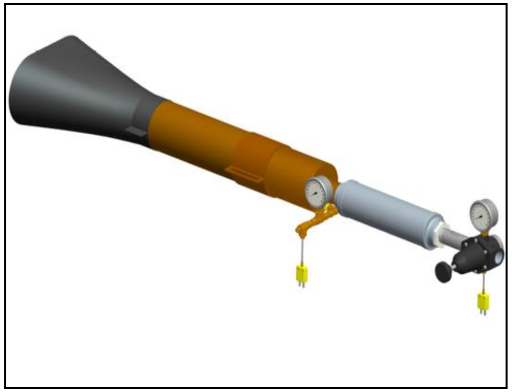
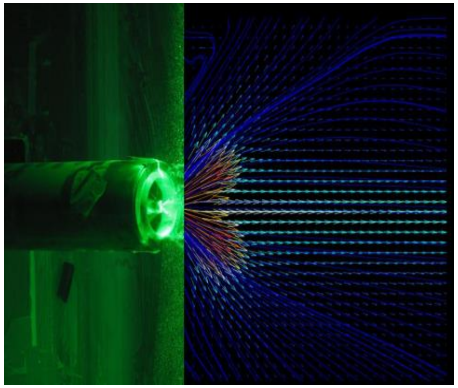
Design and Analysis of the Federal Aviation Administration Next Generation Fire Test Burner

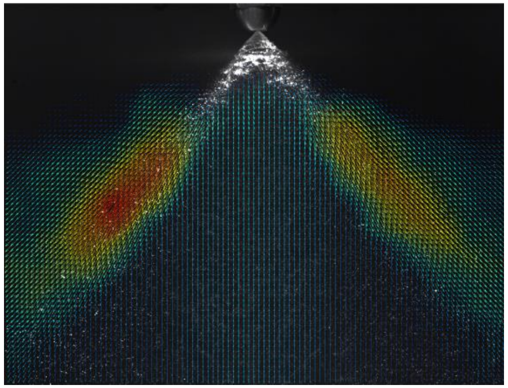
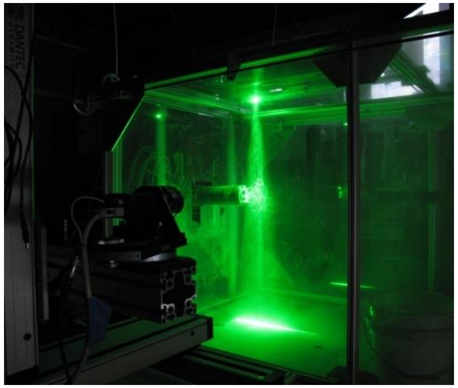





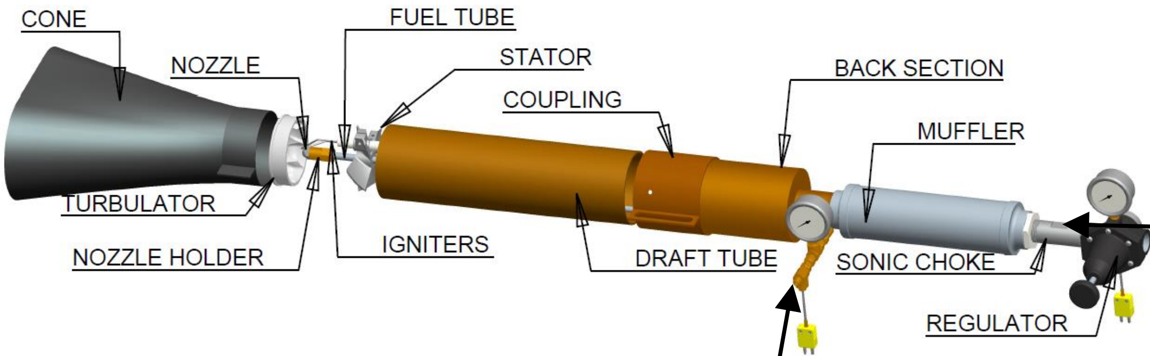
RUTGERS

Robert I. Ochs

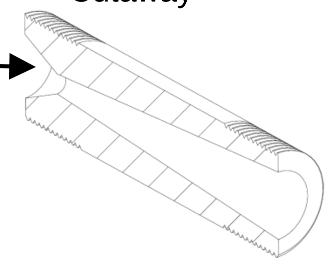
Federal Aviation Administration


Next Generation Burner Development



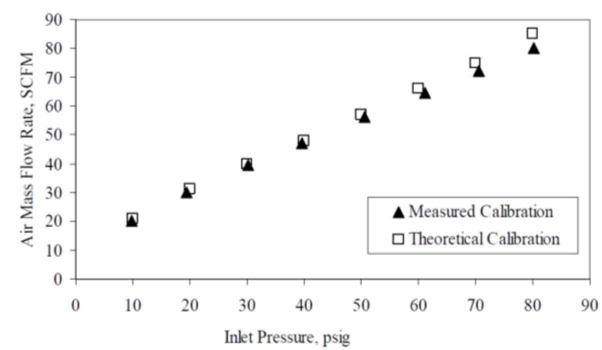
Sonic Nozzle Cutaway



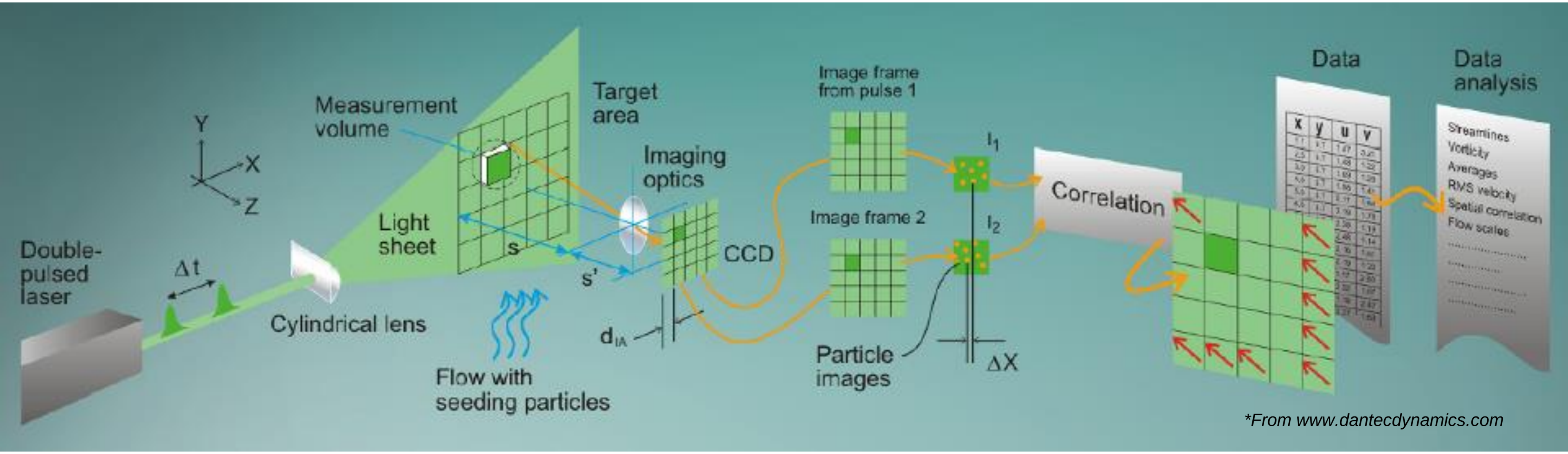
- NexGen burner developed to be a drop-in replacement for Park DPL3400
- Relies on similar operation principles and components
- Electric motor functions replaced by sonic nozzle, pressurized fuel tank

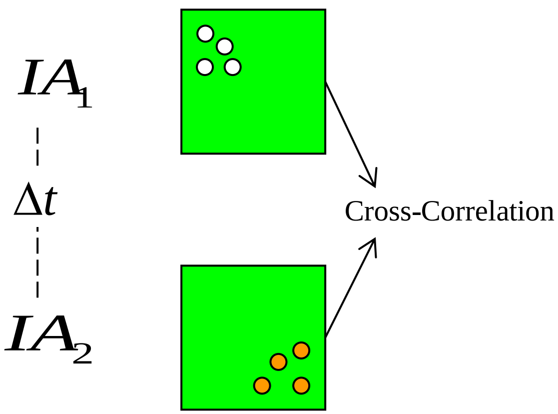
Pressurized JP8 Fuel Tank

Mass Flow Rate vs. Inlet Pressure

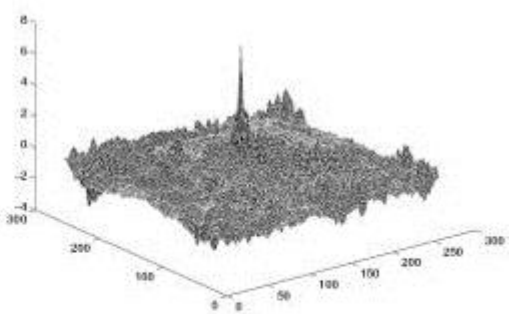


Particle Image Velocimetry

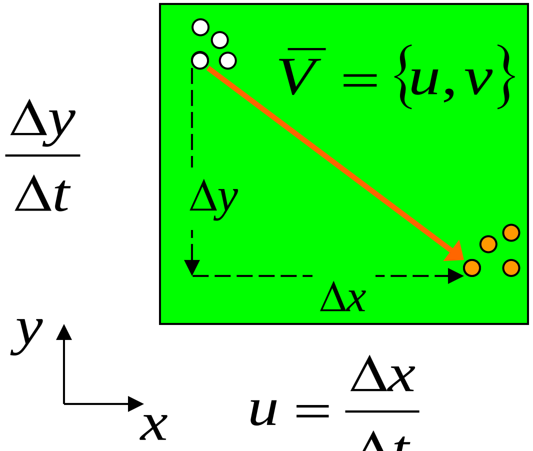




Peak Detection



$$v = \frac{\Delta y}{\Delta t}$$



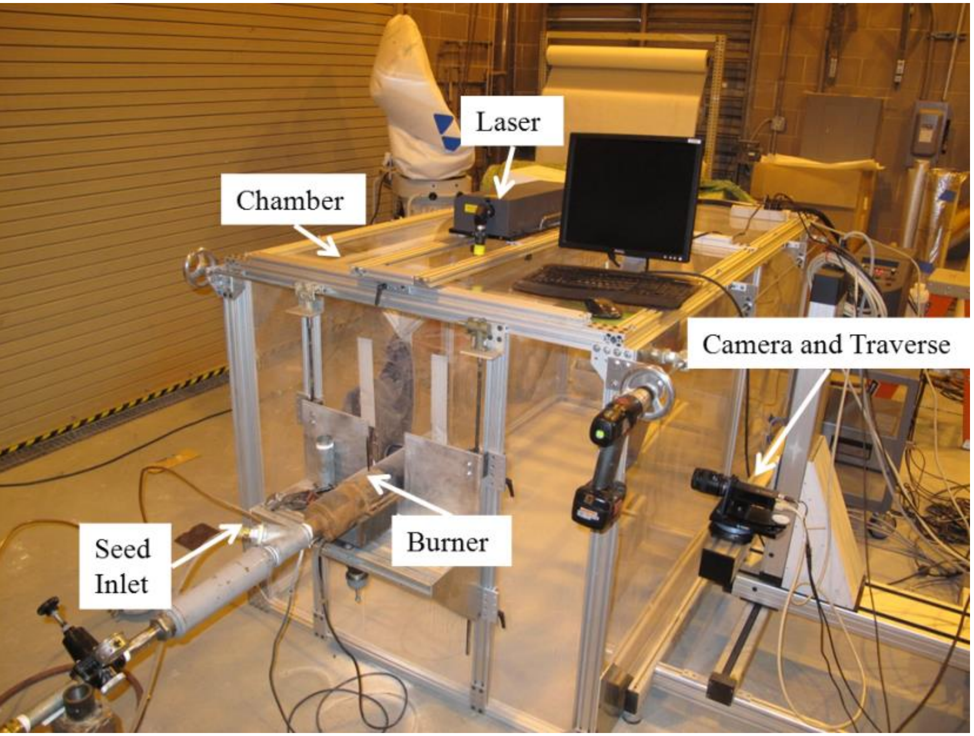
$$u = \frac{\Delta x}{\Delta t}$$

Objective

- Measure non-reacting burner flow fields with PIV
  - Determine effect of stator, turbulator, nozzle on flow field
  - Compare measured flow fields with standard burner performance metrics
    - Flame temperature measurement
    - Material burnthrough time
  - Assess potential design improvements
    - Flow field
    - Flame temperature
    - Material burnthrough
- Identify critical parameters, components that have most significant effect on burner performance

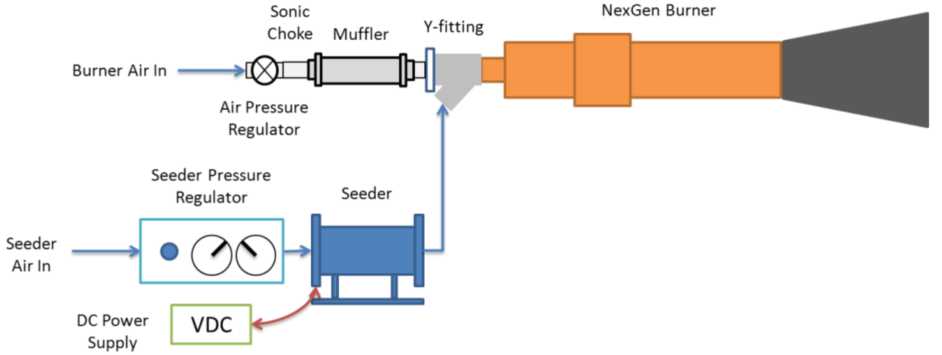
PIV Test Chamber

Test Chamber



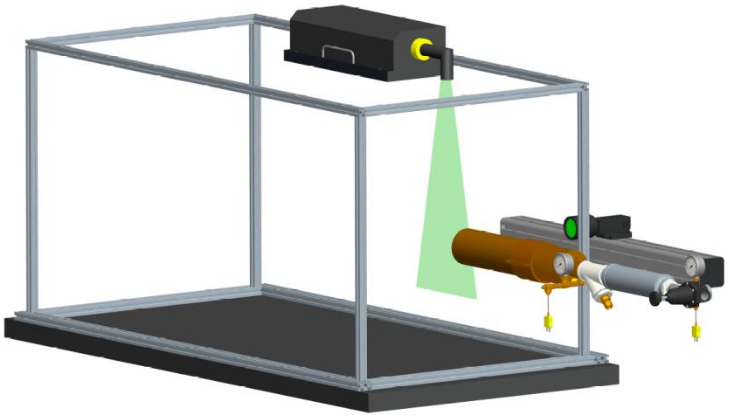
- 1.2 x 1.2 x 2.4 meters
- 2.45 cubic meters volume
- Custom traversing mounts for laser, burner
- 3D computer controlled traverse for cameras

NexGen Burner Seeding



- Solid particle seeding system
- Al_2O_3 particles, 15 µm

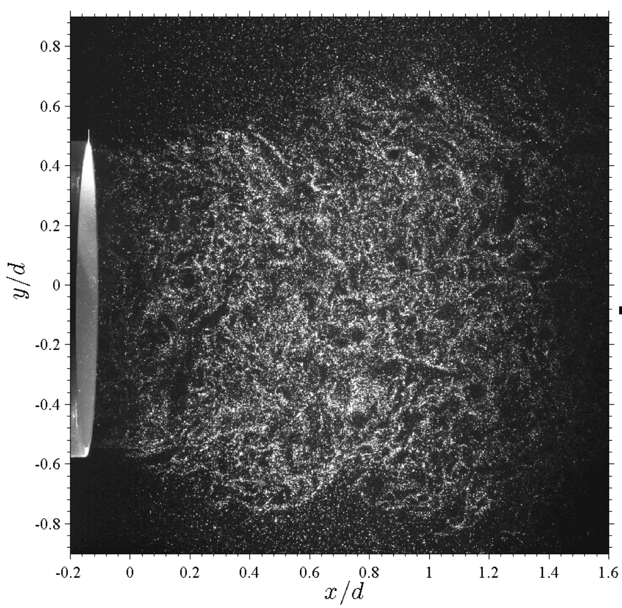
2D PIV Burner Exit Flow Measurements



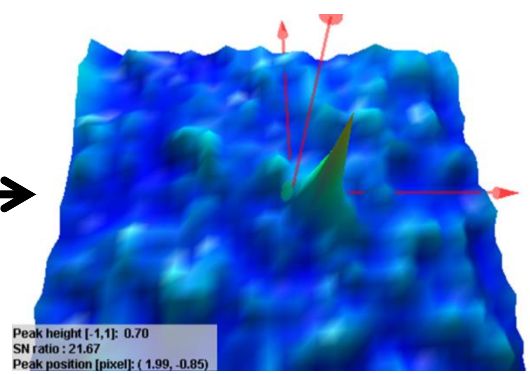
Acquisition Properties:

