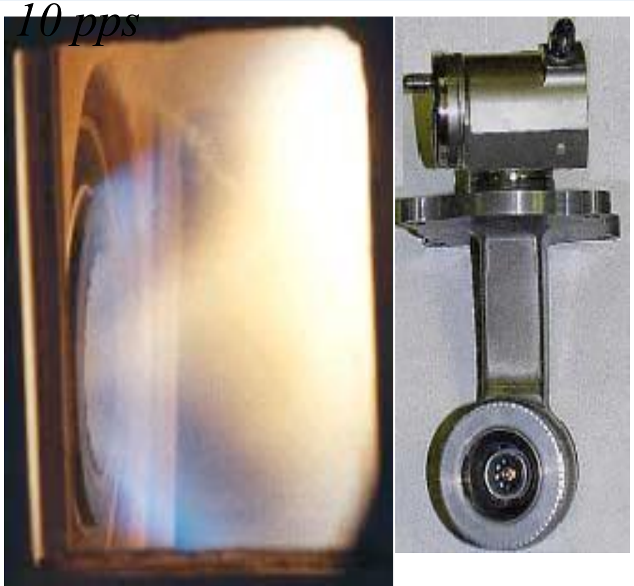
- Two Separate Test Legs
- Dual Fuel Capability w/On-Line Blending
- Gaseous and Particulate Emissions
- Windowed Test Sections
- Laser Diagnostics
- High Speed Imaging

Pressures: up to 275 psia (windows) or 450 psia
Inlet Temperature: 505 K (450 ° F) – 827 K (1030 ° F)
W_{air}: up to 10 pps

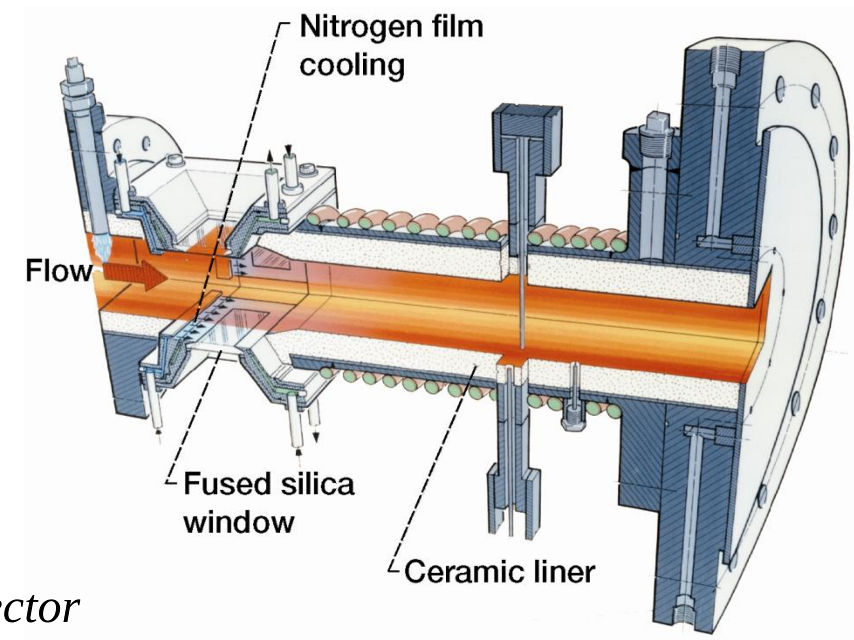




NASA multipoint LDI injector



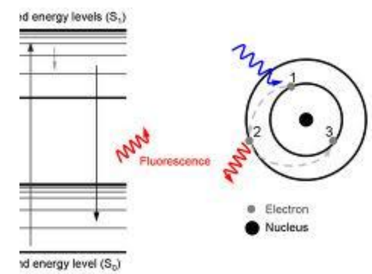
A complex swirl-cup injector



Optical Diagnostics Measurement Suite

Species, temp via PLIF, elastic scatter, Raman scatter

- *2D, 3D mapping of: OH, NO, fuel liquid and vapor CH, profile and pattern factor*
- *1D mapping of major combustion species: CO_2, O_2, N_2, hydrocarbons, H_2O*

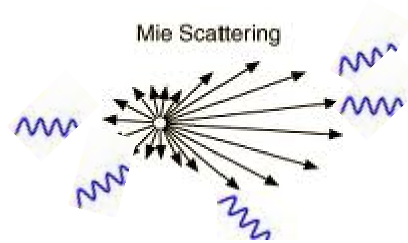


Global Chemiluminescence Imaging of C_2, CH, OH, NO

*[**A**] + [**B**] → [◊] → [Products] + light*

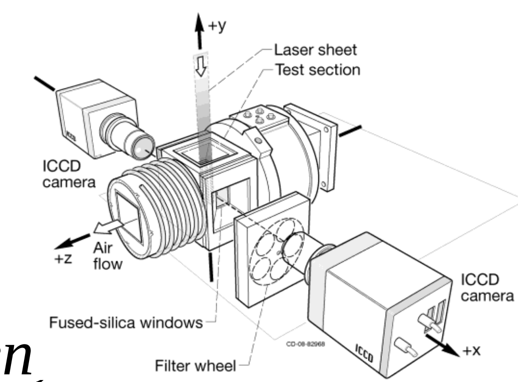
Velocity

- *2 component mapping via images—PIV*
- *3 component pointwise—LDV/PDI*



Drop Sizing

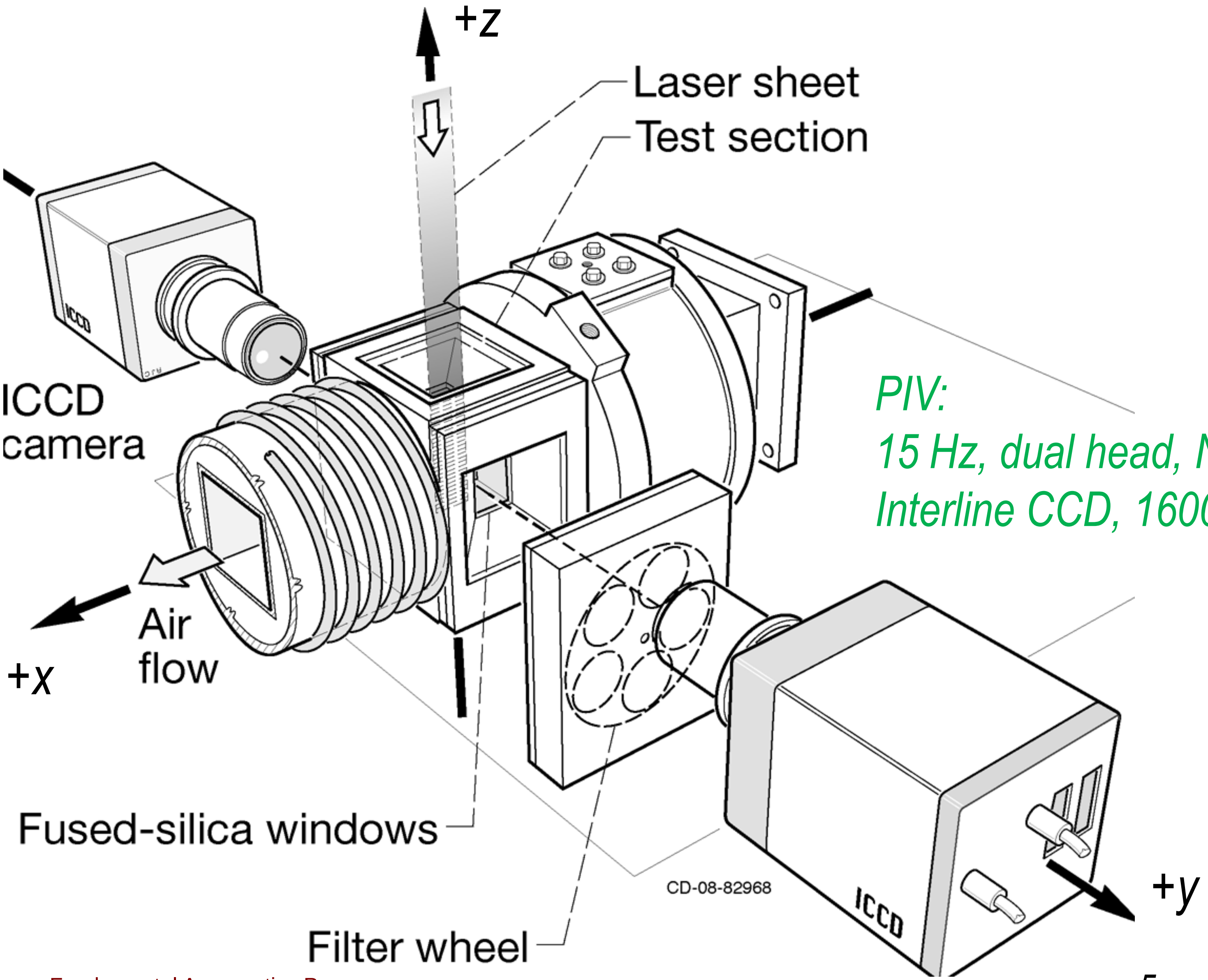
- *3 component pointwise—PDI*
- *shadowgraph-based, long range microscope*



