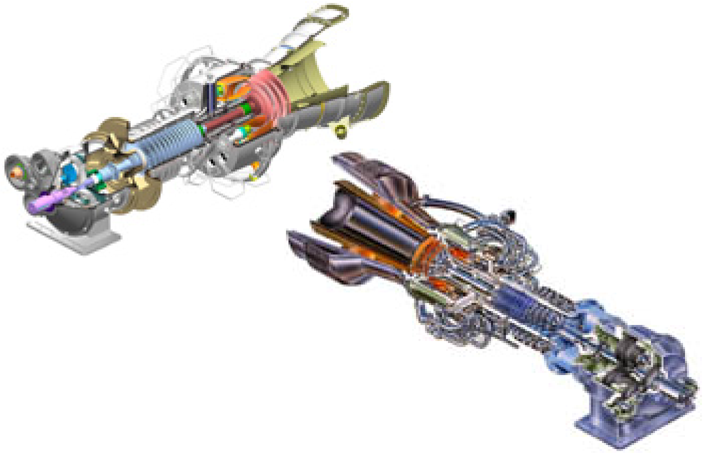
UTSR Workshop 2016
Flow and Heat Transfer Characterization of Lean Pre-mixed Combustor Systems



Taurus 65 and Taurus 70 Turbines
Courtesy of Solar Turbines Inc.

Presented by:
Srinath V. Ekkad, PhD.

Project sponsored by:
Department of Energy
Solar Turbines, Inc.

Current Status of Project: Original Milestones

Objective: Determine **convective heat transfer** at the liner walls and characterize the **flow-field** within the combustor at non-reacting and reacting conditions.

Plan for Solar/UTSR combustor

Year 1	
Combustor simulator design	Jan-14
Fabrication of apparatus	Apr-14
Shakedown and testing of apparatus (non-reacting)	Jul-14
Baseline Computations on Simulated Combustor	Oct-14
Year 2	
Design/Modification necessary for reacting flow testing in simulator	Dec-14
Shakedown/Testing of apparatus (reacting)	Oct-15
Comparison of non-reacting and reacting flow apparatus data	July-16
Comparison of turbulence models	Sep-15
Year 3	
Retrofit of industrial nozzles into apparatus design	Sep-15
Testing of industrial nozzles in simulator	Feb-16
Testing and simulations under reacting conditions (flow and heat transfer)	Oct-16
Testing in industrial apparatus	Dec-16
Comparison of Computational Effort to Industrial tests	Dec-16
Year 4	
Testing of various liner designs	Feb-17
Final report	Jan-18

Working on it
Delayed
Completed

Optical Combustor Rig- Design

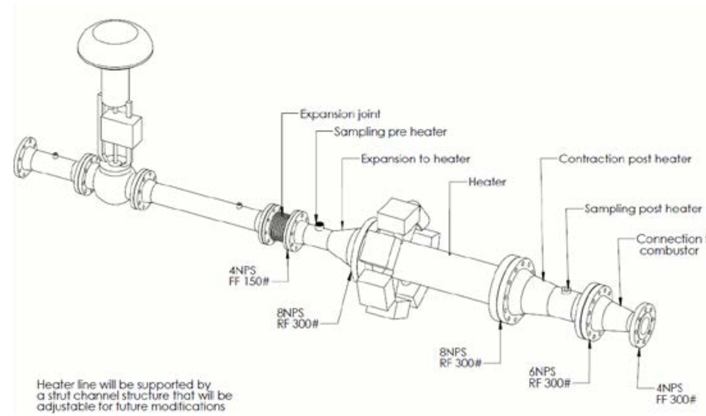
Motivation:

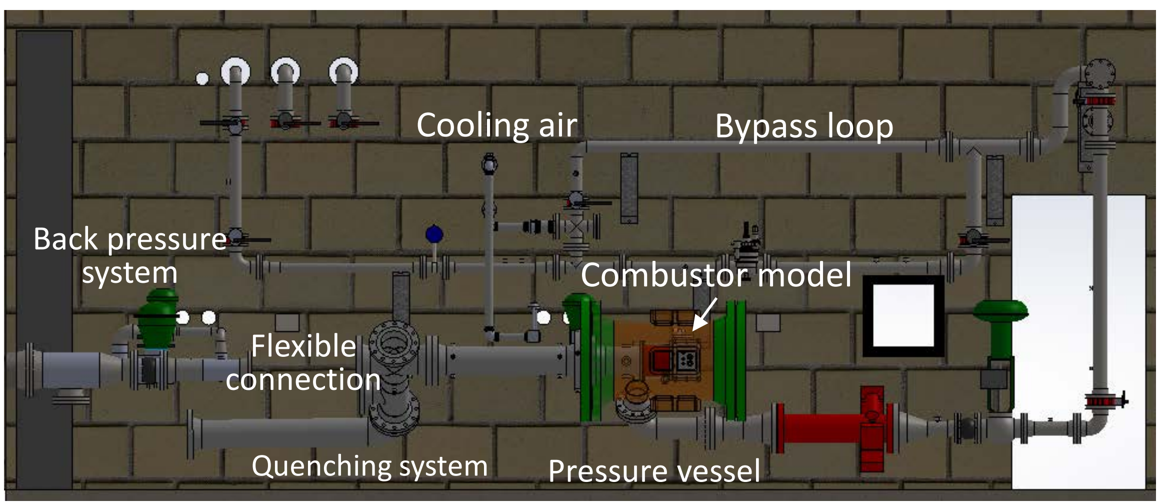
Combustor cooling technologies key for efficiency and emissions control

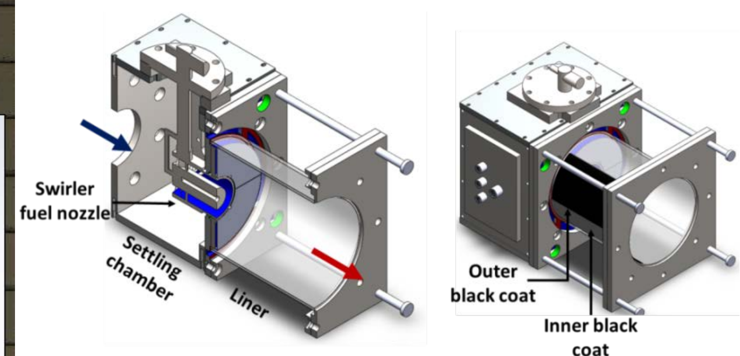
Objective:

Investigation of combustor flow field and liner wall heat loads

- Liner wall heat loads under realistic conditions
- Effect of swirling flow field on liner heat transfer







Schematic the setup for the heat transfer measurements

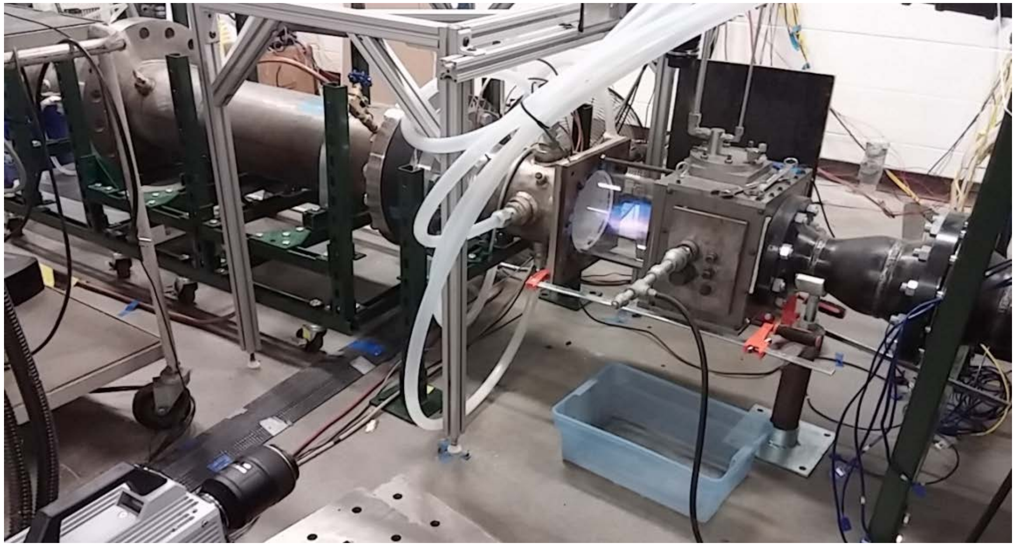
Optical Combustor Rig- Features

Features:

- Industrial nozzle testing
- Air flow 2.8 lbm/s at 150 psig
- Flow metering 2% accuracy, 0.25% repeatable
- 192 kW inline heater (700 K inlet air)

Flexibility:

- Outlet geometries, dome assemblies, swirl fuel nozzles, liners.



Optical access for flame diagnostics and liner/fuel nozzle evaluation:

- PIV and IR thermography.
- Potential for absorption measurements, Laser Induced Fluorescence (LIF), thermographic phosphors.

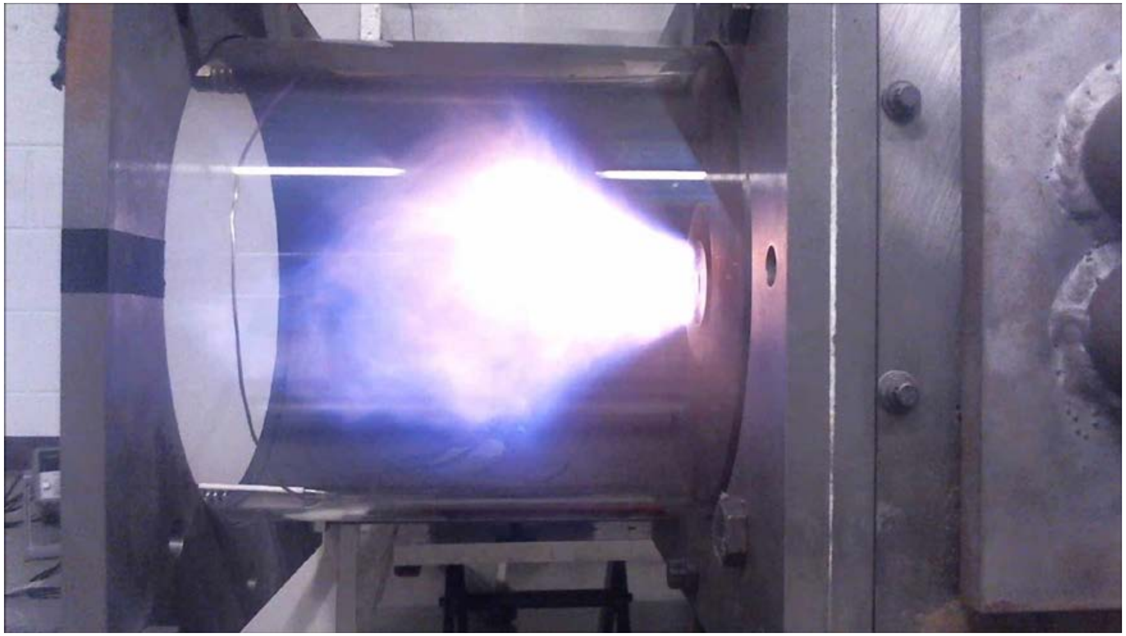
Future phase:

- Pressure vessel for pressurized tests up to 10 atm at 700K inlet temperature

Reacting studies- Heat load on liner wall

Development of **reacting** heat transfer methodology

Representative reacting flow studies



Creating a method that **does not rely on a wall heater** or probes.