- 2 x 500 image pair acquisitions
- Adaptive Correlation
    - 128 x 128 px initial IA
    - 64 x 64 px final IA
    - 50% overlap
    - Peak validation 1.2 x peak 2
    - Moving average 3x3 local validation
- Vector Statistics – ensemble averaging

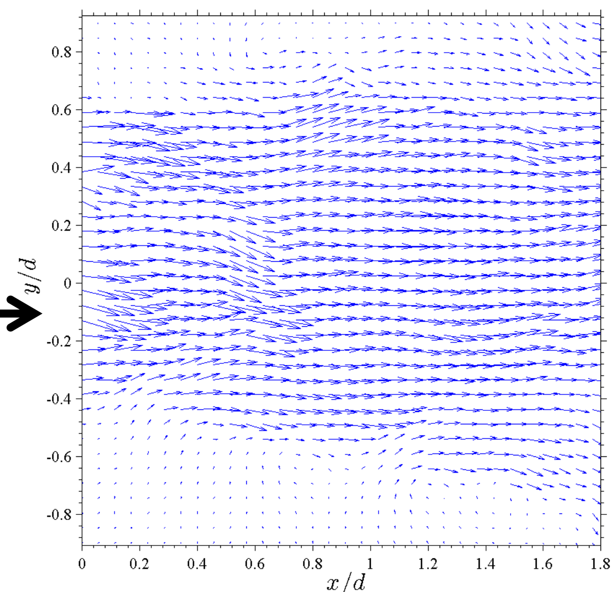
Raw PIV Image



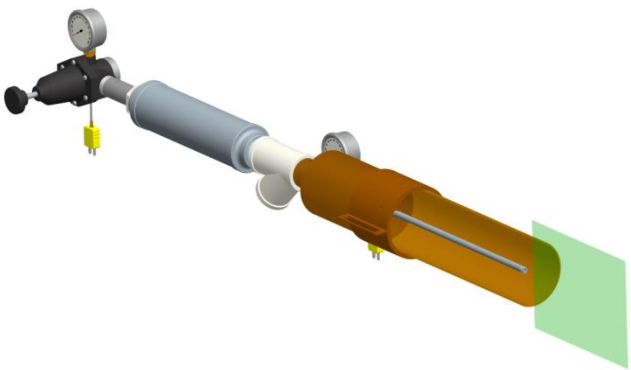
Adaptive Correlation



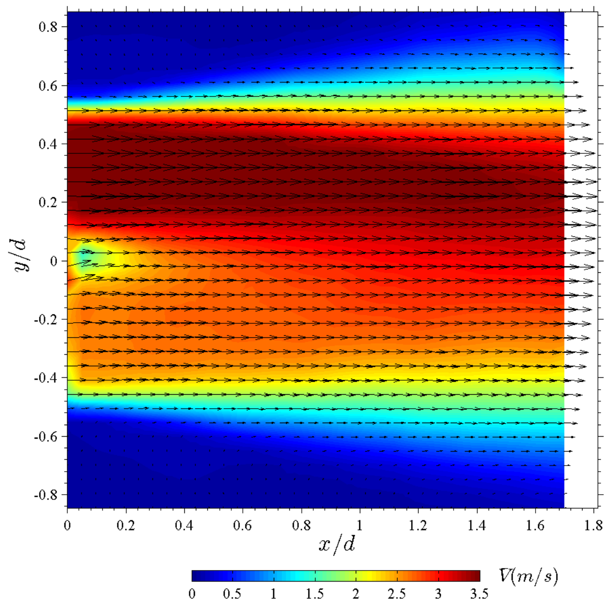
Instantaneous Vector Field



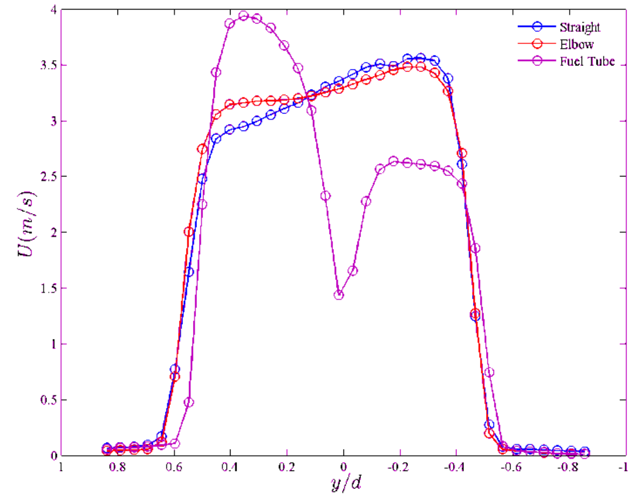
Fuel Pipe - 2D PIV



Mean In-Plane Velocity Field



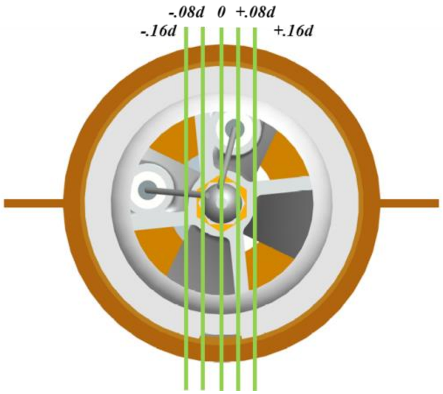
Axial Velocity Profiles at *x/d*=0.2

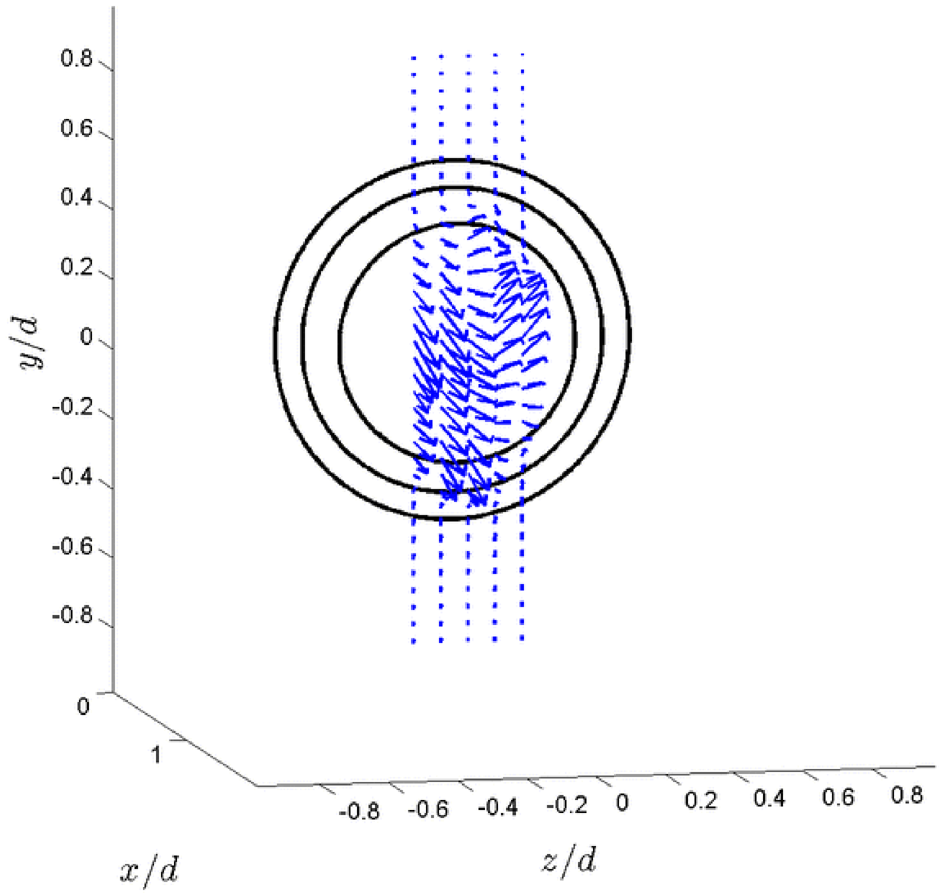


- Asymmetric in-plane flow field, axial velocity profile
- Dogleg bend in fuel tube influences flow field

Off-Centerline Planes - 2D PIV

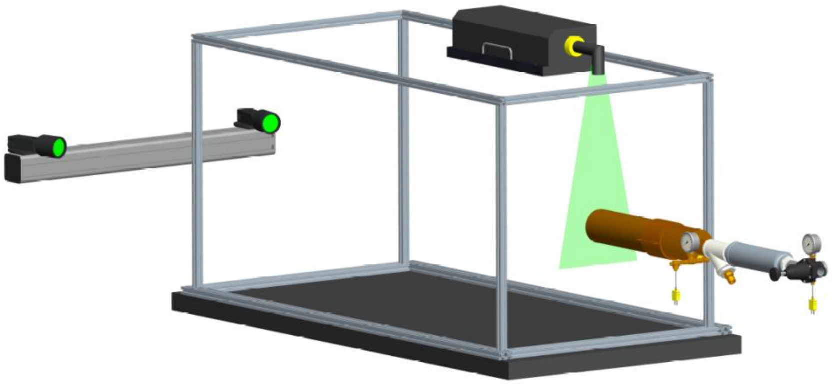
Turbulator Exit Plane – Front View



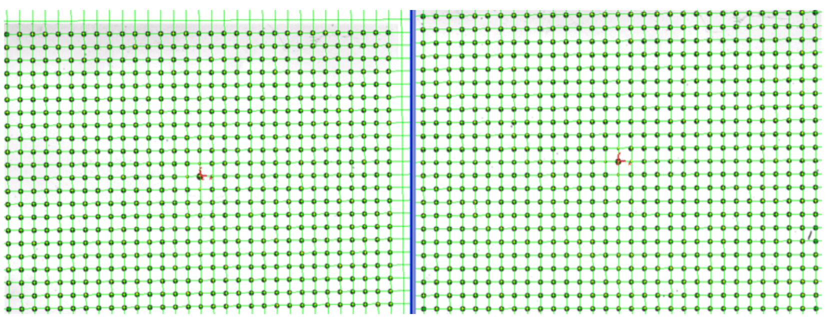


- Off-centerline measurements show directionality of burner exit flow
- 5 downstream locations were chosen from each cross-streamwise plane to visualize exit flow

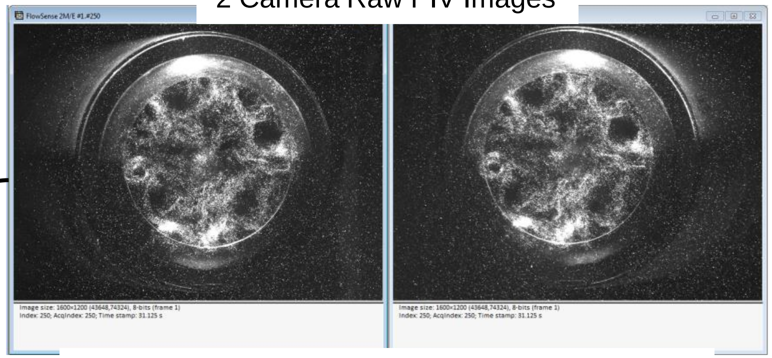
3D Stereoscopic PIV – Turbulator Exit Flow



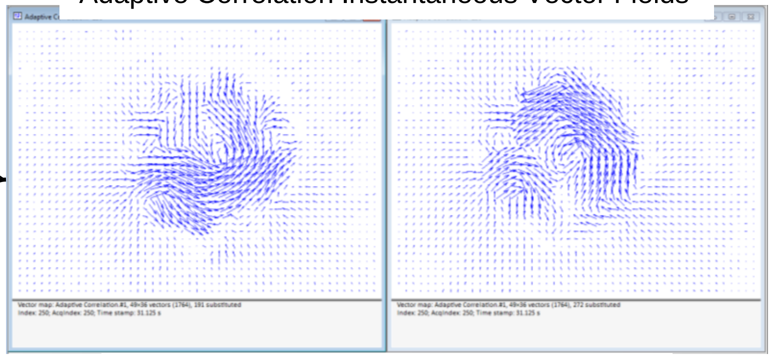
Stereo Calibration



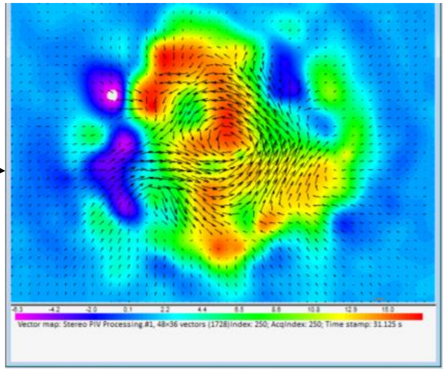
2 Camera Raw PIV Images



Adaptive Correlation Instantaneous Vector Fields



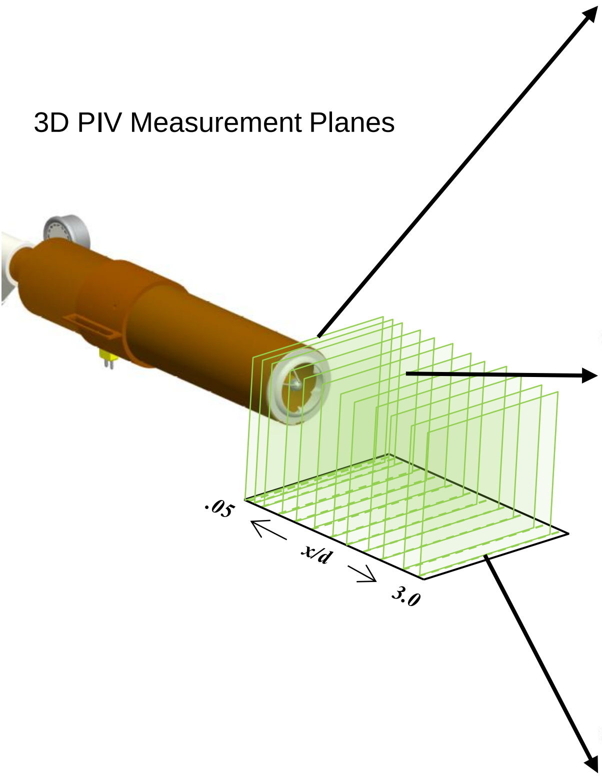
3 Component Instantaneous Velocity Field

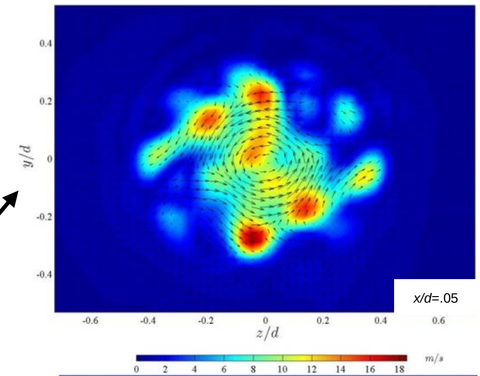


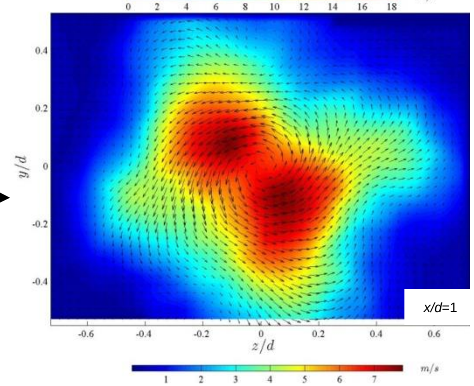
3D Stereoscopic PIV – Turbulator Exit Flow