Flow/flame visualizations

movies: video, high speed photography, schlieren

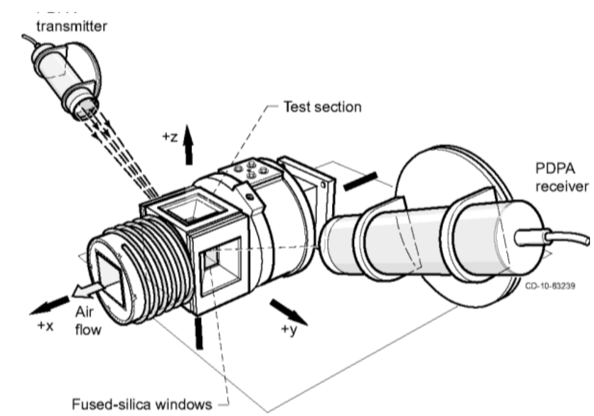
Typical Imaging Setup

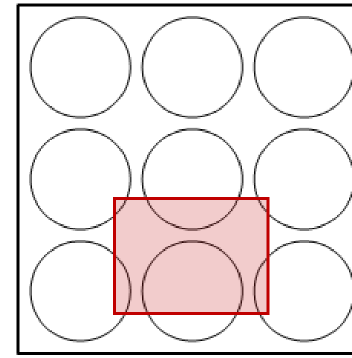


PIV:
15 Hz, dual head, Nd:YAG532-nm
Interline CCD, 1600x1200 px

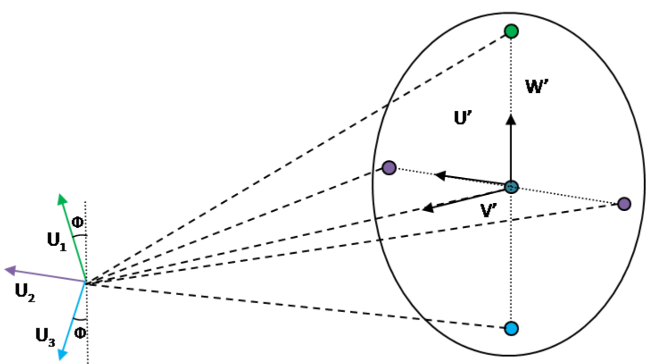
5

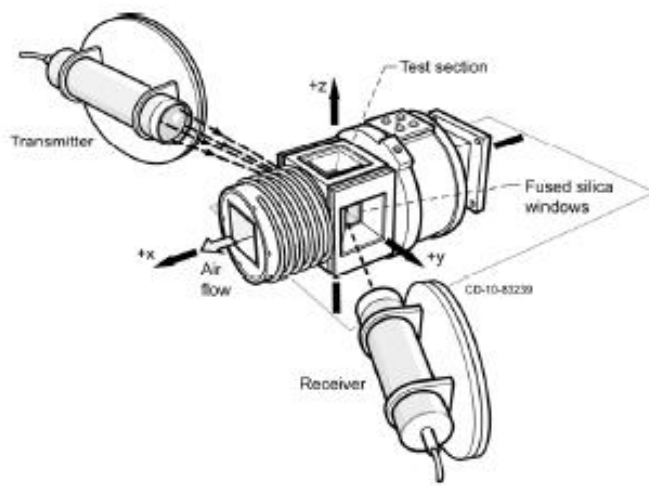
3D Phase Doppler Interferometry

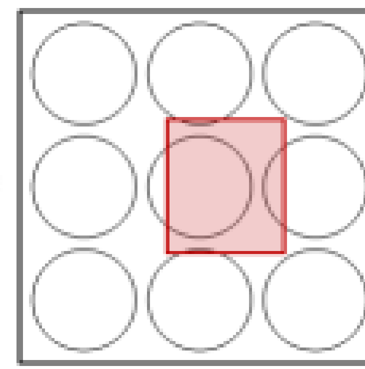




- *3-color, 6 beams in a 5 beam layout*
  Center has one blue and one green collinear



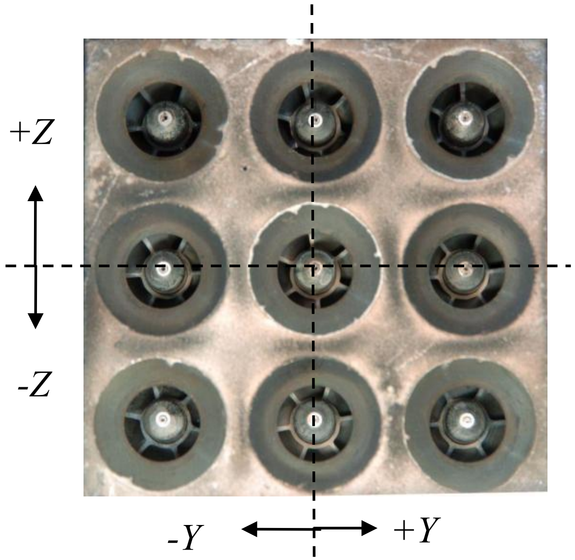




Examples

- Fuel Mass/Pattern Comparison CFD, Fuel PLIF
- Particle Image Velocimetry, Air and Fuel drop velocities
- Phase Doppler Interferometry—Drop sizes, velocities, Turb Int.
- Alternative Fuel Comparison using high speed flame imaging, chemiluminescence