Time-Dependent, Non-Intrusive IR measurement

IR camera to measure inner and outer **surface temperature**

↓

Boundary conditions in a finite difference model of the liner

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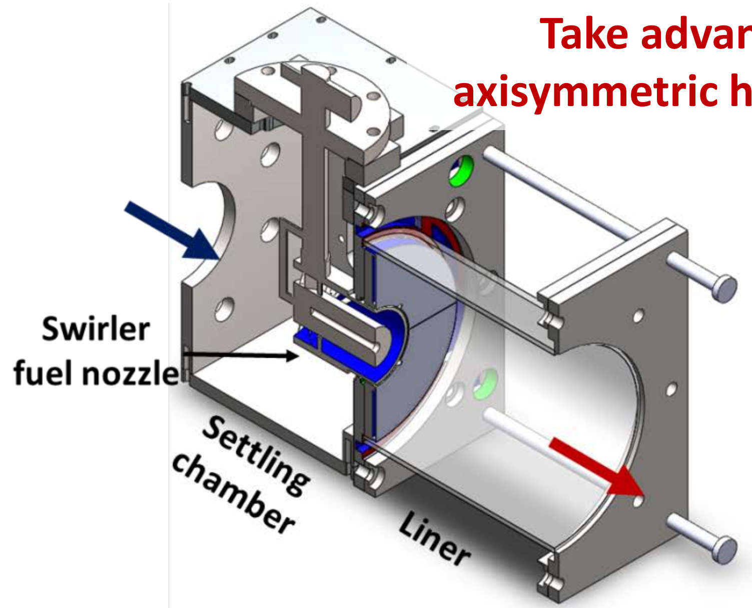
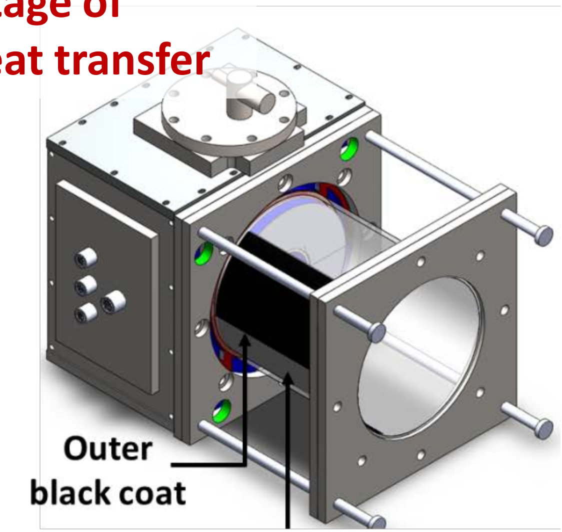
Calculate **heat flux into the liner** from the normal temperature gradient

↓

Estimate HTC based on reference gas temperature

Take advantage of axisymmetric heat transfer





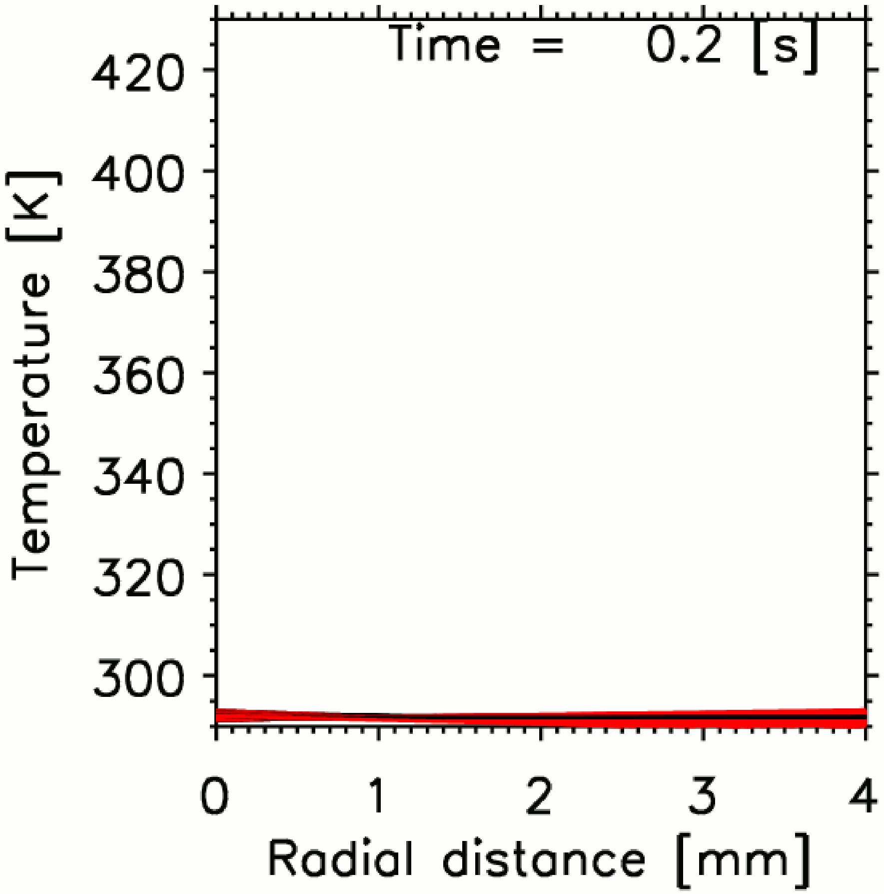
Heat conduction equation for the quartz liner