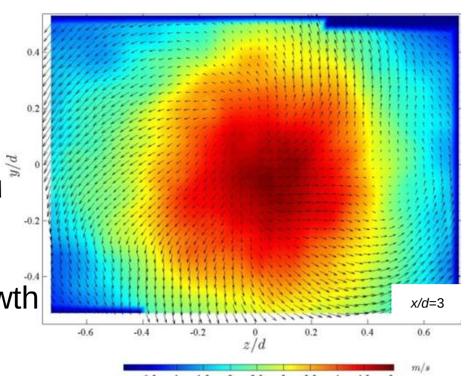
3 Component Mean Velocity Fields

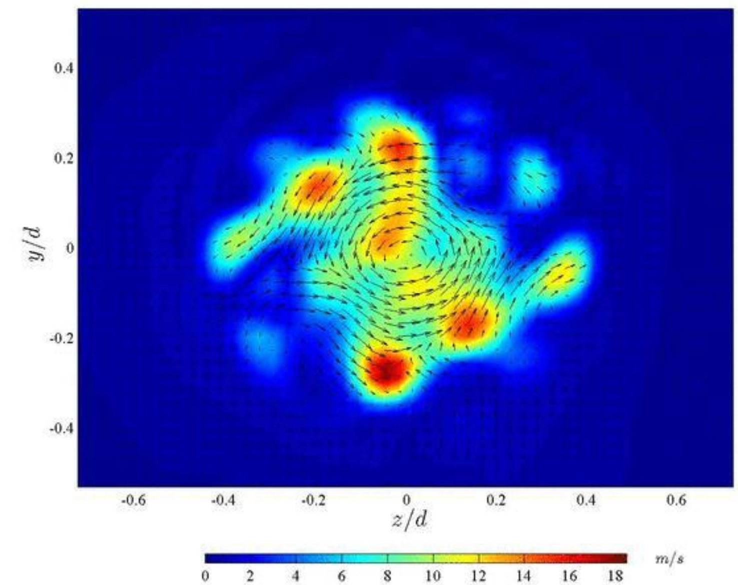
3D PIV Measurement Planes



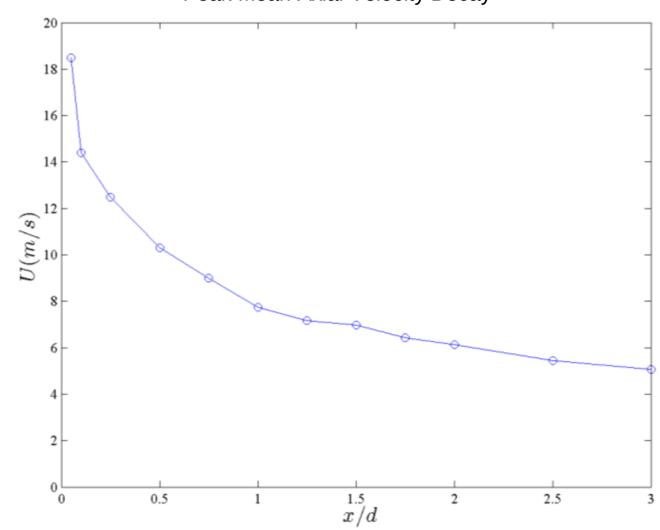








Peak Mean Axial Velocity Decay

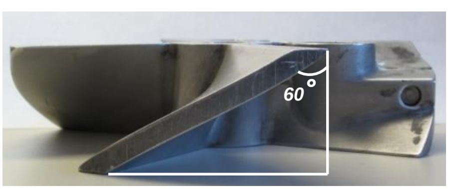


- Evolution of swirling flow is visualized
- Swirl-induced mixing increases jet growth
- Axial velocity decays downstream

Swirl Number

- Swirl number defined as the ratio of axial flux of the tangential momentum to the axial flux of axial momentum times the nozzle radius
- For axial vane swirlers, the swirl number is proportional to the vane angle ϕ
- The stator has a vane angle of approximately 60°, resulting in an estimated swirl number of 1.15
- Flows with S<0.4 considered low swirl, S>0.6 high swirl with reverse flow
- Stator has high swirl on its own, turbulator is seen to reduce swirl and eliminate reverse flow

$$S = \frac{\int_0^R U\,W\,r^2\,dr}{R\int_0^R U^2 r\,dr} \cong \frac{2}{3}\tan\phi^{*}$$

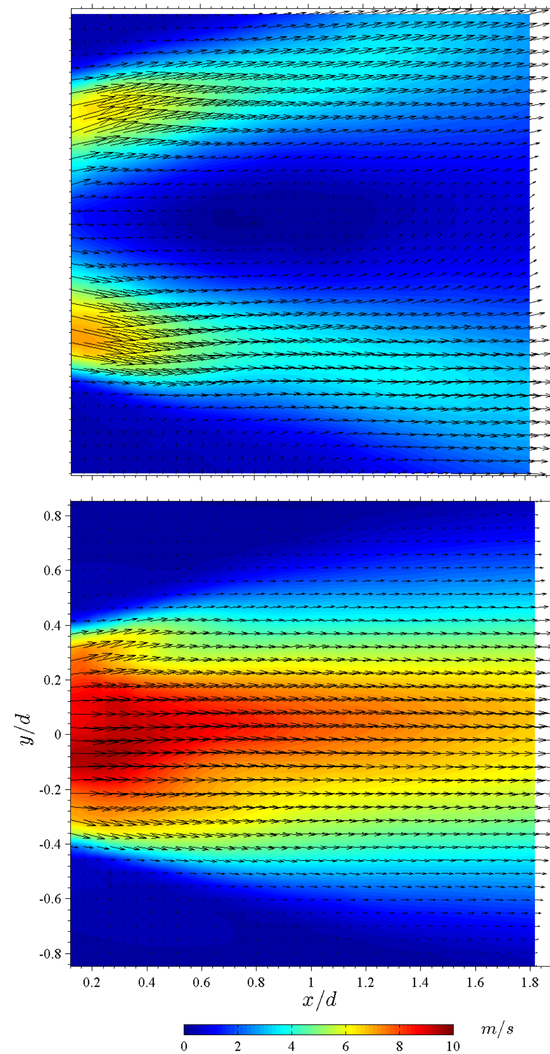


Stator vane angle – side view

Mean In-Plane Velocity Fields

Stator Only

Stator and Turbulator



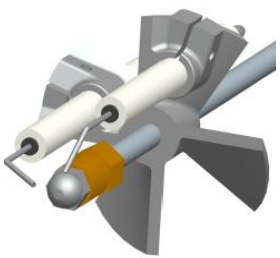
*So et al. 1985 *Jet Characteristics in Confined Swirling Flows*

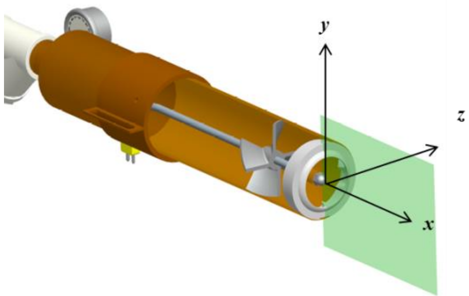
Burner Airflow- Summary

- The flow exiting the empty draft tube is non-symmetric, due to slight misalignment of the burner air inlet
- Insertion of a 90° elbow upstream of the burner provides a similar velocity profile to that of a straight air entry
- The fuel pipe is found to influence the air flow due to the dogleg bend near the burner inlet
- The stator was found to provide a flow field typical of a swirling jet with low and reverse flow on the burner axis. The velocity and degree of jet growth was found to be dependent upon the axial location of the stator
- The turbulator was found to increase exit velocity due to the area contraction and reduce the swirling effects created by the stator, reducing the growth of the swirling jet and creating a more uniform flow
- Stereoscopic measurements of the unconfined swirling flow show the evolution of the flow exiting the burner, eventually forming a round jet shape on the burner axis at 3 diameters downstream

2D PIV Symmetric Stator

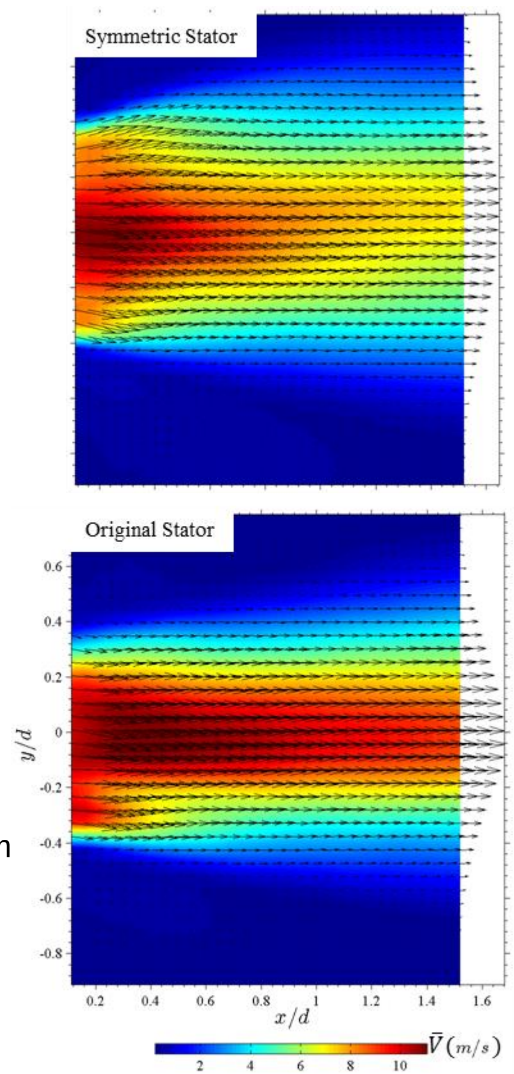
Original Stator Symmetric Stator



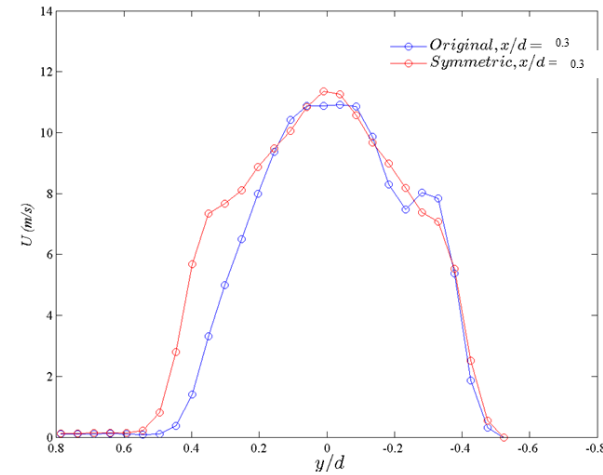


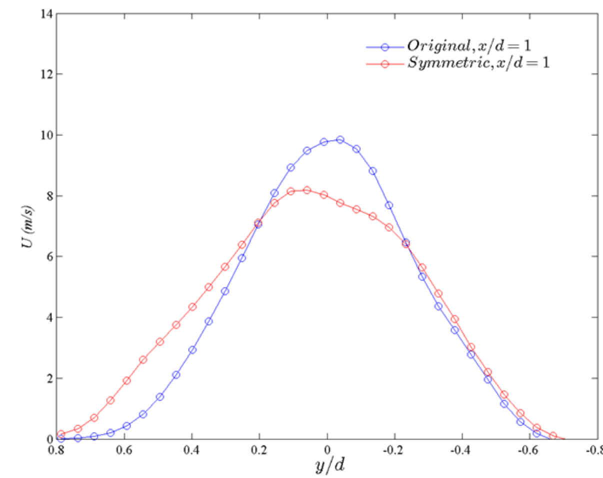
- Symmetric stator provides more uniform velocity distribution