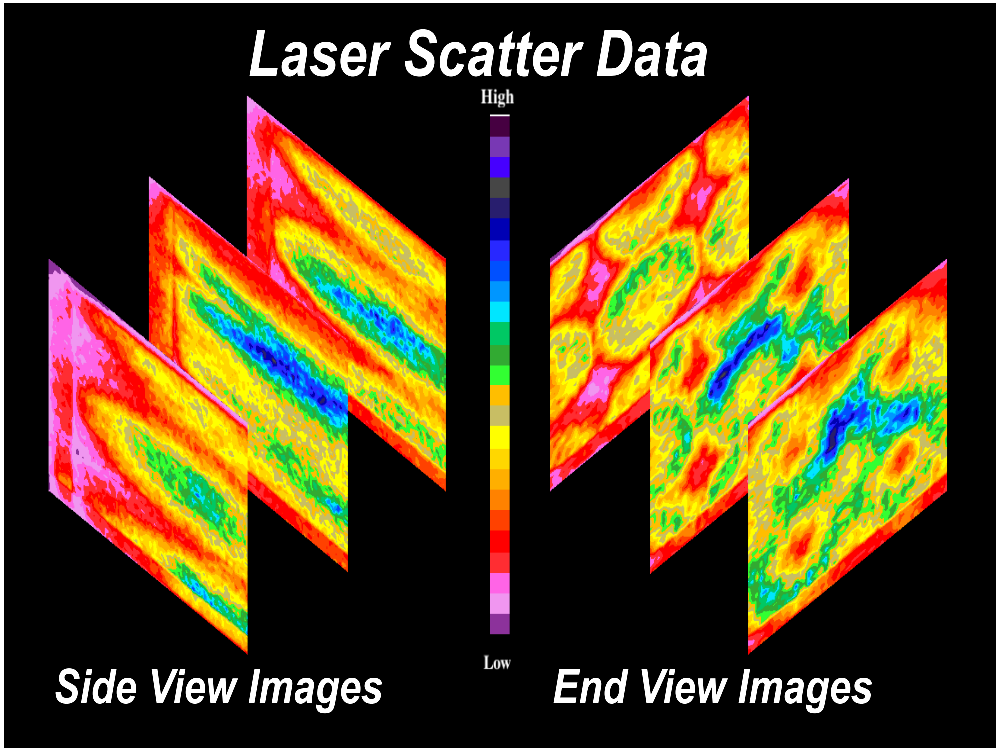
Coordinate & Setup Definitions



+ X (Out of Page)
"End View"

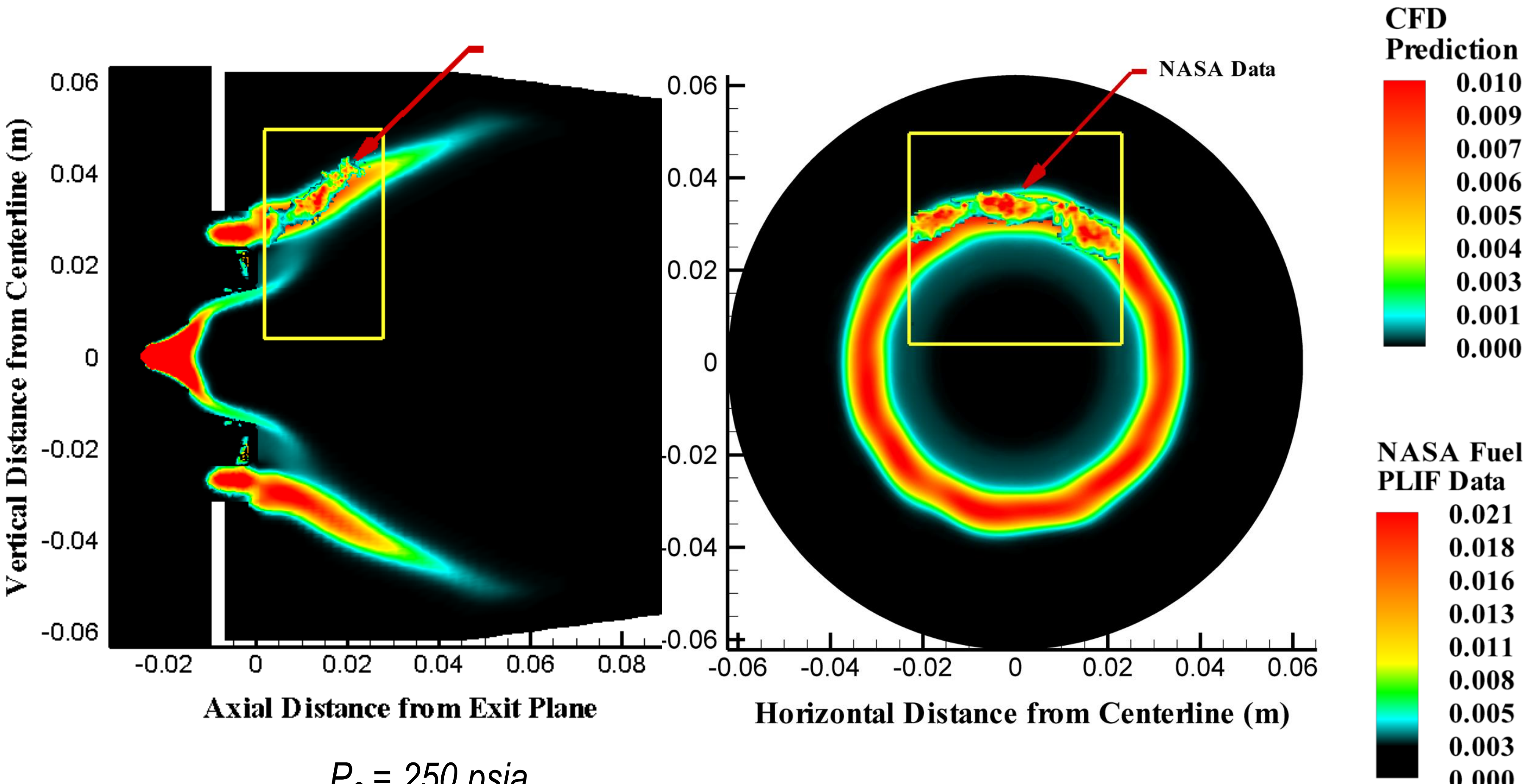
Test Space Coordinate Definition

X → Axial Flow Direction (U-Velocity)
Y → Lateral Flow Direction (V-Velocity)
Z → Vertical flow Direction (W-Velocity)



Fuel Pattern/Fuel Mass Comparison   NASA Data: Fuel PLIF

Comparing primarily flow in the main injector region, which has several discrete injection points