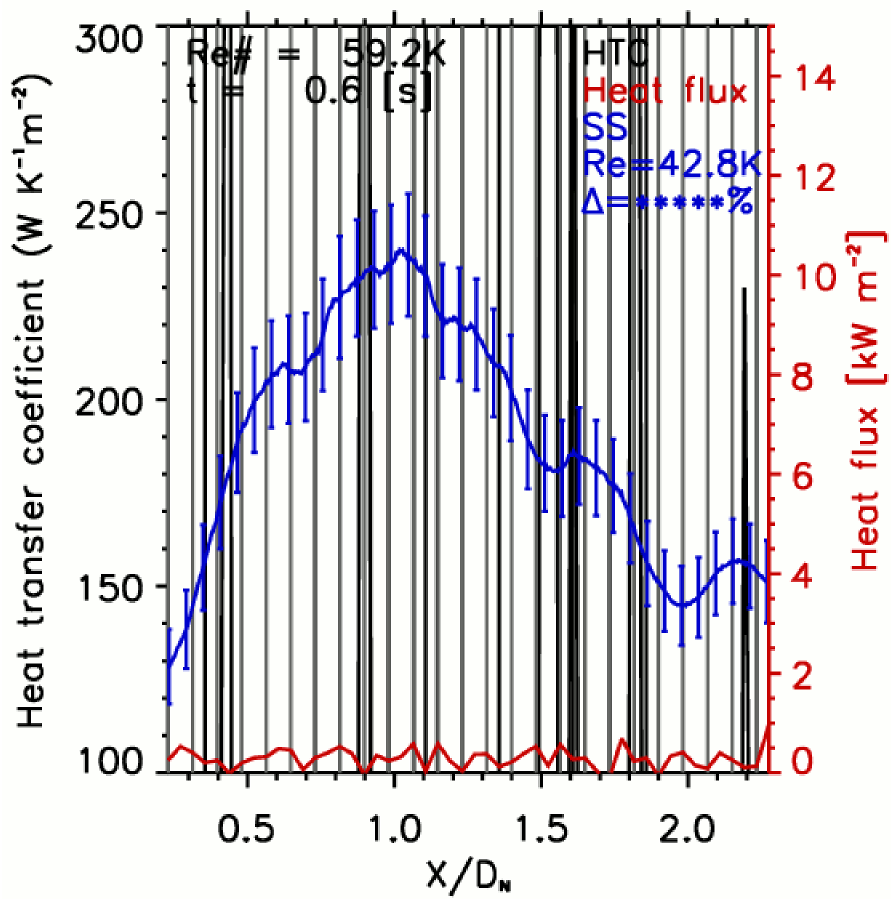
$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)$$

Energy balance at the inner surface

$$-k\frac{\partial T}{\partial r}\bigg|_{r=r_0} = h\left(T_{r=r_0} - T_\infty\right)$$