Mean In-Plane Velocity



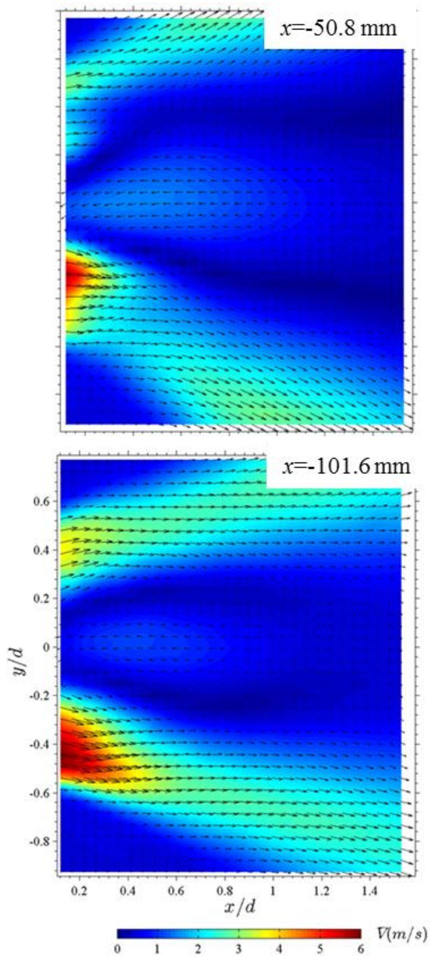
Axial Velocity Profiles



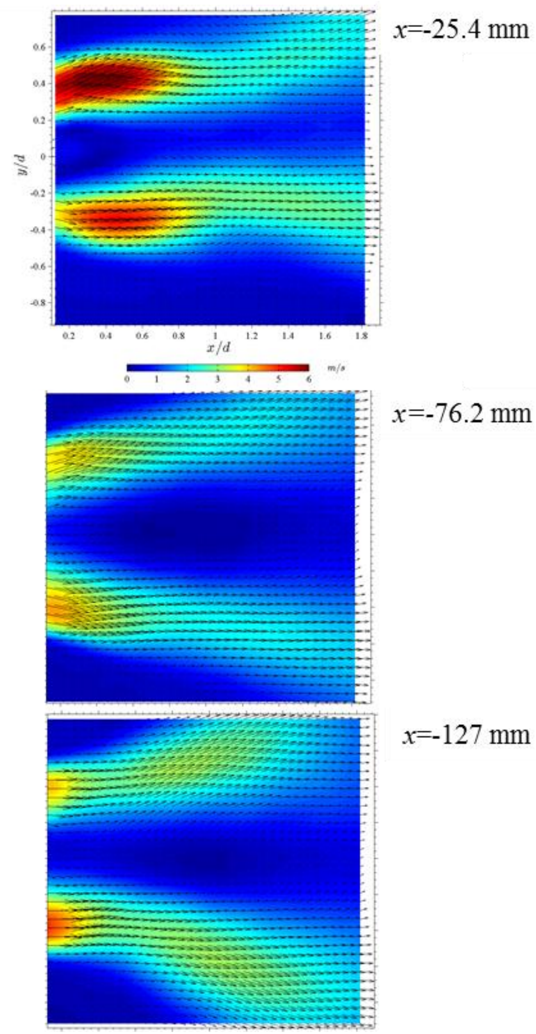


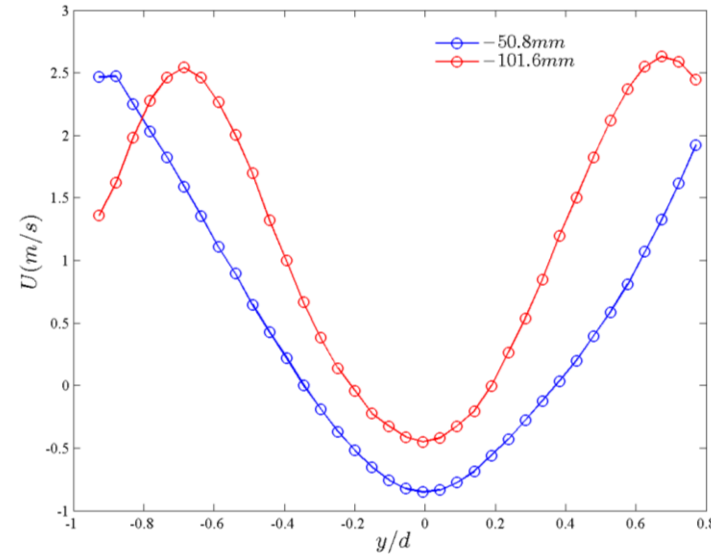
2D PIV Symmetric Stator

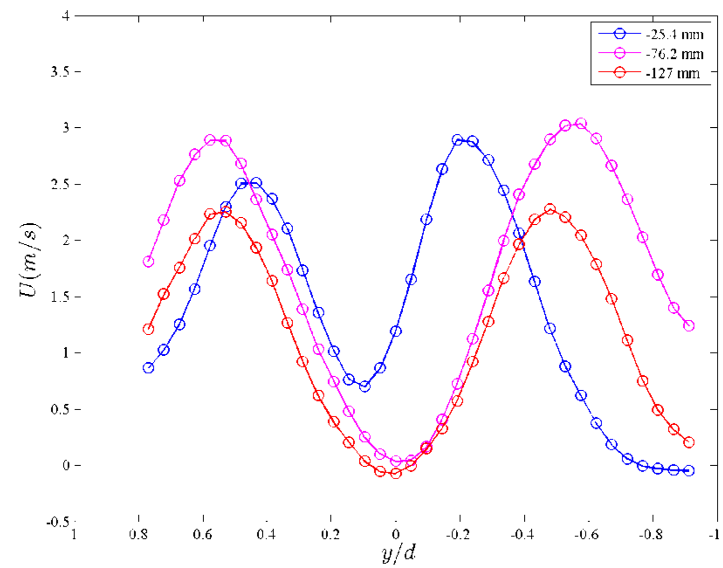
Symmetric Stator



Original Stator



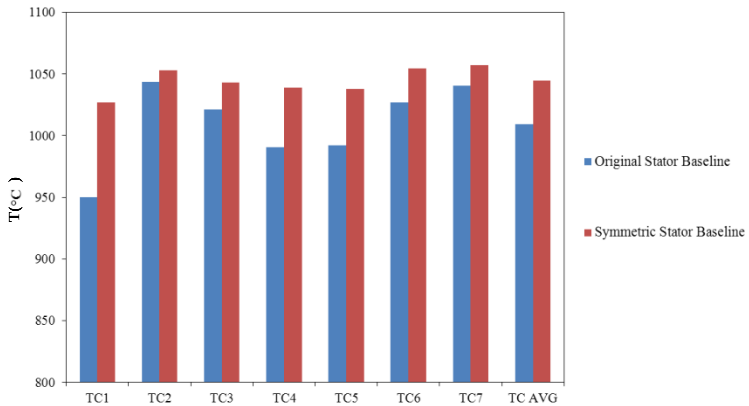




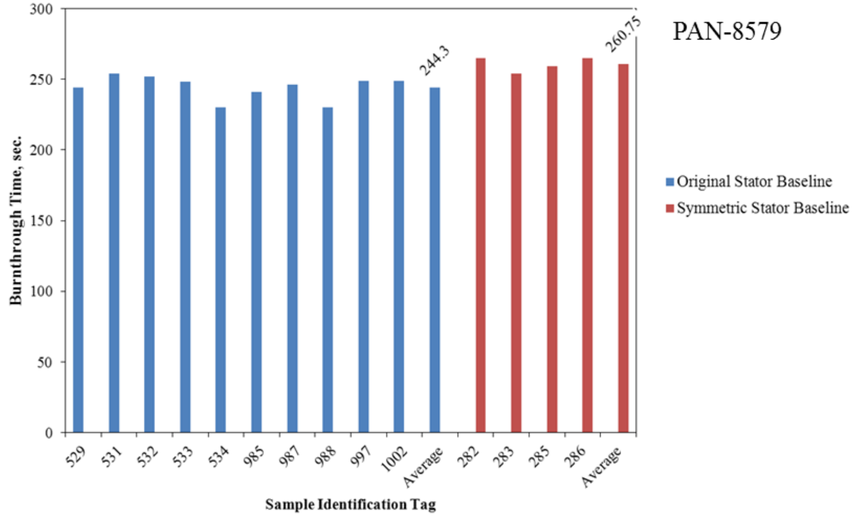
- Symmetric stator provides greater jet growth, reverse flow

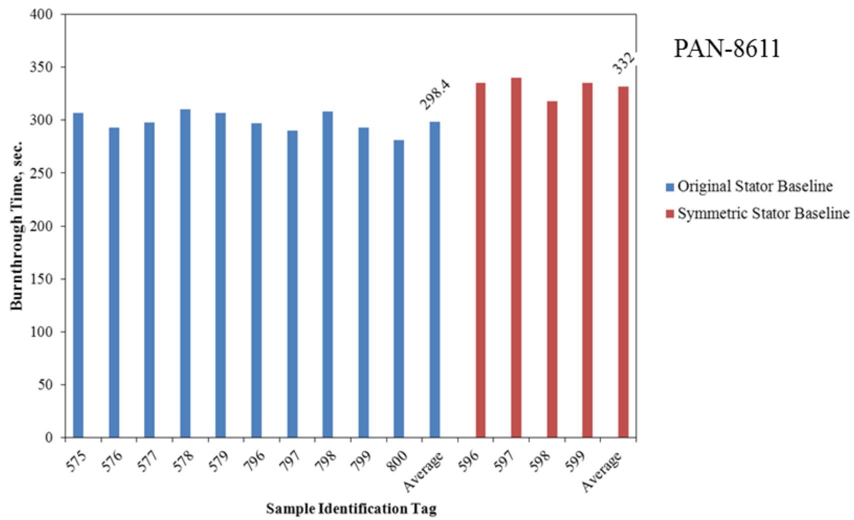
Symmetric Stator Baseline Performance

Measured Flame Temperature



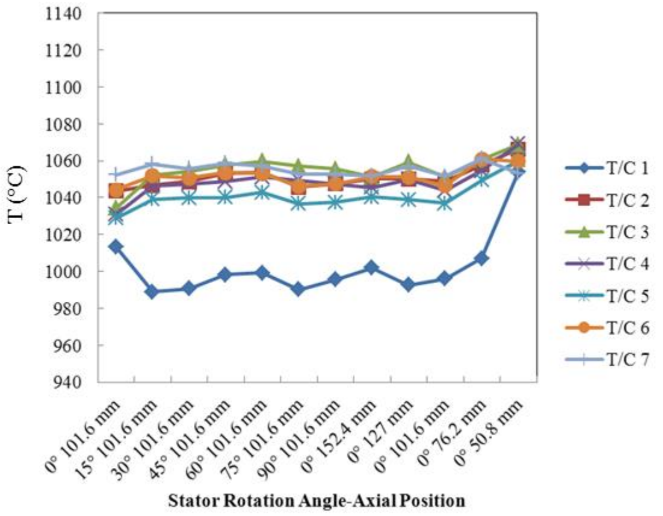
Material Burnthrough Time

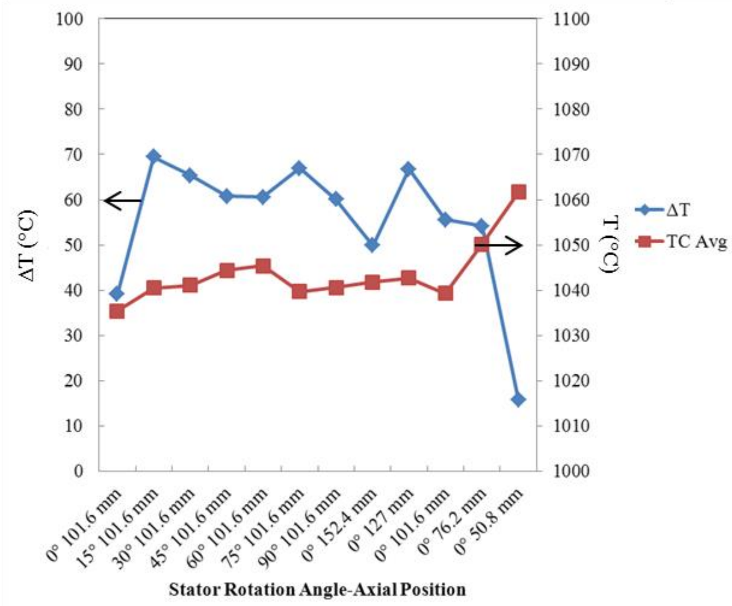


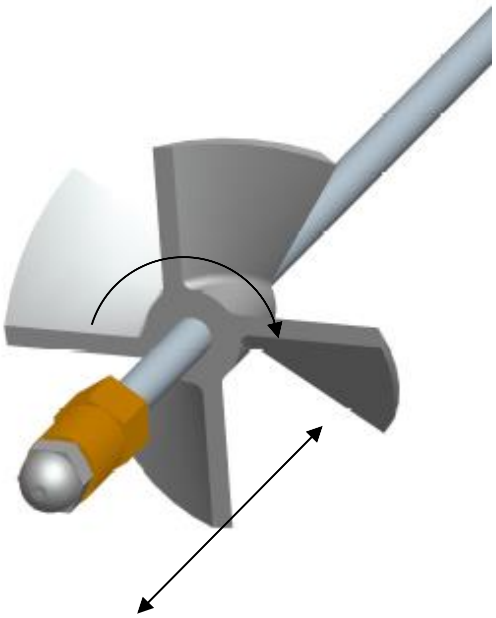


- Both stators tested at identical air, fuel flow rate
- Higher flame temperature found with symmetric stator
- Longer burnthrough times found with symmetric stator

Symmetric Stator Position Refinement



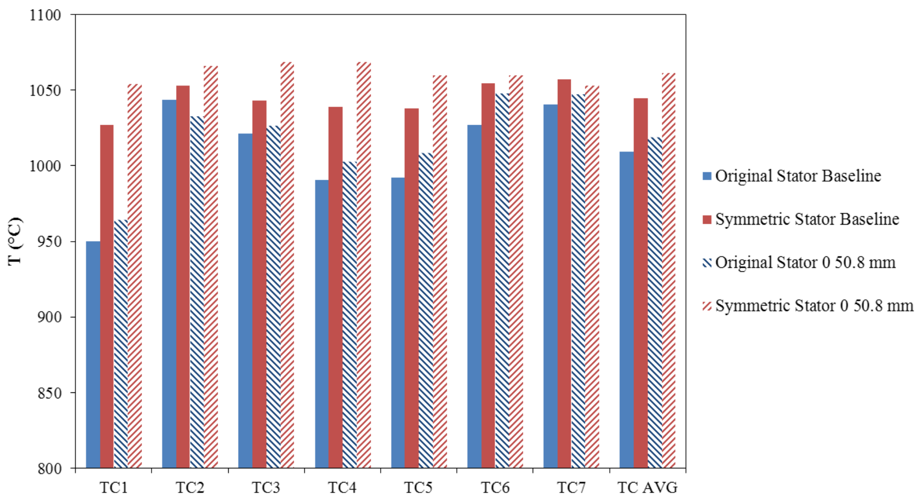




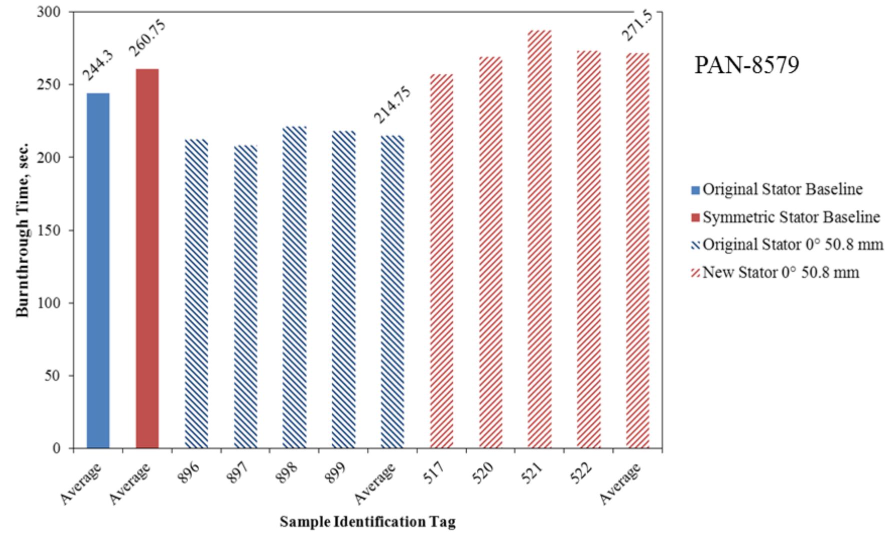
- A series of rotations and translations were attempted to find a position yielding highest and most uniform flame temperature

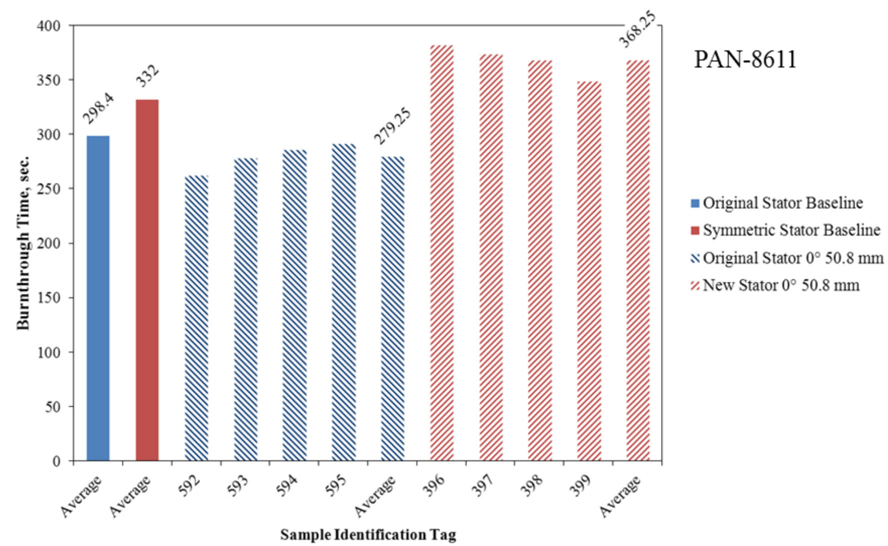
Symmetric Stator 0° 50.8 mm Performance

Measured Flame Temperature



Material Burnthrough Time

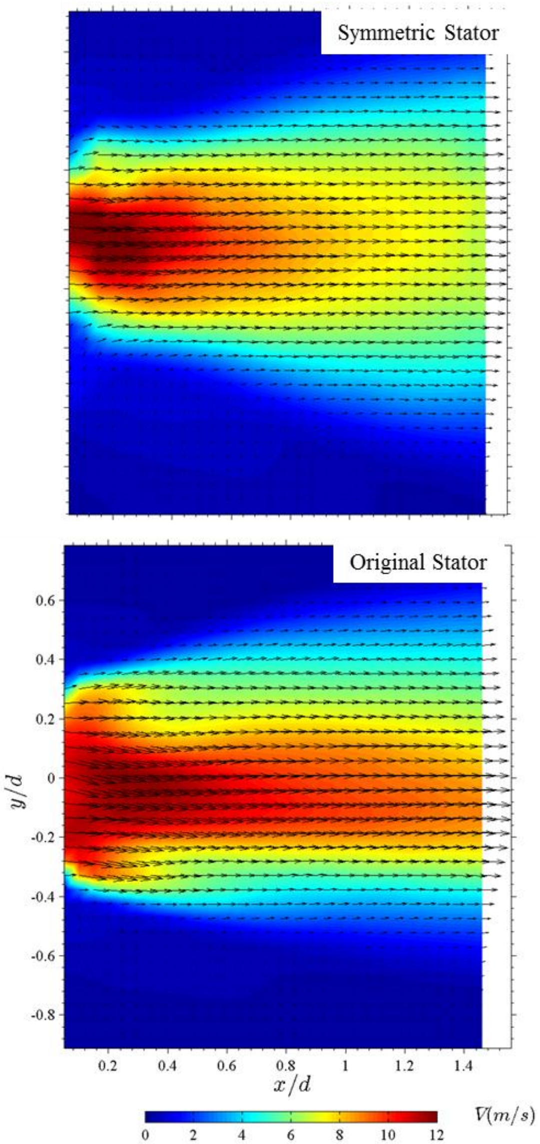




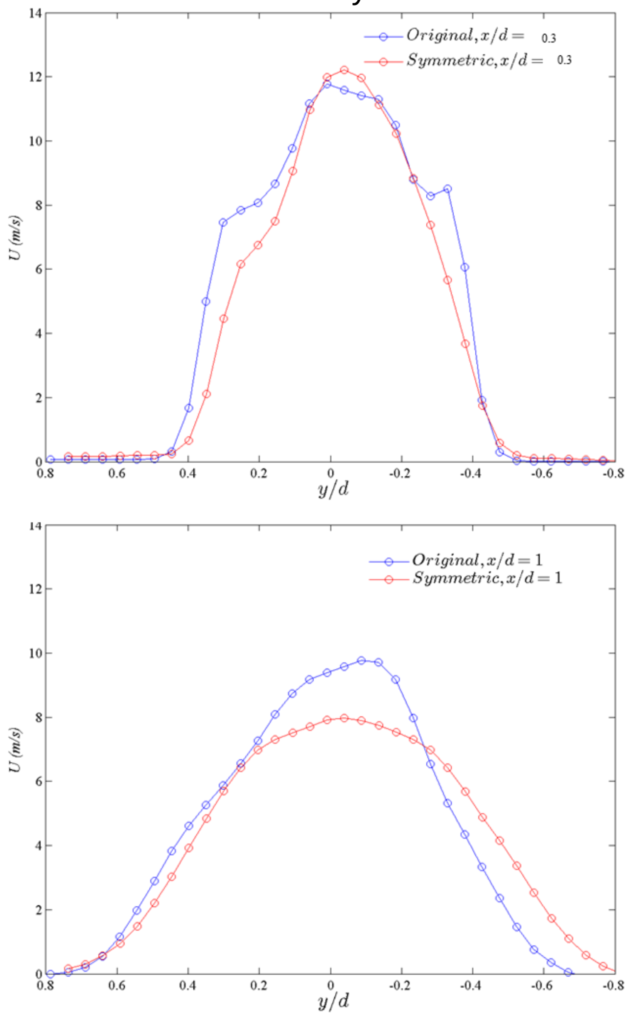
- Highest flame temperature found with symmetric stator at this position
- Longest burnthrough times found with symmetric stator at this position