P_3 = 250 psia,
T_3 = 1000 °F

Axial position: 12mm downstream from injector exit

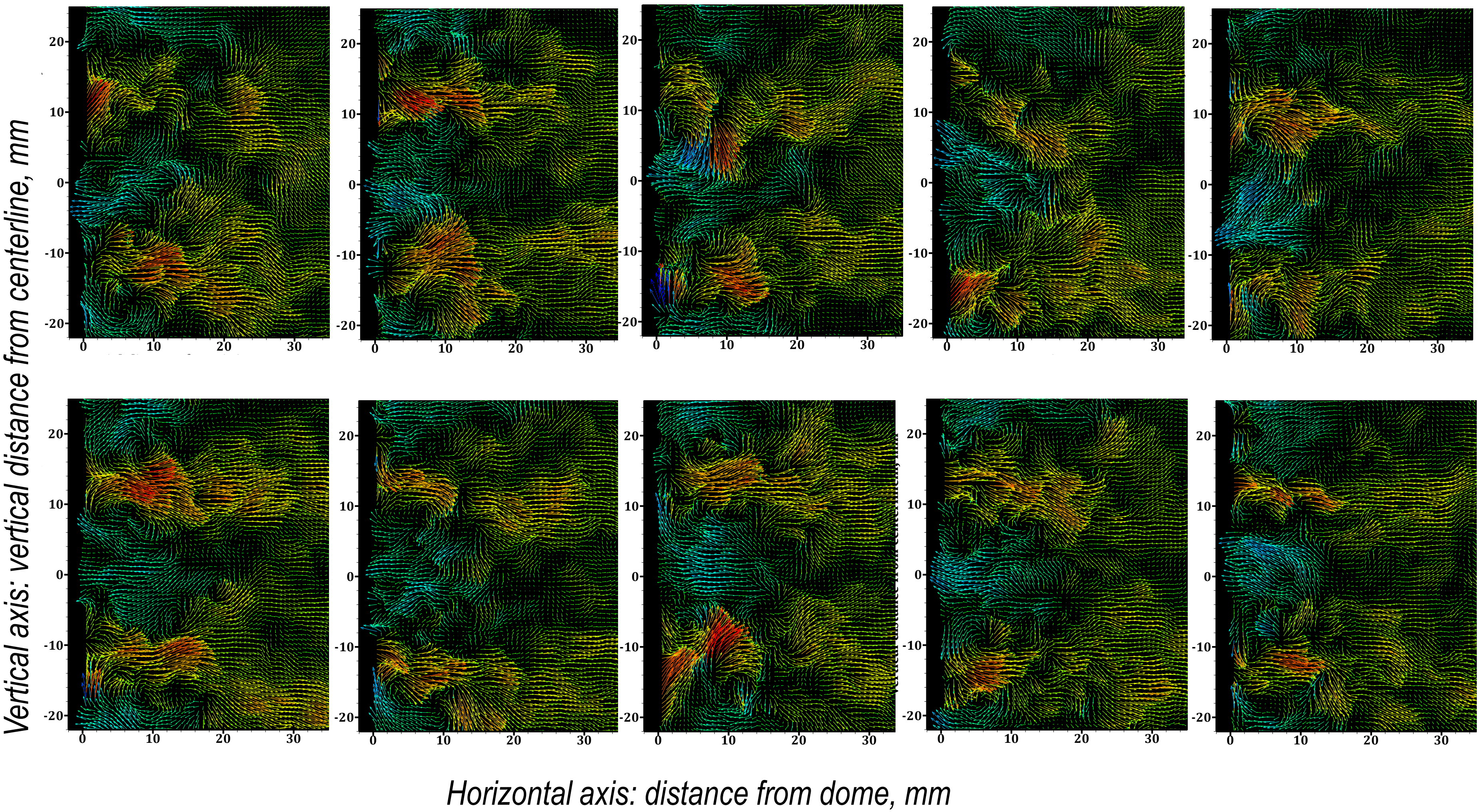
Velocity, drop size measurements, LDI injector

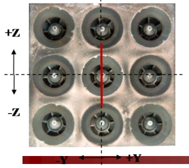
Air only, 2-D velocity measurements, PIV

- "instantaneous" (5-μsec Δt) vector fields
- Average results

Fueled, combusting results, PDI and PIV

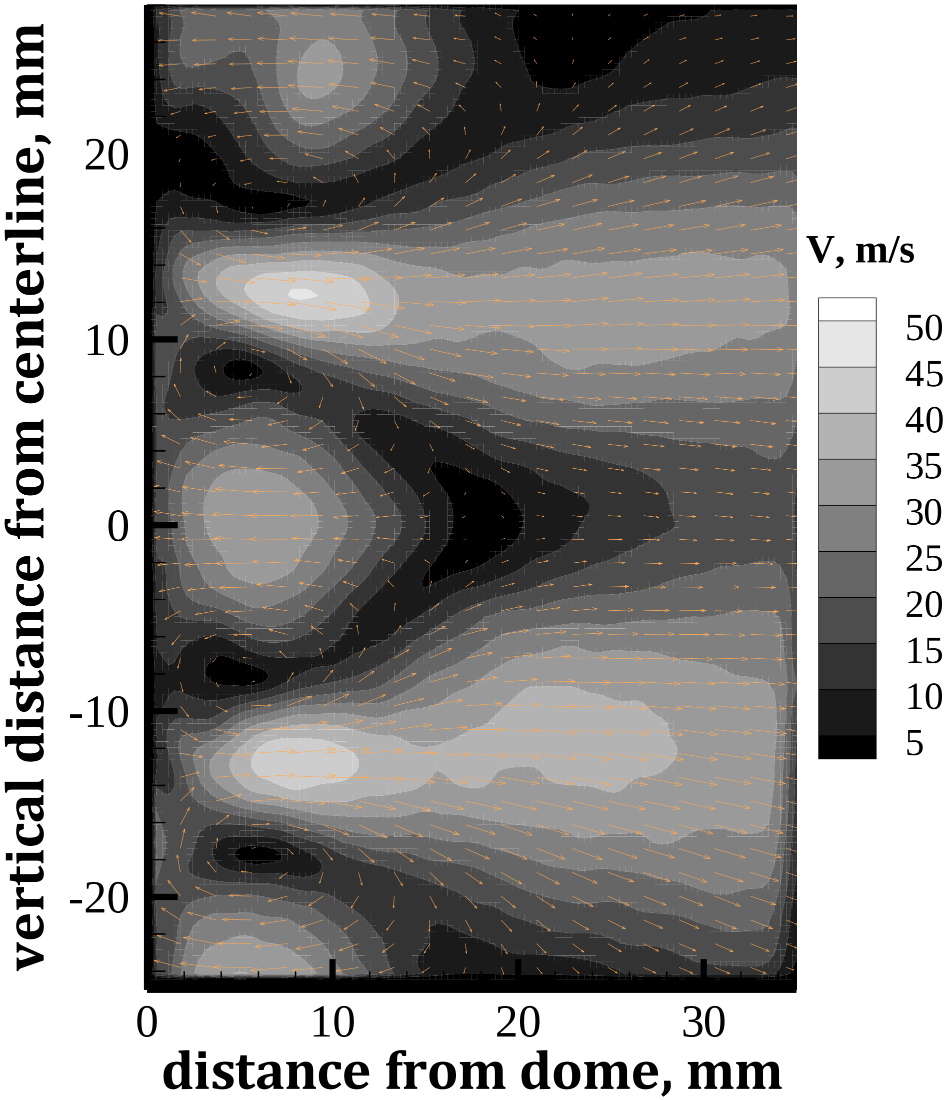
Ten Consecutive Instantaneous PIV Axial-Vertical Velocity Fields
Air only. T_3 = 1030° F, P_3 = 150 psia