2D PIV at 0° 50.8 mm

Mean In-Plane Velocity



Axial Velocity Profiles

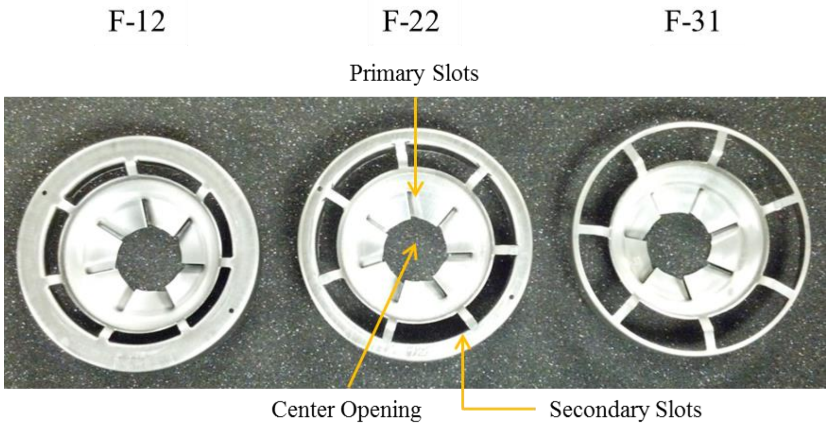


- Symmetric stator found to consistently provide more spread out velocity profile

Symmetric Stator - Summary

- Increased growth of the swirling jet and lower peak axial velocity.
- More symmetric and uniform temperatures and an overall higher average flame temperature.
- Longer burnthrough times for the symmetric stator than the original stator.
- Highest overall flame temperature and most uniform temperature profile was found at 0° 50.8 millimeters, but longest BT time

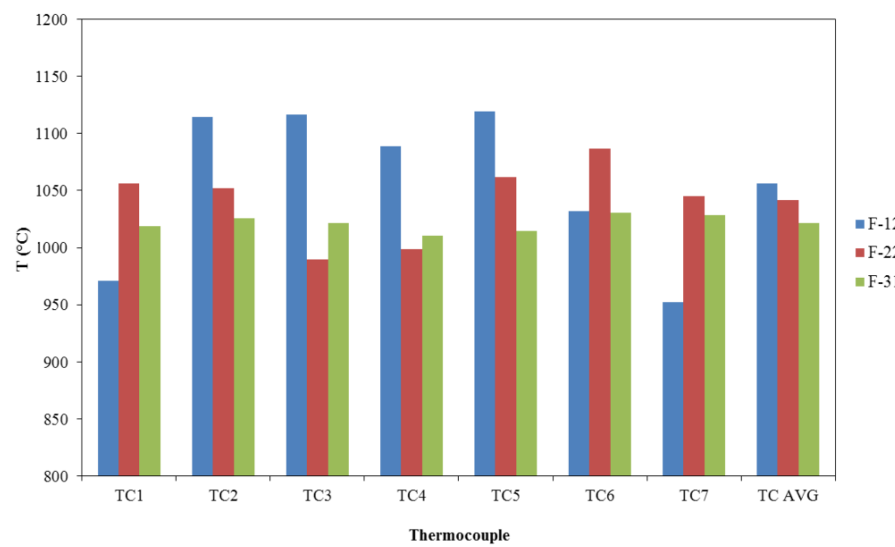
Flame Retention Heads (FRH)



	Units	F12	F22	F31	Turbulator
Center Hole Area	mm^2	660.52	660.52	660.52	3739.28
Primary Slots Area	mm^2	260.17	260.17	260.17	
Secondary Slots Area	mm^2	903.85	1697.61	3206.29	
Total Area	mm^2	1824.54	2618.30	4126.98	3739.28

Turbulator

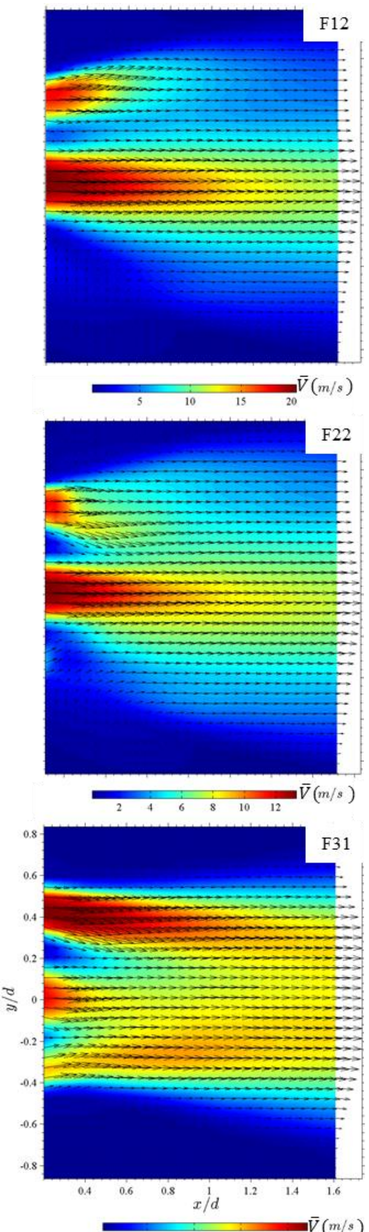
Measured Flame Temperatures



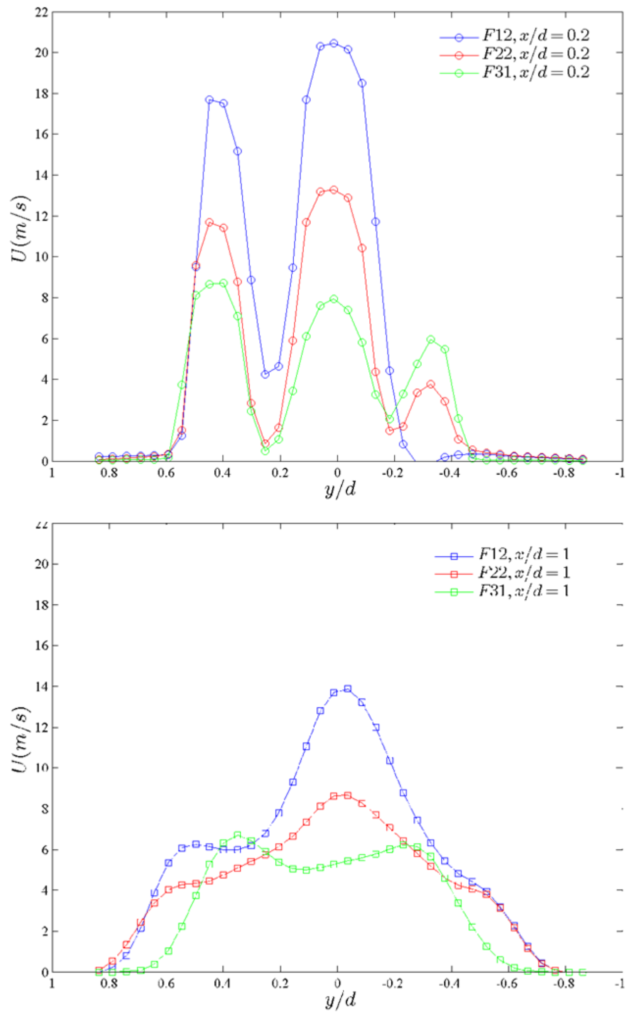
- Flame retention heads used on modern oil burners
- Combination of swirl-creating primary slots and swirl-confining secondary slots
- One-component replacement of 2 components (stator & turbulator)
- Minimal specification for set up compared to stator, turbulator

2D PIV FRH Flow Field & Burnthrough

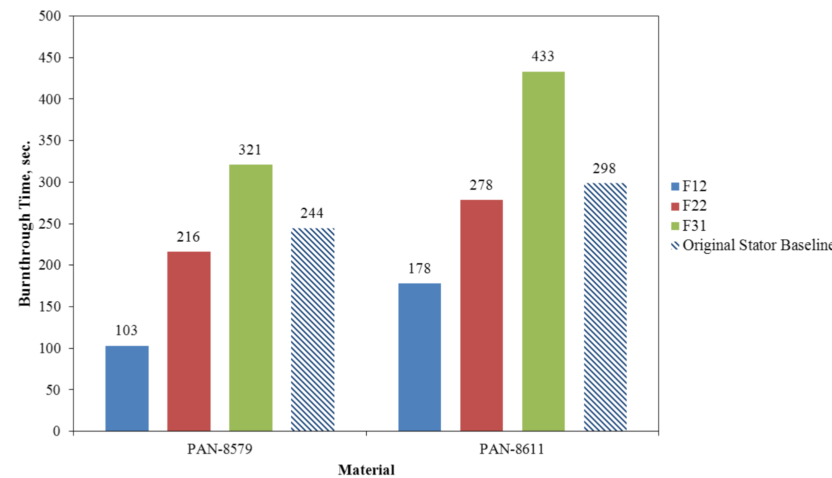
Mean In-Plane Velocity



Axial Velocity Profiles



Material Burnthrough Times

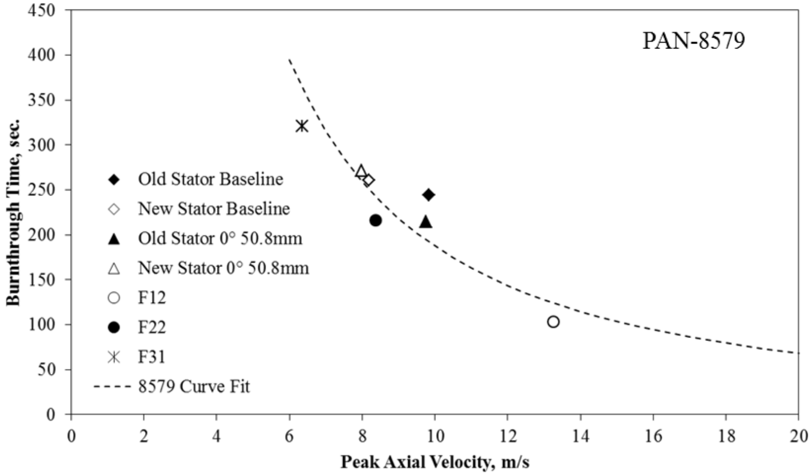


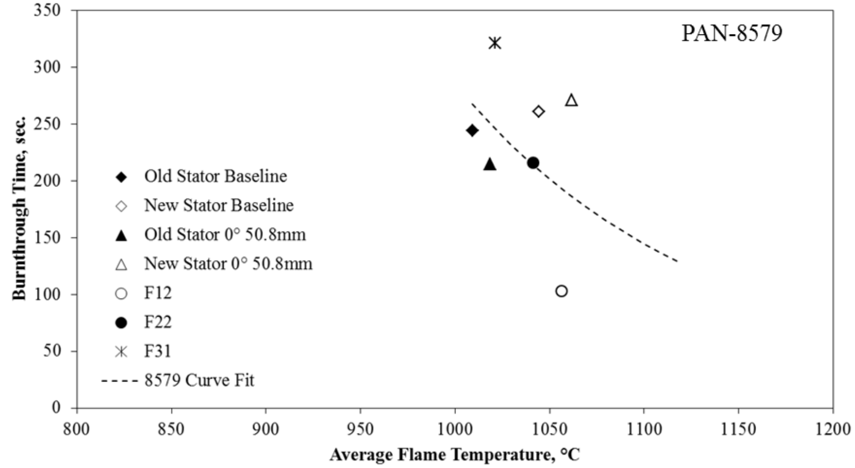
- FRHs provide a wide range of velocity distributions
- The size of the secondary openings dictate magnitude of peak velocity
- A wide range of material BT times were obtained from the FRHs

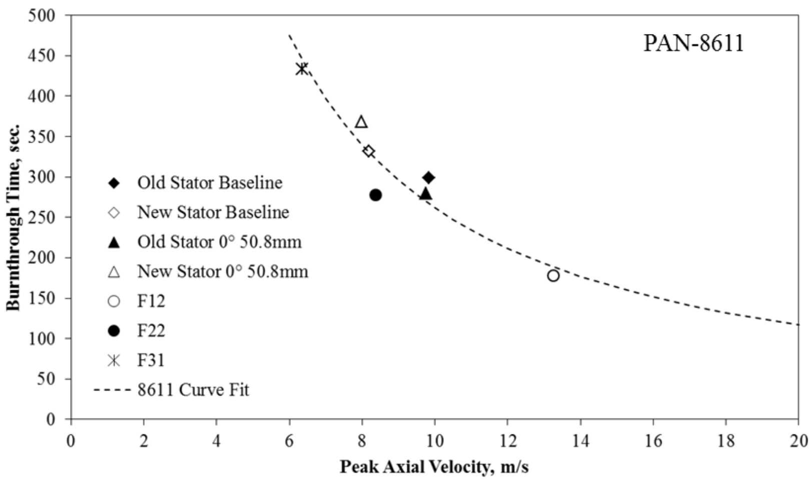
Correlation of BT Time w/ Velocity, T_{avg}

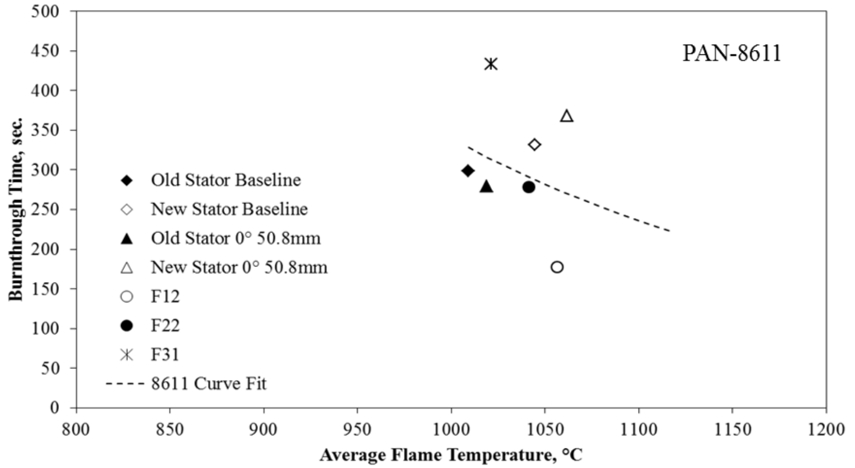
BT Time vs. Peak Axial Velocity @ *x/d*=1

BT Time vs. T_{avg}









Flame Retention Heads - Summary

- Higher temperatures for the FRH vs. the stator-turbulator combination
- F12 yielded the fastest burnthrough time while the F31 yielded the longest, with the F22 being most comparable to the NexGen burner baseline.
- Similarly shaped axial velocity profiles at the draft tube exit, though significant variation in magnitude.
- A correlation between peak axial velocity at x/d=1 and material burnthrough time was made for original stator, symmetric stator, and FRH
- Average flame temperature did not correlate as well with material burnthrough time, indicating that

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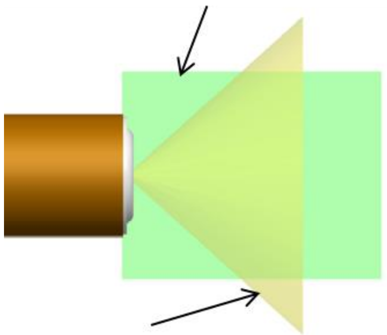
2D PIV Fuel Spray Measurement – Nozzle M

Laser Sheet – Measuring Plane

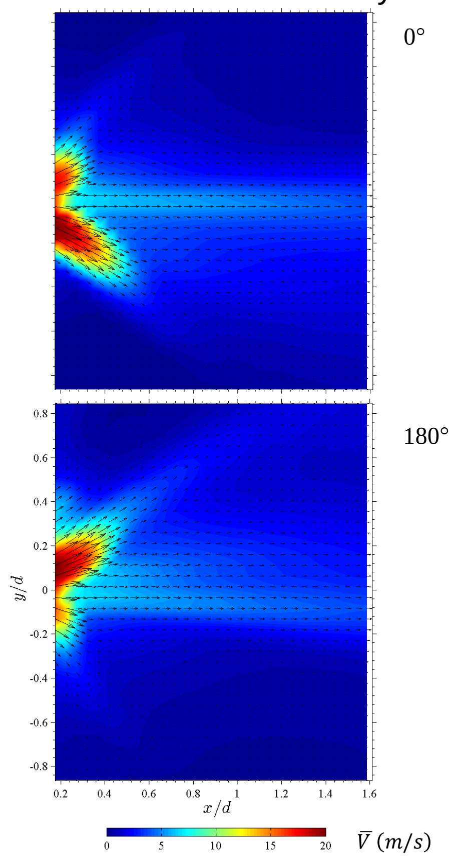


Spray Cone

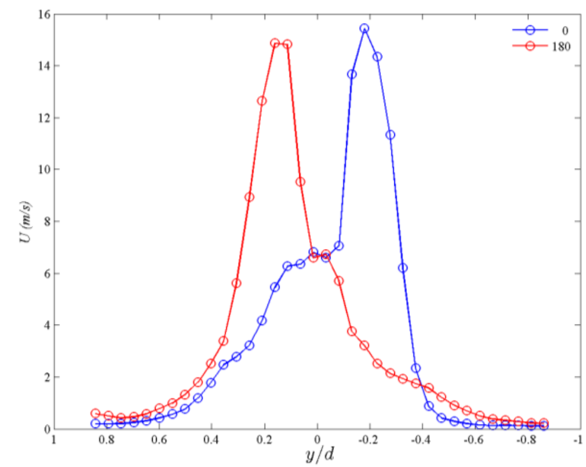
Nozzle Rotation

Nozzle M

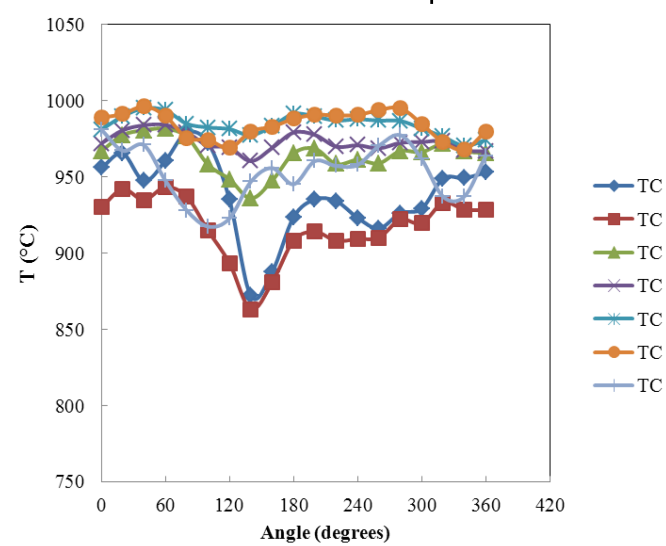
Mean In-Plane Velocity



Axial Velocity Profiles



Measured Flame Temperatures

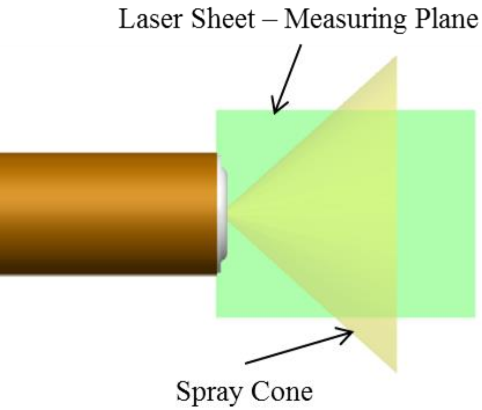


- Measurements were spray only – no airflow
- Nozzle spray pattern is highly asymmetric
- Nozzle spray pattern affects measured flame temperature

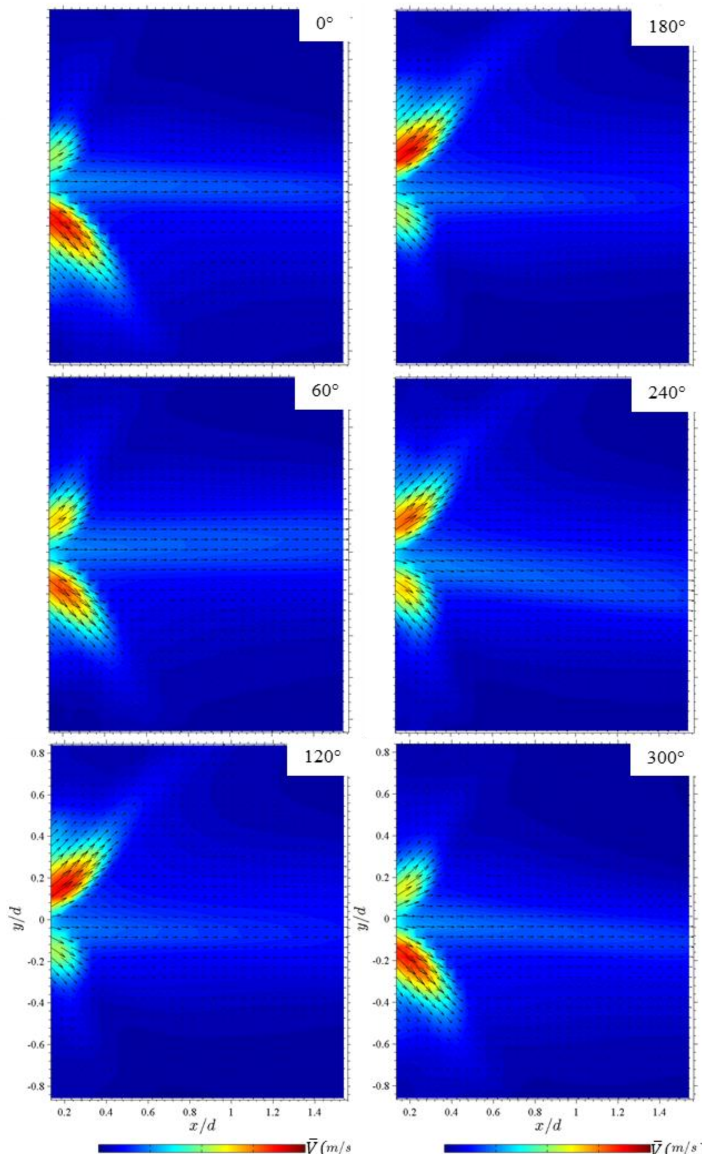
Spray Nozzle - Summary

- In-plane 2D PIV measurements of nozzle M indicate a strongly asymmetric hollow velocity field
- Rotation of the nozzle 180° results in a near mirror-image of the velocity profile, revealing circumferential asymmetry of the nozzle
- Flame temperature measurements of nozzle M rotated over 360° in increments of 20° indicate that the flame temperature profile is dependent upon the alignment of the high and low velocity regions of the spray cone. A single measurement location had a maximum variation of 11% over the range of rotation.

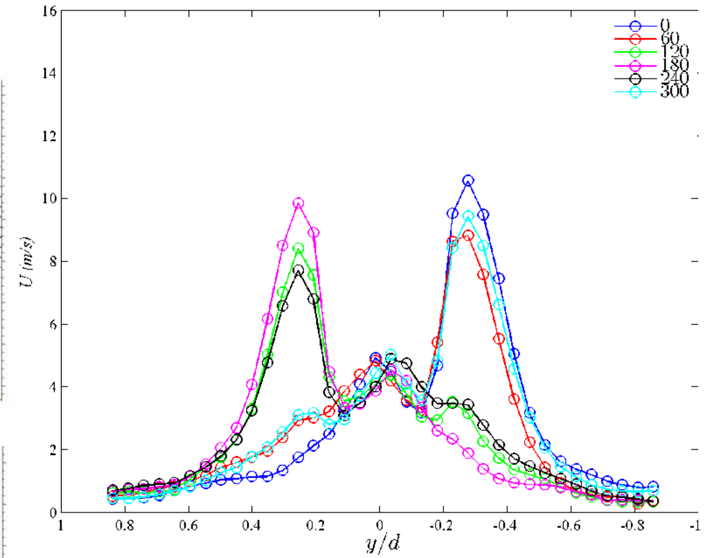
2D PIV Nozzle D



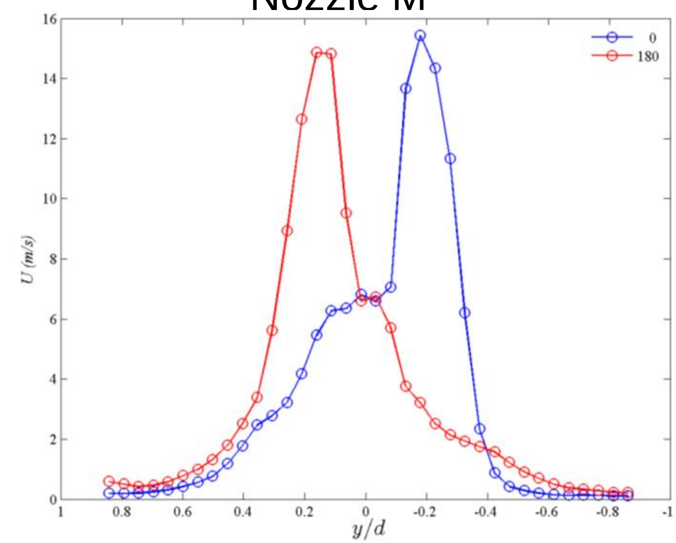
Mean In-Plane Velocity



Nozzle D



Nozzle M

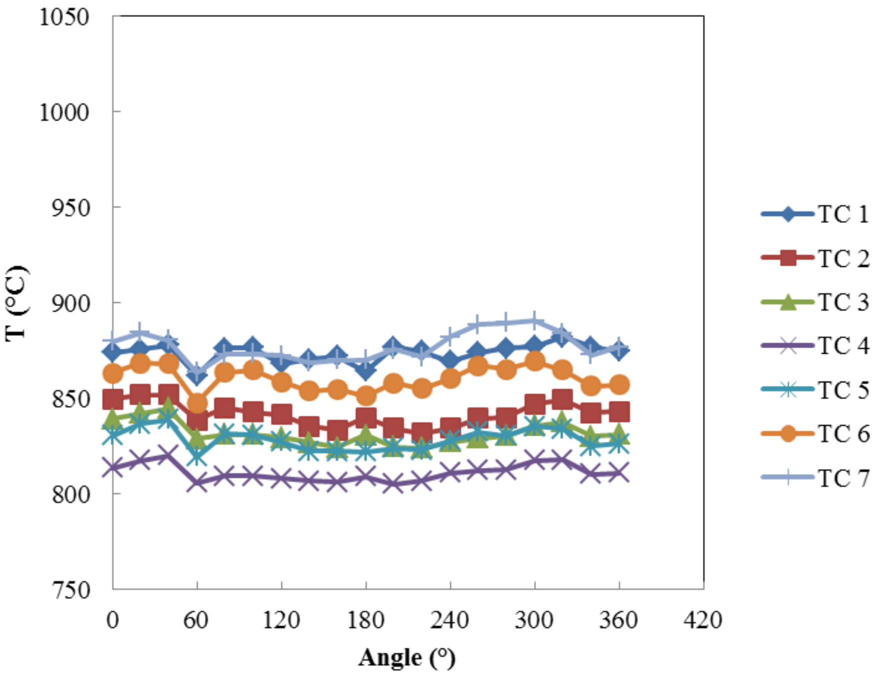


- Nozzle D also asymmetric
- Lower velocity magnitude
- Wider spray angle

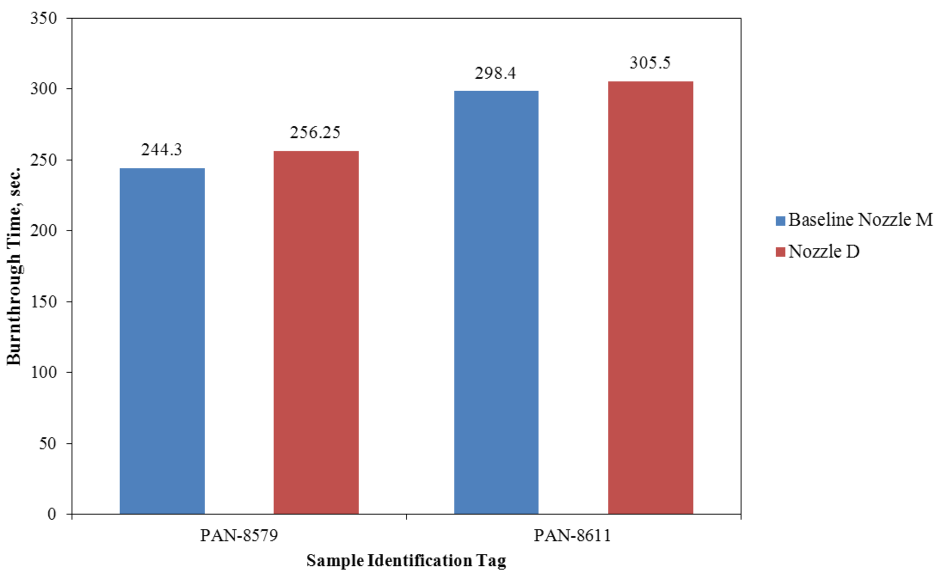
Nozzle D

Nozzle D – Burner Performance

Measured Flame Temperature



Material Burnthrough Time



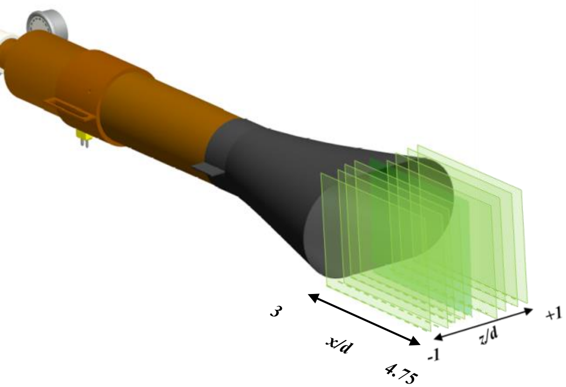
- Flame temperatures less sensitive to spray asymmetry
- Material burnthrough times similar to Nozzle M