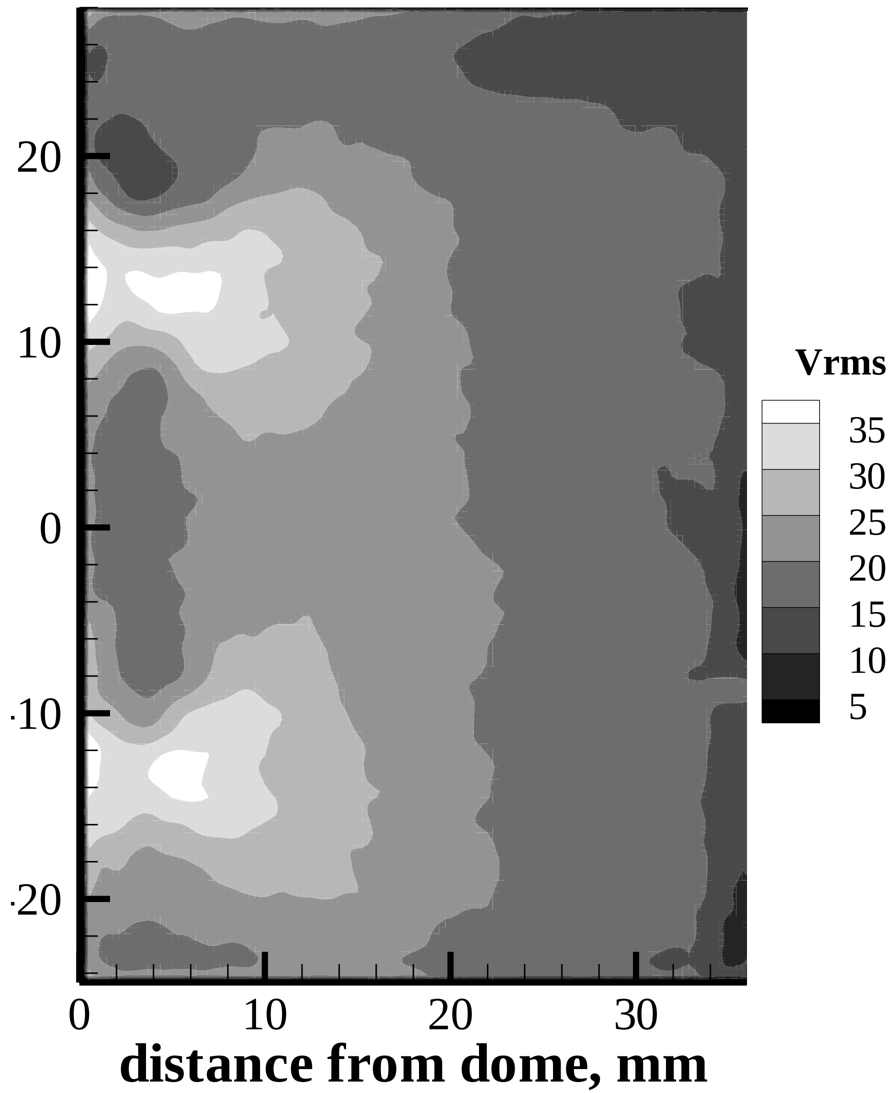




2D velocity

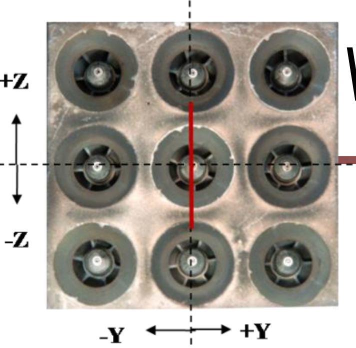
RMS velocity





- *Recirc zones directly downstream of injectors*
- *Black bands—location of zero velocity*

Average, 500 image pairs

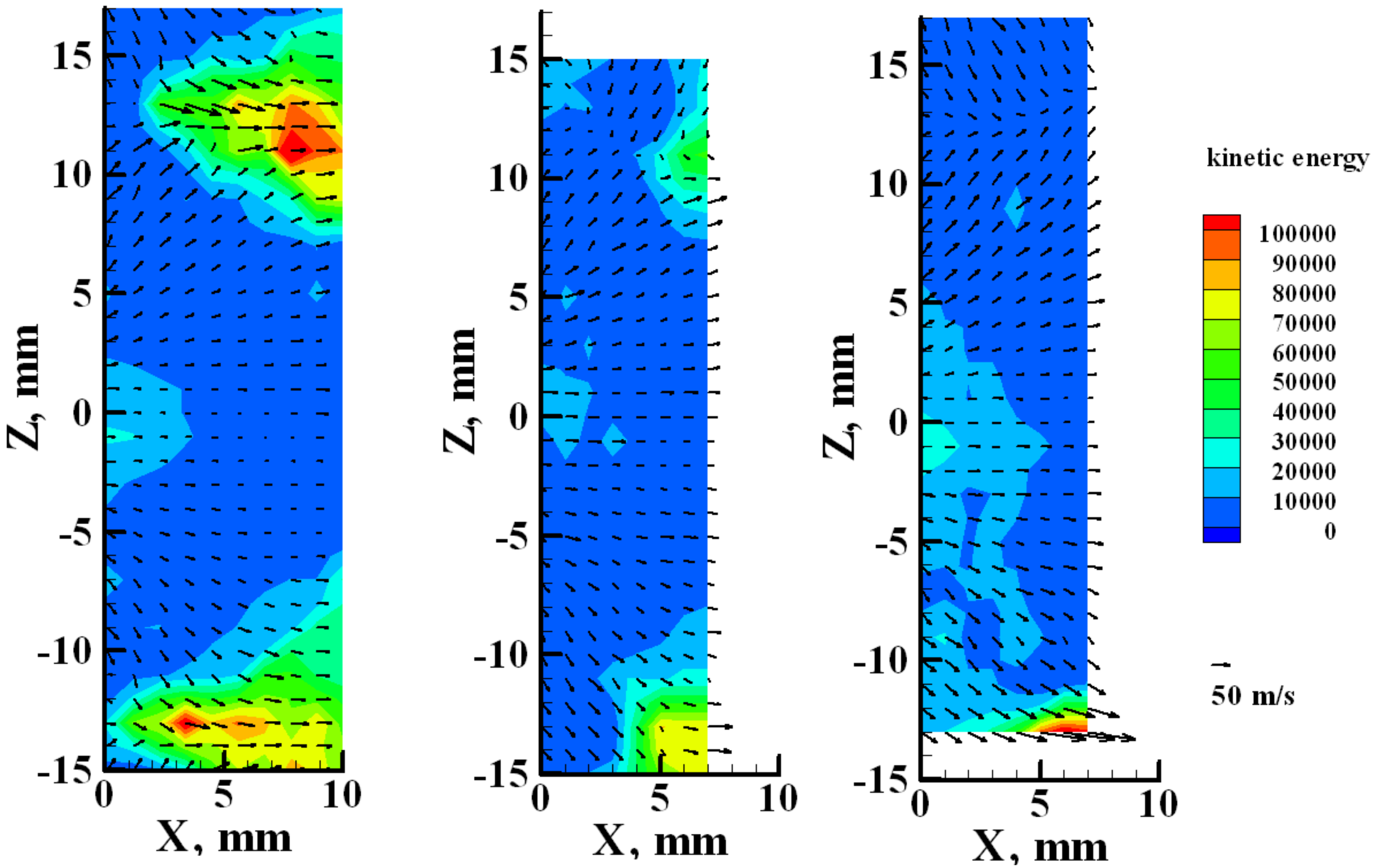


Velocities and KE at Y = 0 (results from PDI drops)

Observations:

Lowest velocities occur along the centerline indicating the spray pattern resembles that of a hollow cone spray with recirculation.

Greatest velocities and turbulence are evident in the regions probed between injectors where the fuel spray from adjacent injectors mix.