Nozzle D - Summary

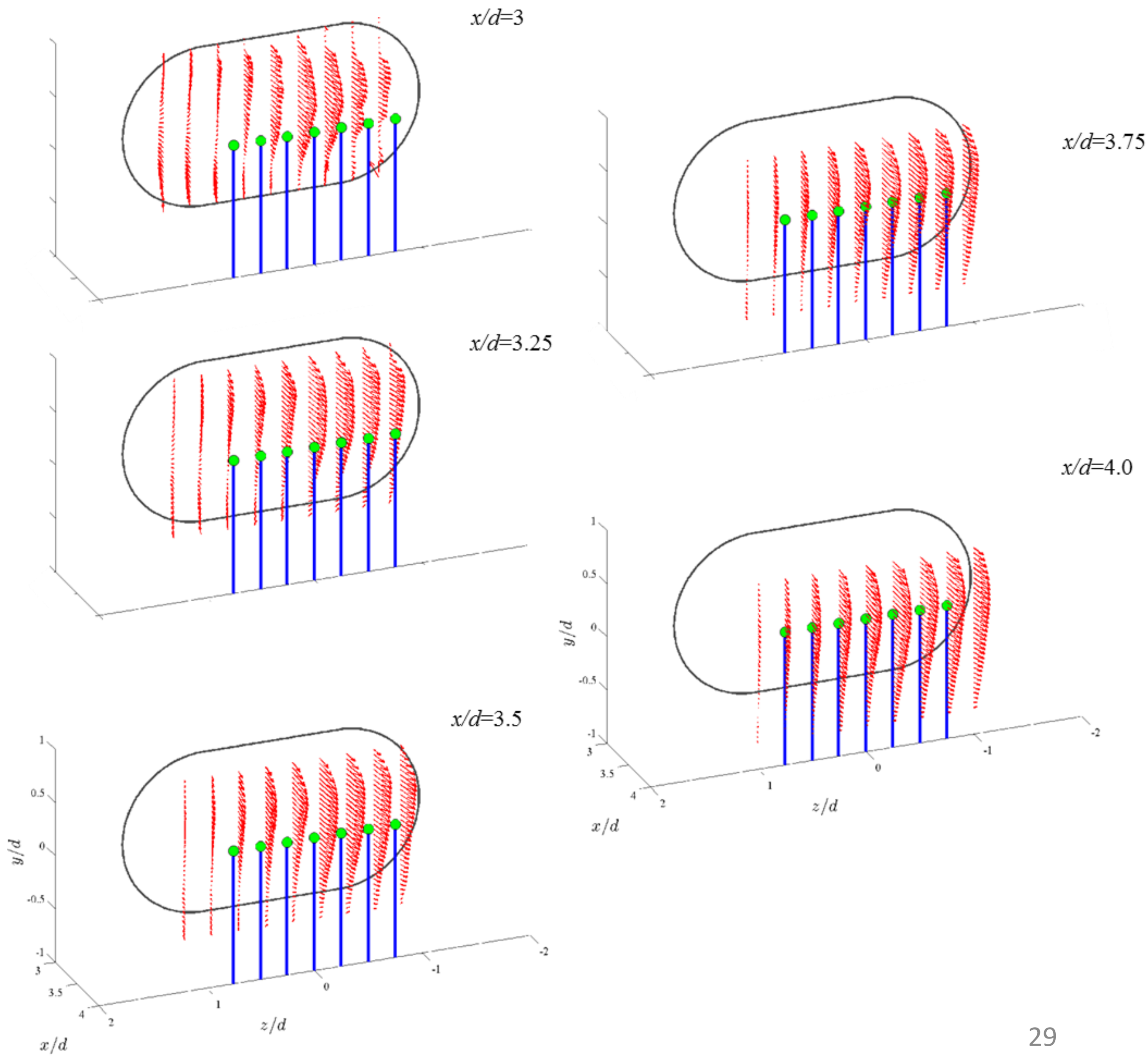
- A series of 6 rotations of the nozzle reveal spray pattern asymmetry in each plane similar to the standard NexGen nozzle.
- Flame temperature measurements reveal less rotational sensitivity to spray asymmetry than the standard nozzle
- Material burnthrough testing indicates burnthrough times similar to the standard nozzle, indicating less dependence of material burnthrough on spray pattern when impinging upon a large, flat test sample.

2D PIV Cone Exit Flow Measurement

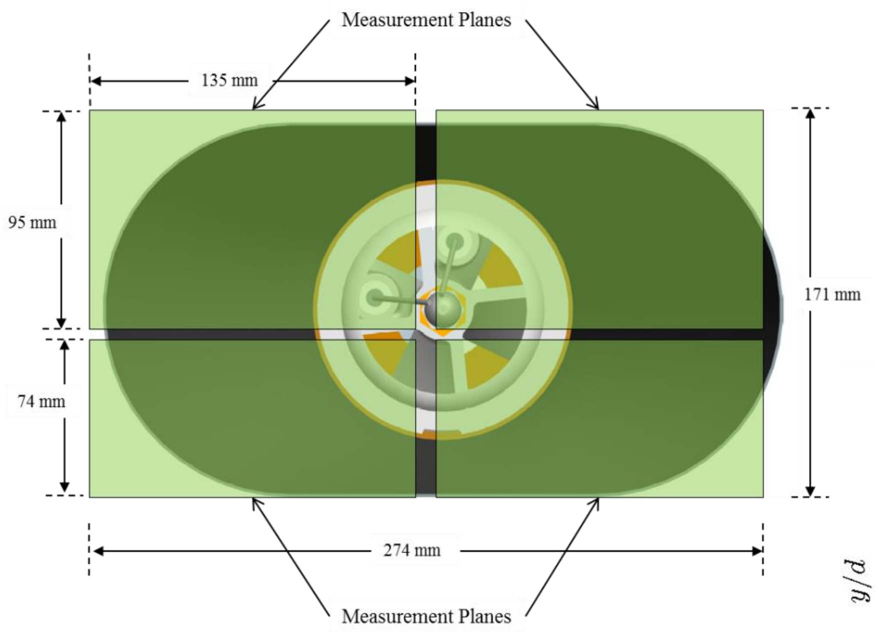
Cone Exit Flow Measurement Planes

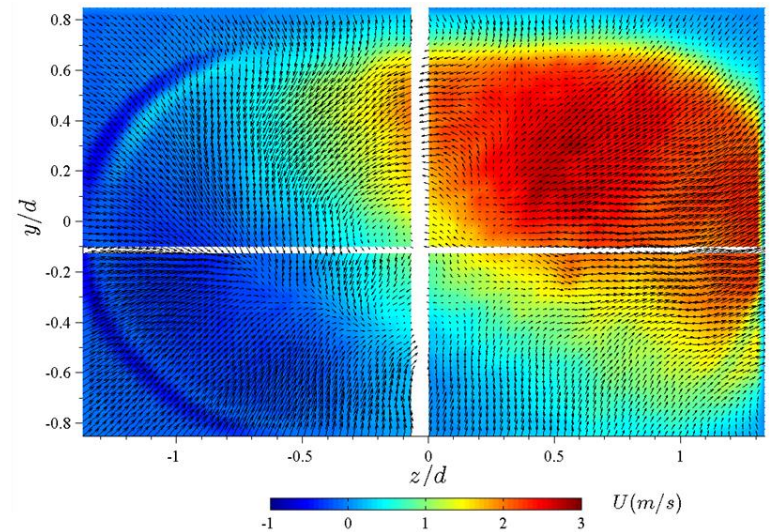


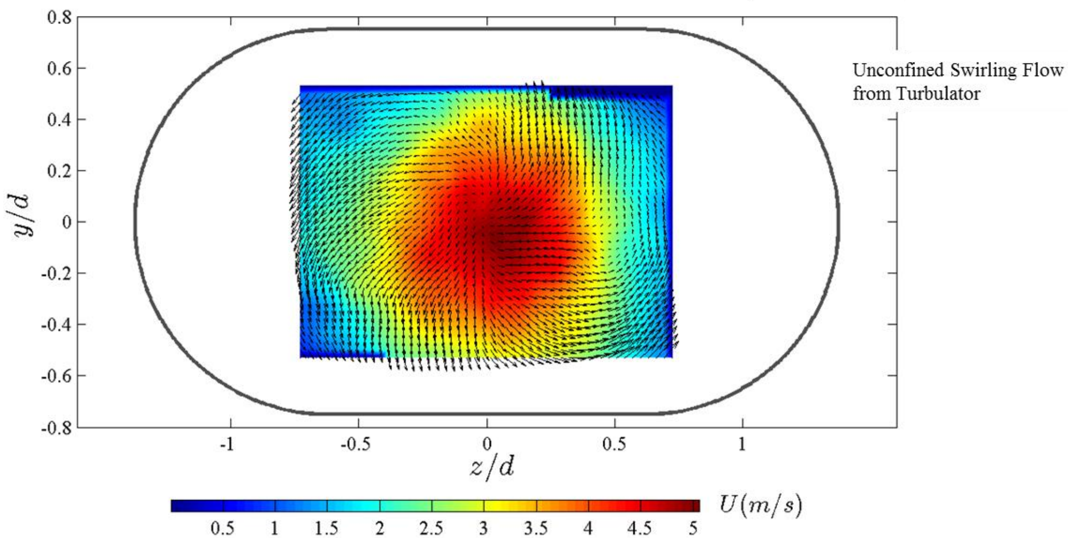
- Largely axial flow
- Highly irregular flow pattern
- Reverse flow near cone exit plane



3D PIV Cone Exit Flow Measurement

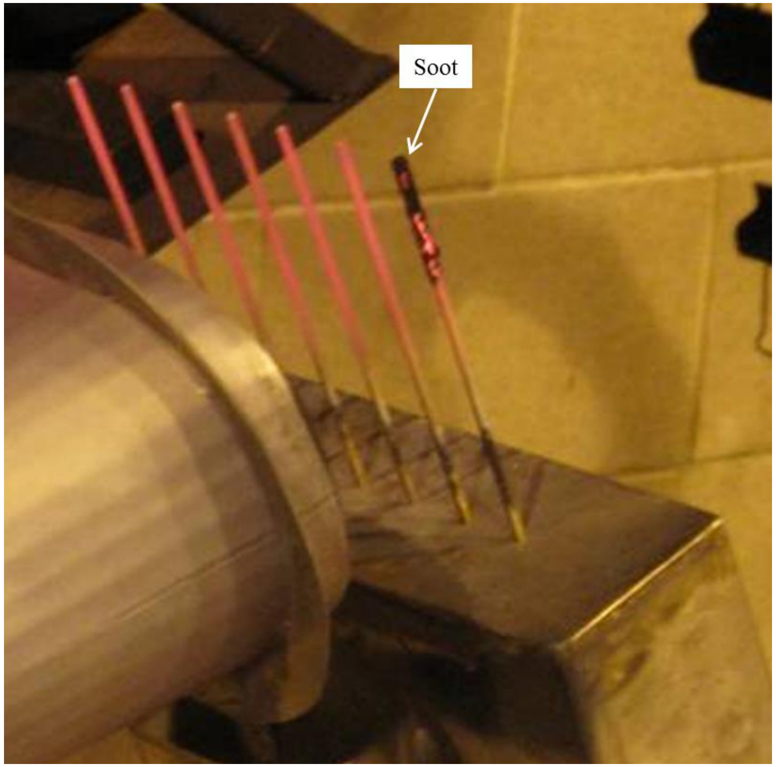


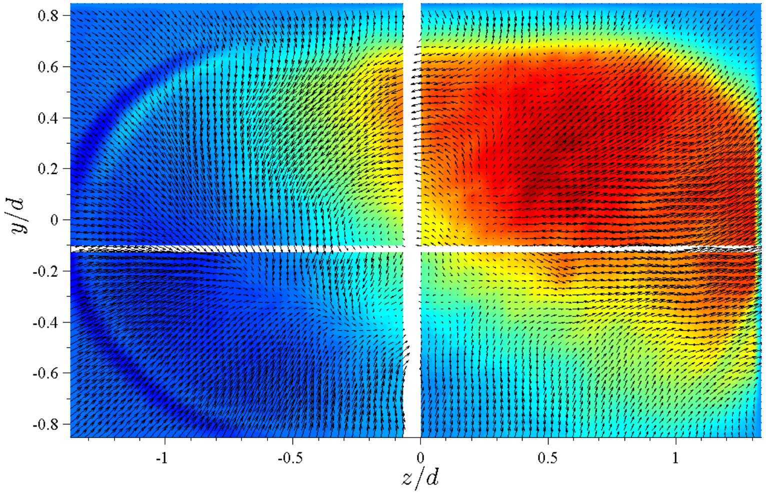


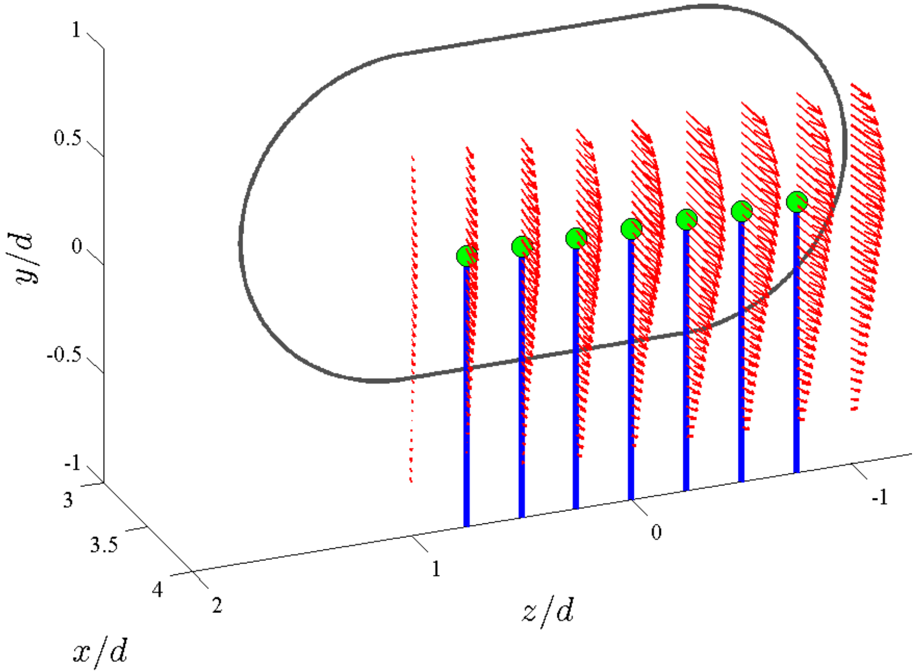


- Cone exit flow drastically altered by cone geometry

Effect of Cone Exit Flow on Soot Formation





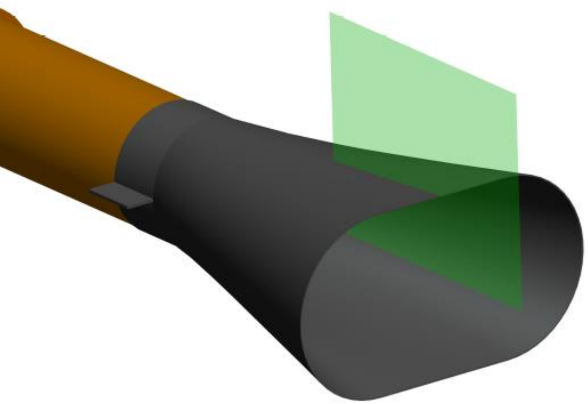


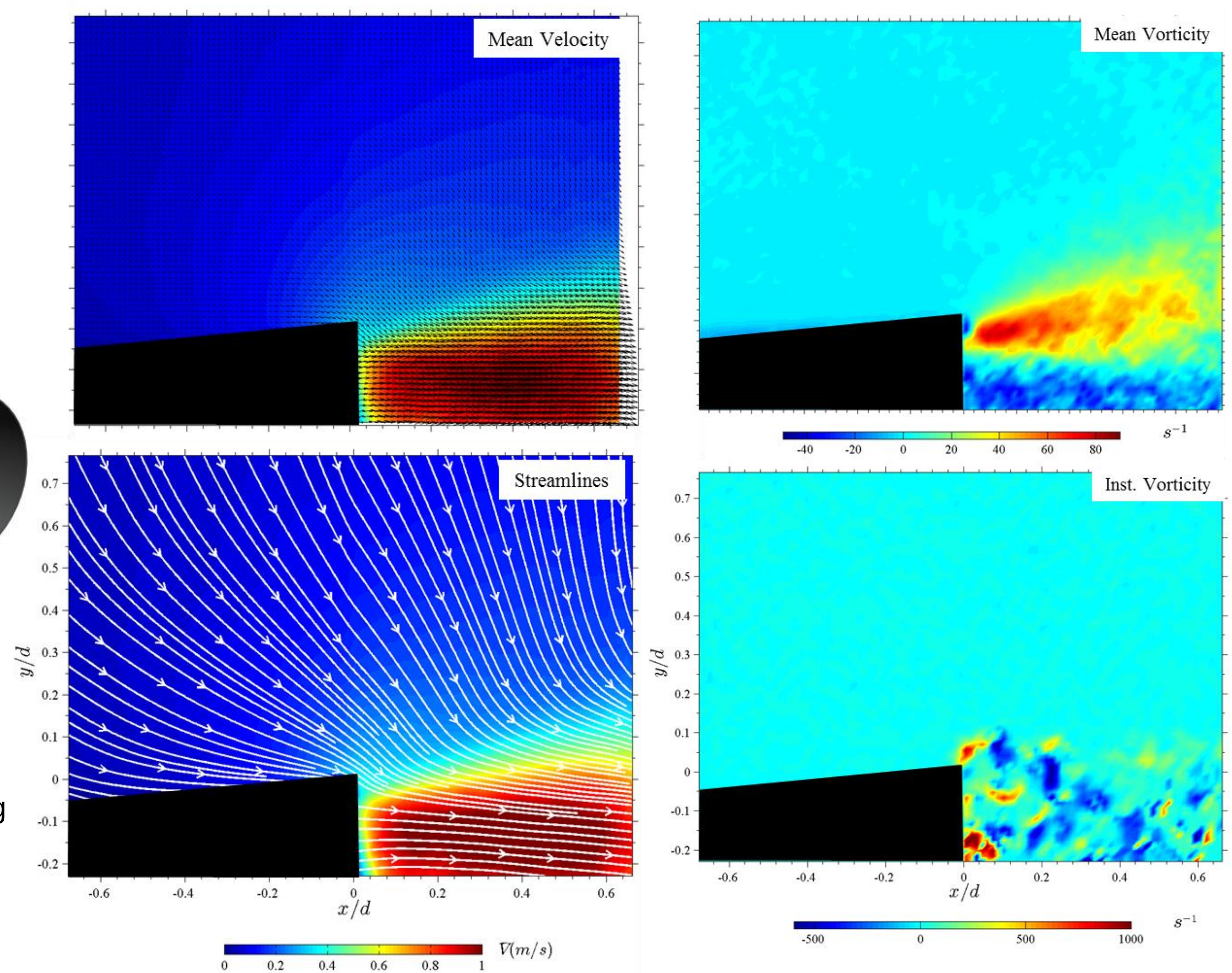
- Soot formation higher near TC1 due to
  - Low velocity – increased residence time
  - Increased fuel/air ratio due to low air flow