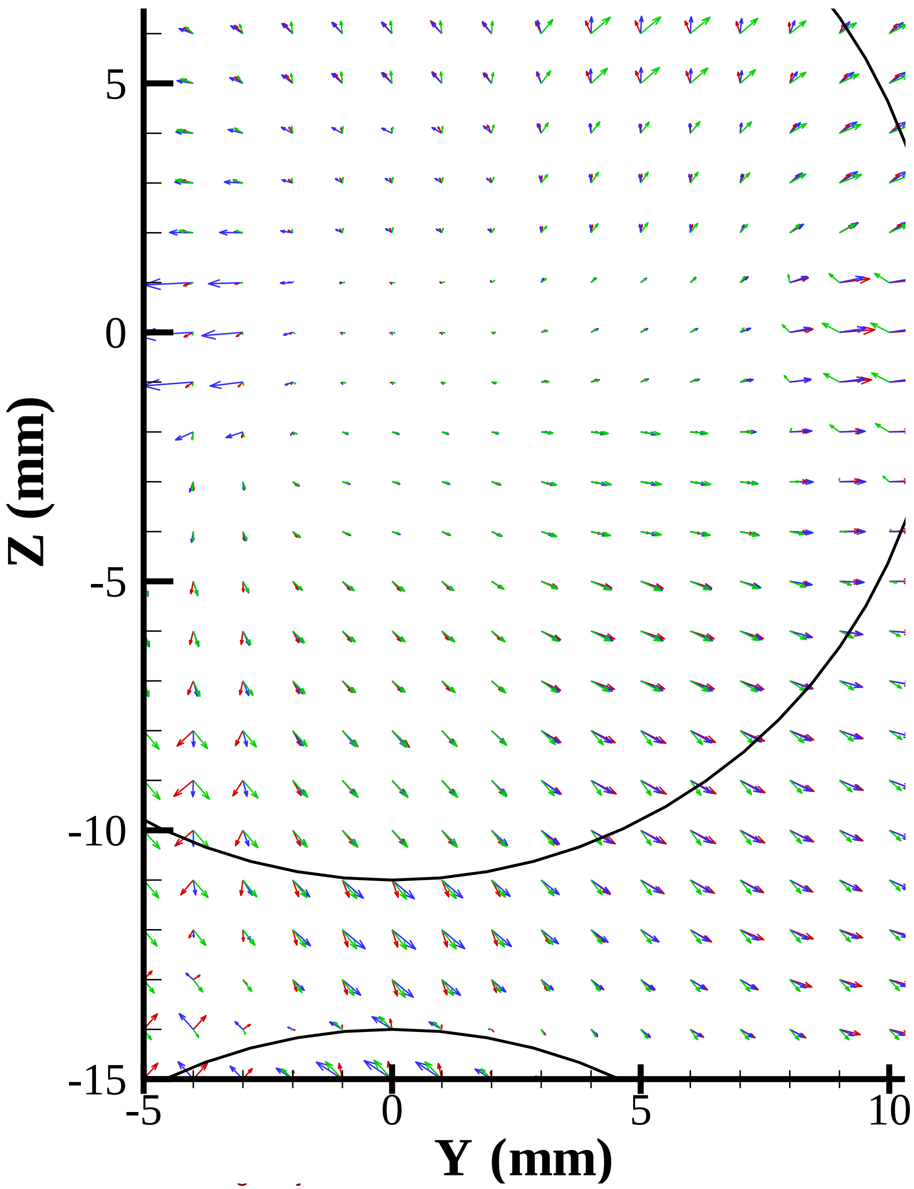


T_3 = 850° F (728 K)	T_3 = 850° F (728 K)	T_3 = 1030° F (828 K)
P_3 = 150 psia (1034 kPa)	P_3 = 200 psia (1379 kPa)	P_3 = 150 psia (1034 kPa)
$\Phi = 0.45$	$\Phi = 0.45$	$\Phi = 0.45$

$$KE = \frac{1}{2}\left(U_{RMS}{}^2 + V_{RMS}{}^2 + W_{RMS}{}^2\right)$$

Downstream

Drop Size Differentiated Flows (Azimuthal Velocity)



Inlet Conditions:

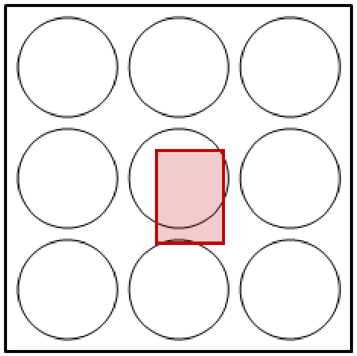
$T_3 = 1030^\circ$ F
$\Delta P/P = 4\%$
$P_3 = 200$ psia *$\Phi = 0.45$*

X = 3-mm from injector exit plane

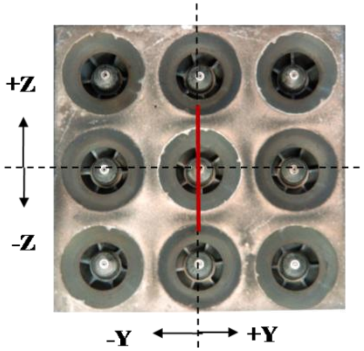
Red = Small Droplets < 10 µm
Blue = Medium Droplets: > 10 µm, < 20 µm
Green = Large Droplets > 20 µm

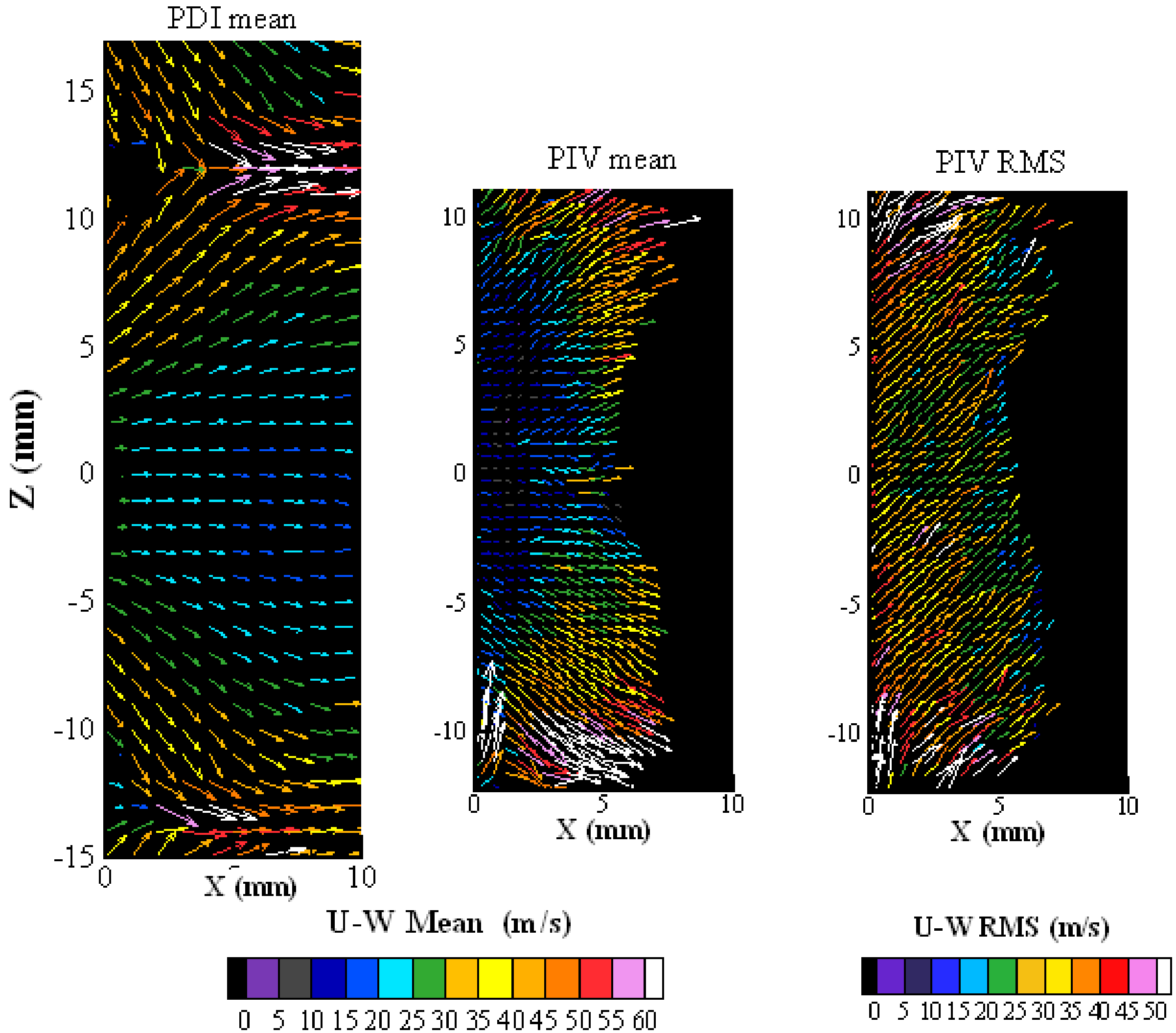
Lowest velocities are noted at the center of the injector indicating the presence of a hollow cone spray. Only slight variations in azimuthal velocity between the three drop size ranges is evident in most locations.

Reference symbols:
→ = 50 m/s



Comparing PDI and PIV, 9pt LDI





T_3 = 850 °F (728 K)

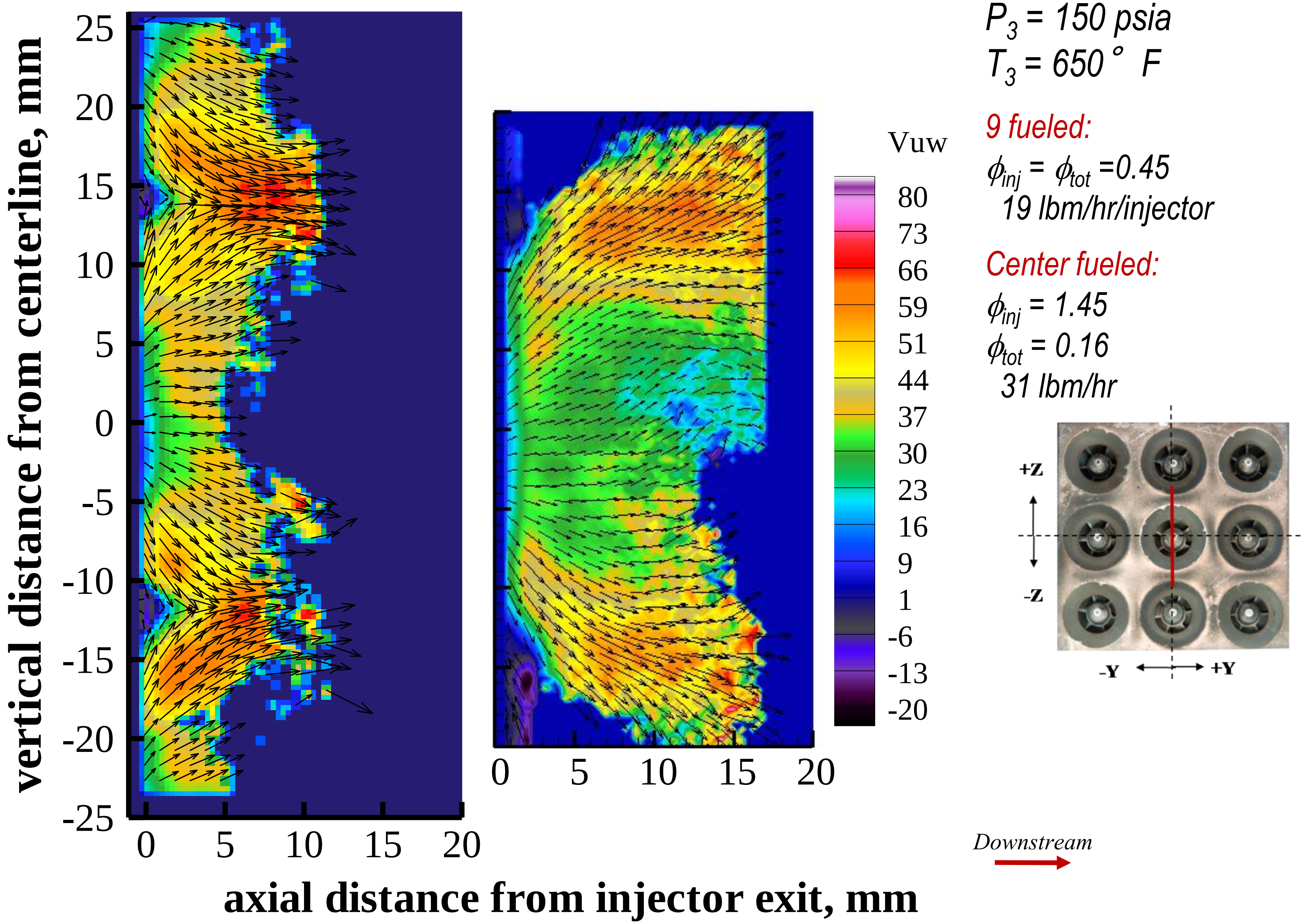
P_3 = 150 psia (1034 kPa)

Φ = 0.45

$\Delta P/P$ = 4%

Downstream

All nine injectors fueled vs center only (PIV)



P_3 = 150 psia
T_3 = 650° F

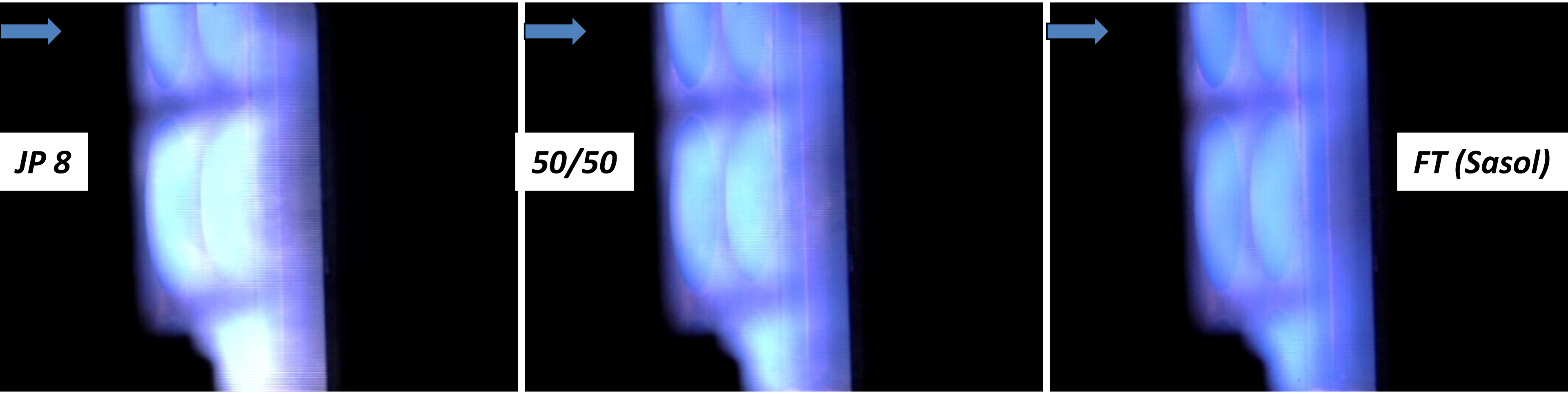
9 fueled:
$\phi_{inj} = \phi_{tot}$ =0.45
19 lbm/hr/injector

Center fueled:
ϕ_{inj} = 1.45
ϕ_{tot} = 0.16
31 lbm/hr

Alternate fuel testing in CE-5

The objectives of this experiment were to visually compare JP-8 flames with FT-2 (Sasol) flames for gross features. Specifically, we wanted to ascertain in a simple way visible luminosity, sooting, and primary flame length of the FT-2 compared to a standard JP grade fuel. We used video imaging and high-speed imaging to achieve these goals.