Cone Exit Flow - Summary

- Flow exiting the burner cone is irregular in both magnitude and direction across the entire exit plane and up to one draft tube diameter downstream.
- The low velocity region coincides with the measurement location for thermocouple #1. The combination of low air flow with high fuel flow can result in an overly fuel rich region near thermocouple #1 causing soot to form on the thermocouple sheath.
- The unconfined swirling airflow is altered significantly when confined with the burner cone as evidenced by the cone exit plane measurements.
- Previous studies on swirling flow in circular-to-round transition ducts have also found that the shape of the transition results in a skewed velocity distribution due to the flow impinging on the top and bottom surfaces of the duct.

2D PIV External Cone Flow



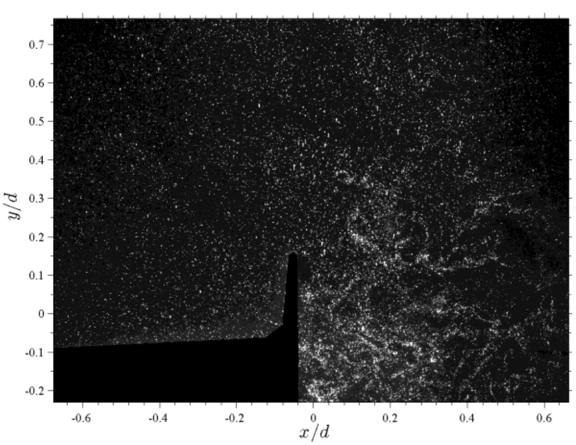


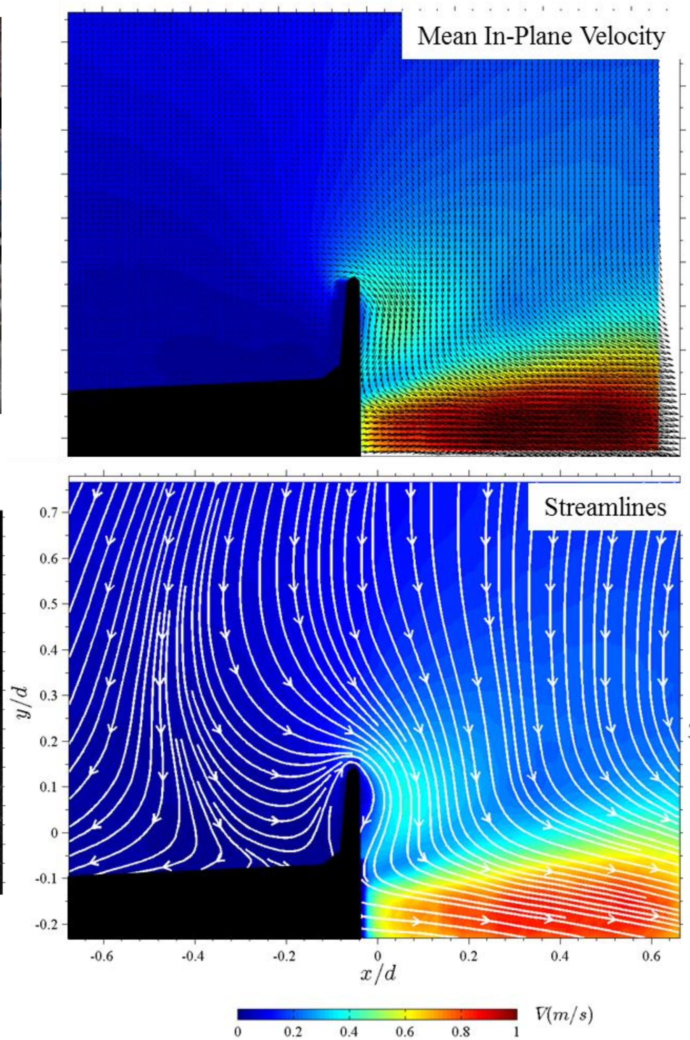
- Entrainment of surrounding air is evidenced by streamlines
- Vorticity plots show turbulent mixing

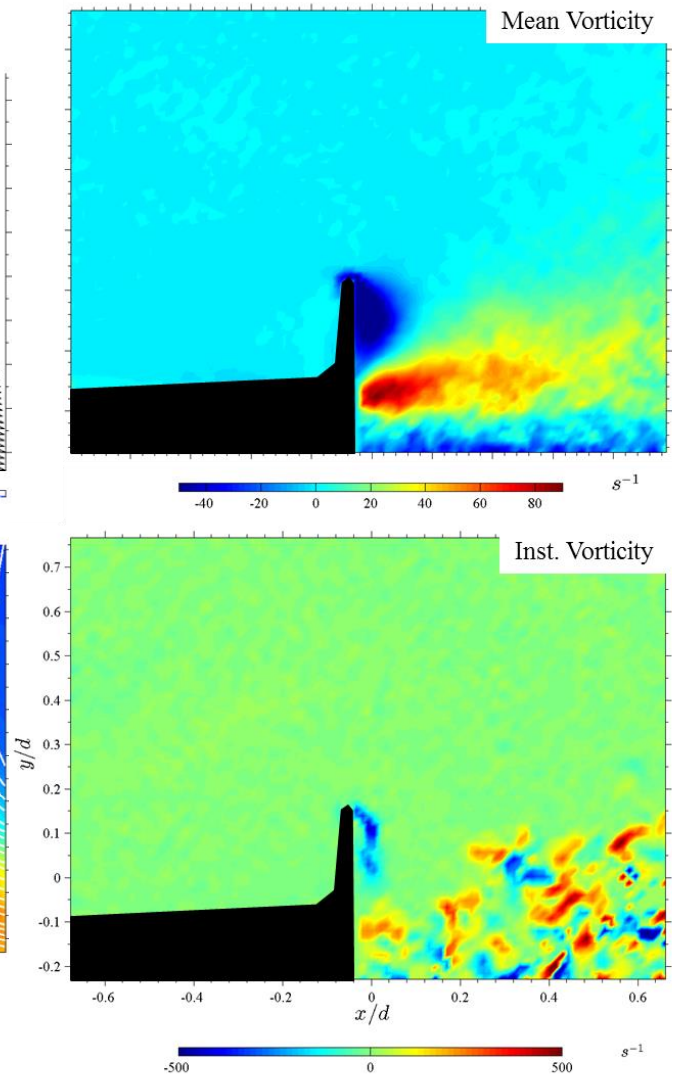
External Cone Flow - Summary

- The measurements made on the exterior of the cone indicate entrainment of the surrounding ambient air into the cone exit flow. Instantaneous and mean vorticity data show vortical structures exiting the burner cone indicating high turbulence
- The entrainment and mixing of surrounding air is evidenced by the counter-rotating structures and by the decay of the mean vorticity and growth of the cone exit flow field.

2D PIV – Reinforced Cone







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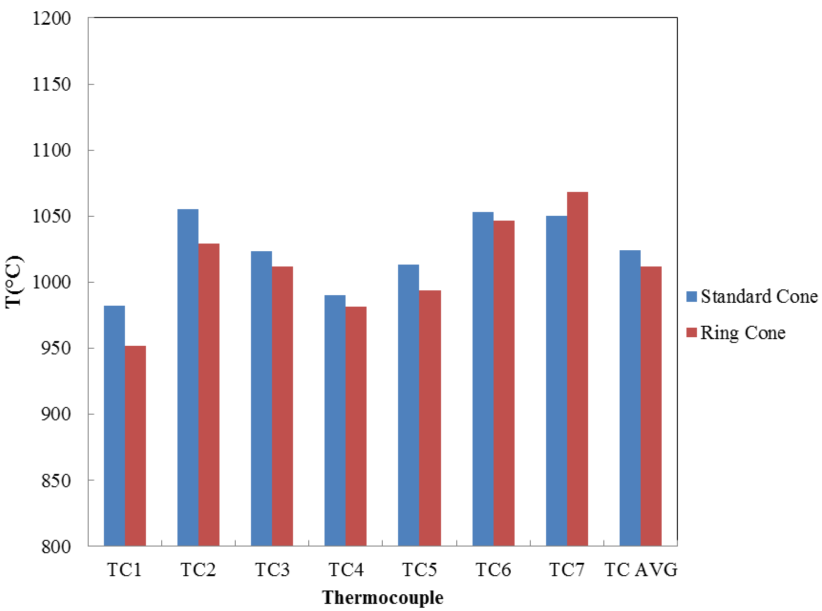
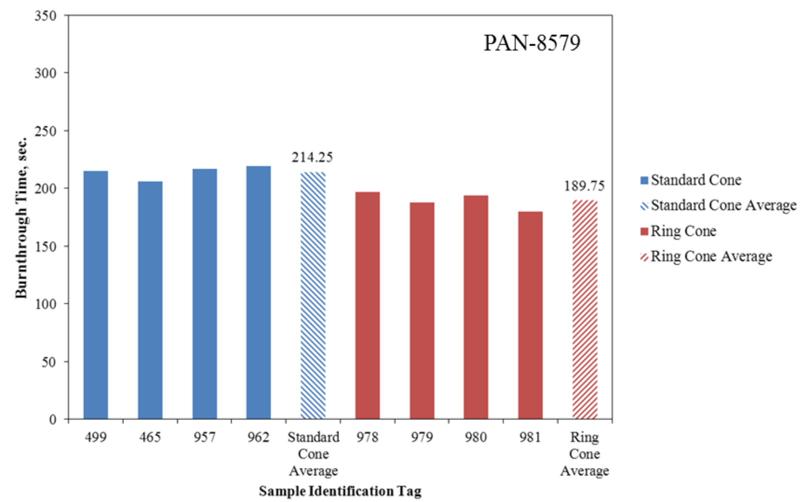
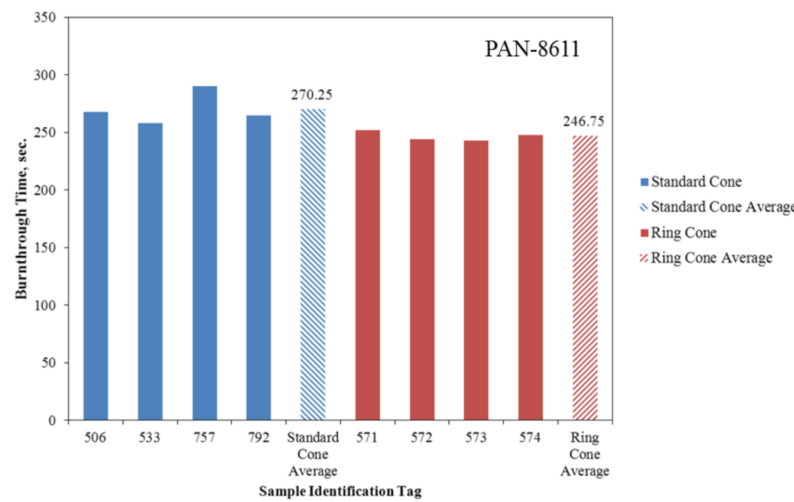
Reinforced Cone – Burner Performance

Material Burnthrough Time

Measured Flame Temperature







- Comparison of two identical, never-used cones
    - Standard cone
    - Ring cone
- Similar flame temperatures found with both cones
- Ring cone provided overall faster BT times

Reinforced Cone - Summary

- PIV measurements of the area above the cone top surface indicate the ring prevents surrounding air from being entrained into the cone exit flow.
- The ring is also found to create large scale vortices just downstream.
- Flame temperature measurements from a new standard cone and a new ring cone reveal only slight differences in temperature magnitude and profile.
- Material burnthrough tests indicate the ring cone provides a more severe configuration as burnthrough times were faster than the standard cone for both materials.
- The ring cone is speculated to block entrained cool air and increase turbulence downstream, resulting in mechanical stressing of the test material

Concluding Remarks

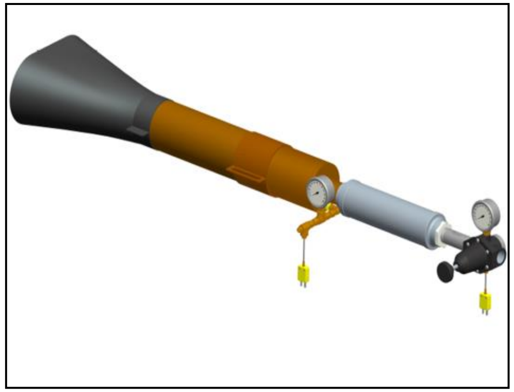
- Flow field, flame temperature, and material burnthrough measurements were made on the NexGen burner
- The most significant parameter for material burnthrough was found to be the magnitude of the peak velocity exiting the draft tube
- Fuel spray asymmetry was found to be influential on flame temperature measurements but not material burnthrough
- Flame temperature measurements do not necessarily indicate burner severity
- The exit flow field of the cone is highly irregular due to the growth of the swirling burner flow and the internal geometry of the burner cone

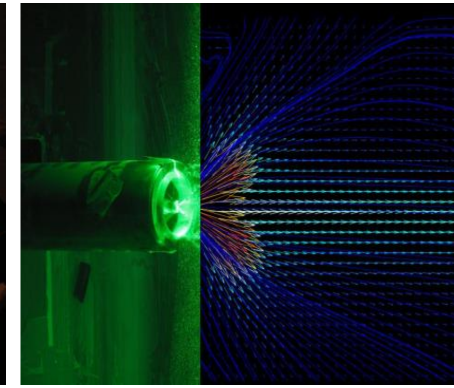
Contributions

- Knowledge of the effect of air flow field on material burnthrough will contribute to a more specified burner configuration
- Future burner designs can incorporate flame retention heads to simplify set up and operation
- A spray nozzle should be found that provides more symmetric spray pattern
- Flame temperature measurements should not be required for testing, but should be recommended for burner check-ups

Recommendations for Future Work

- 3D PIV on flame retention head air flow
- Droplet size and distribution measurements on spray nozzles; correlation of drop size with burner performance
- Reacting flow PIV measurements, impingement of flame on test samples (insulation, seat cushion, cargo liner) and assessment of velocity field around thermocouples during temperature measurement



Thank You

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Questions, Comments, Suggestions?