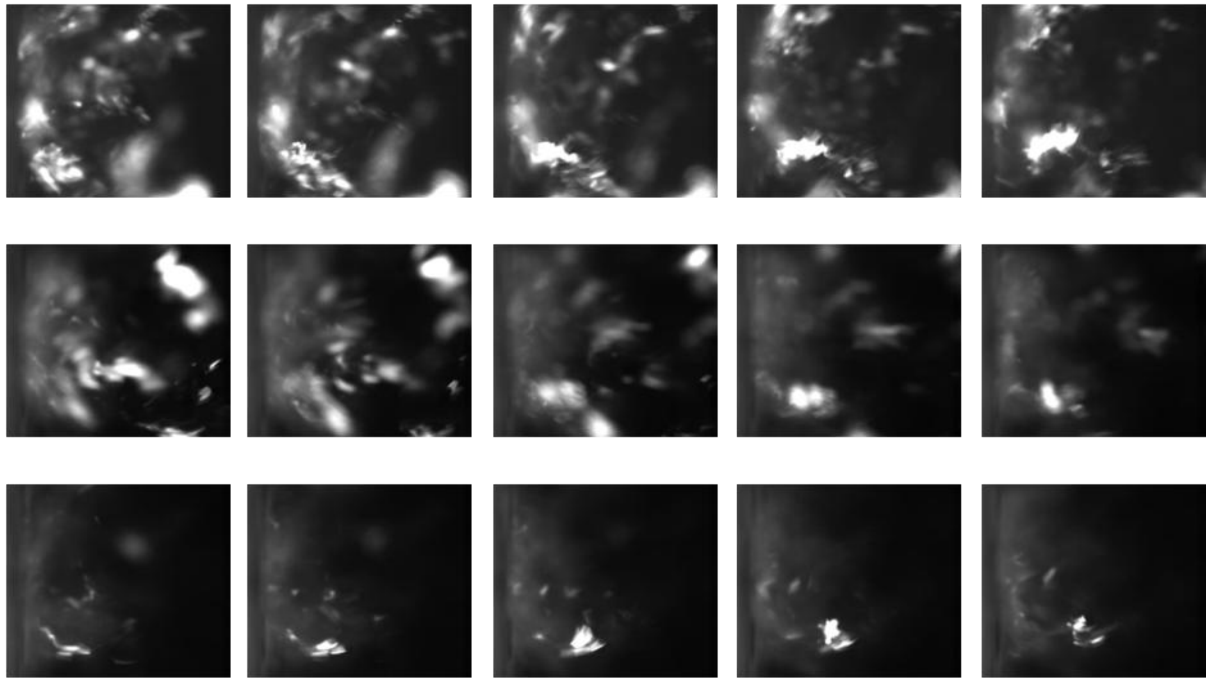
F-T fuel is from Sasol and produced from coal.



150 psia, Inlet Temperature 1030 F, 4% pressure drop, Fuel/Air Ratio=0.030

JP-8, 1030°F	**JP-8**, 850°F	**JP-8**, 650°F
50-50 blend, 1030°F	50-50 blend, 850°F	50-50 blend, 650°F
FT-2, 1030°F	**FT-2**, 850°F	**FT-2**, 650°F
Condition matrix used for alternative fuel flame imaging test.		

Alternate fuel test results, continued



JP-8

50-50

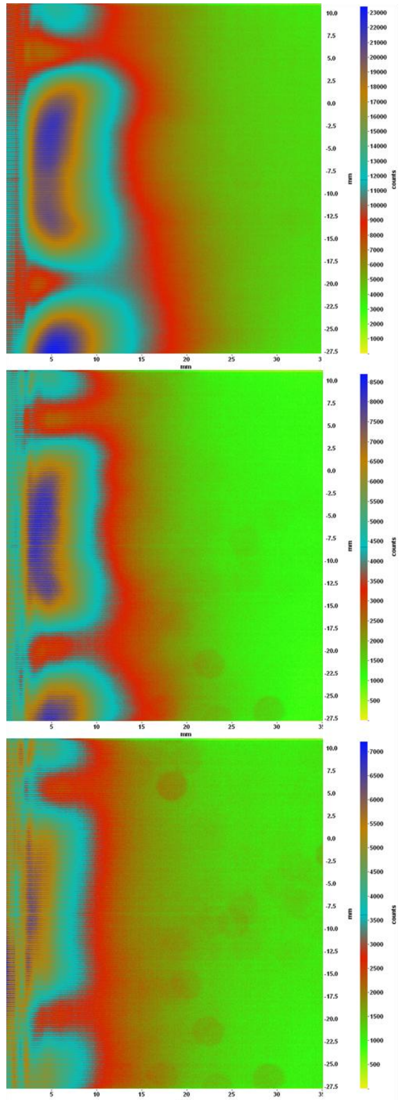
FT-2

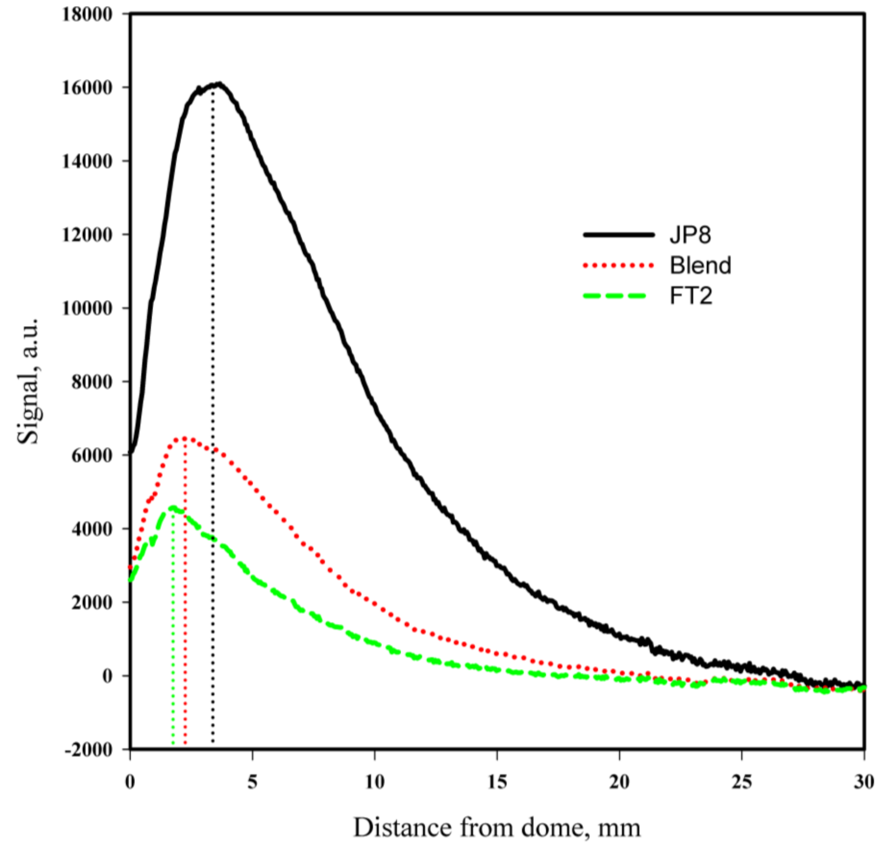
*Five successive frames at **T_3 = 850° F** framed at 30kps that show flames burning JP-8 (top), the 50-50 blend (center) and FT-2. All images are unfiltered. The framing captures the flame from the center row of injectors and extends approximately 26-mm downstream. Flow passes from left to right.*

Alternate fuel test results, continued

Average flame structure and luminous intensity obtained by averaging 1800 frames for the T_3 ***= 1030° F*** *cases. The frame rate was 12 kps. Framing fully incorporates the center row, plus part of the top and bottom rows.*

The axial span is approximately – 1.7-mm to 33-mm downstream from the injector exit. The frame height is approximately 39-mm.





Comparison showing average flame length and luminous intensity for T_3 ***= 1030° F****, for a 0.6-mm strip around the vertical center of the images shown at left.*

Summary

- We use a variety of techniques to get information about the mixing and combustion environment for next-generation fuel-injector-mixer concepts
- Examples demonstrated some of the range and challenges for implementing optical tools in “realistic” combustor environments

Acknowledgment

- We thank the subsonic fixed wing project for sponsoring this work

- We also thank the CE-5 test crew

NASA