Time-Dependent Technique validation with Steady State Measurement

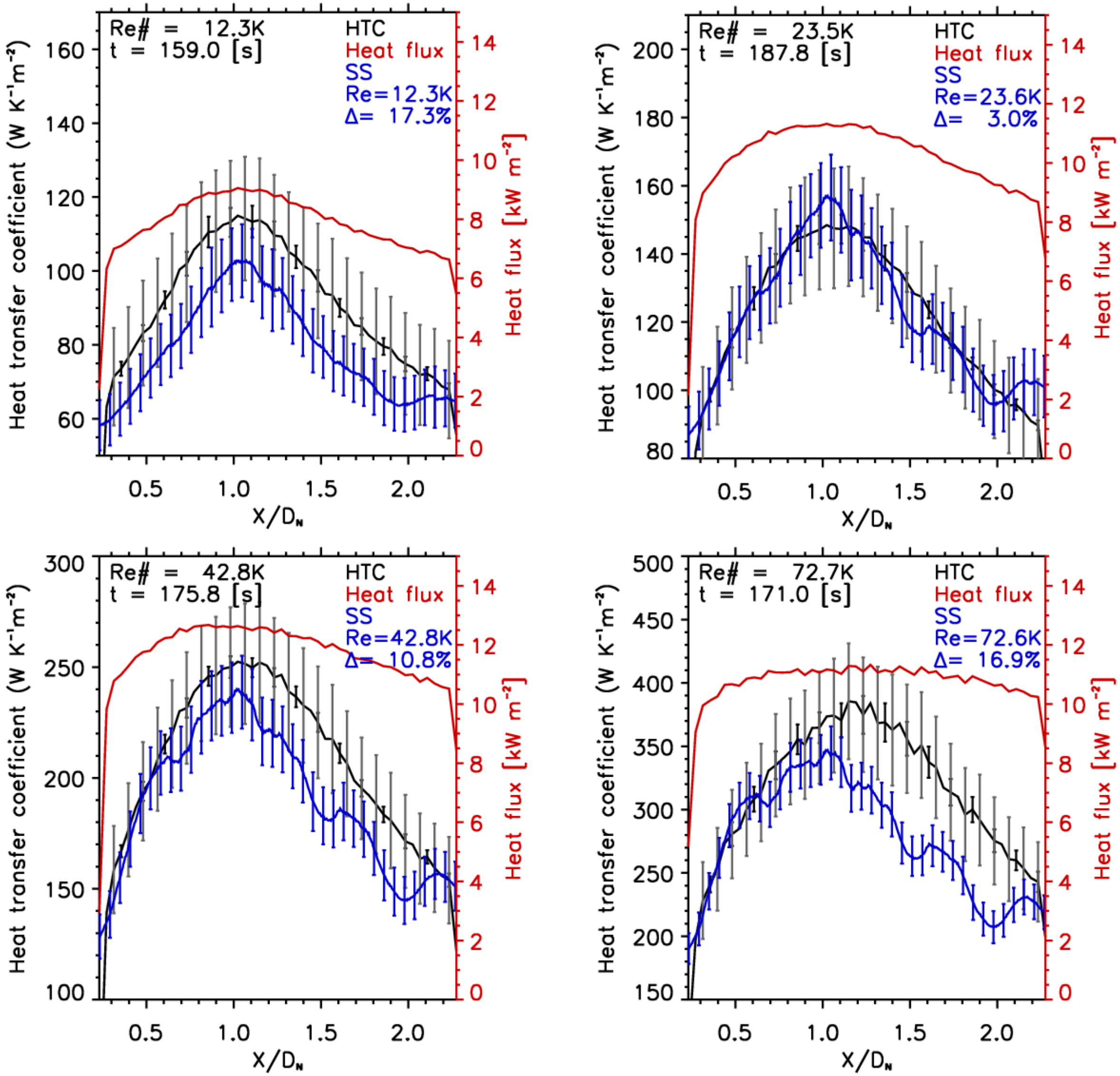




Finite difference code yields the flame side surface heat flux (normal temperature gradient)

Time-dependent HTC matches with the steady state result in non-reacting flow

Validation Holds for Different Reynolds Numbers



Difference between SS and time-dependent results are

3%-17.3%

for each

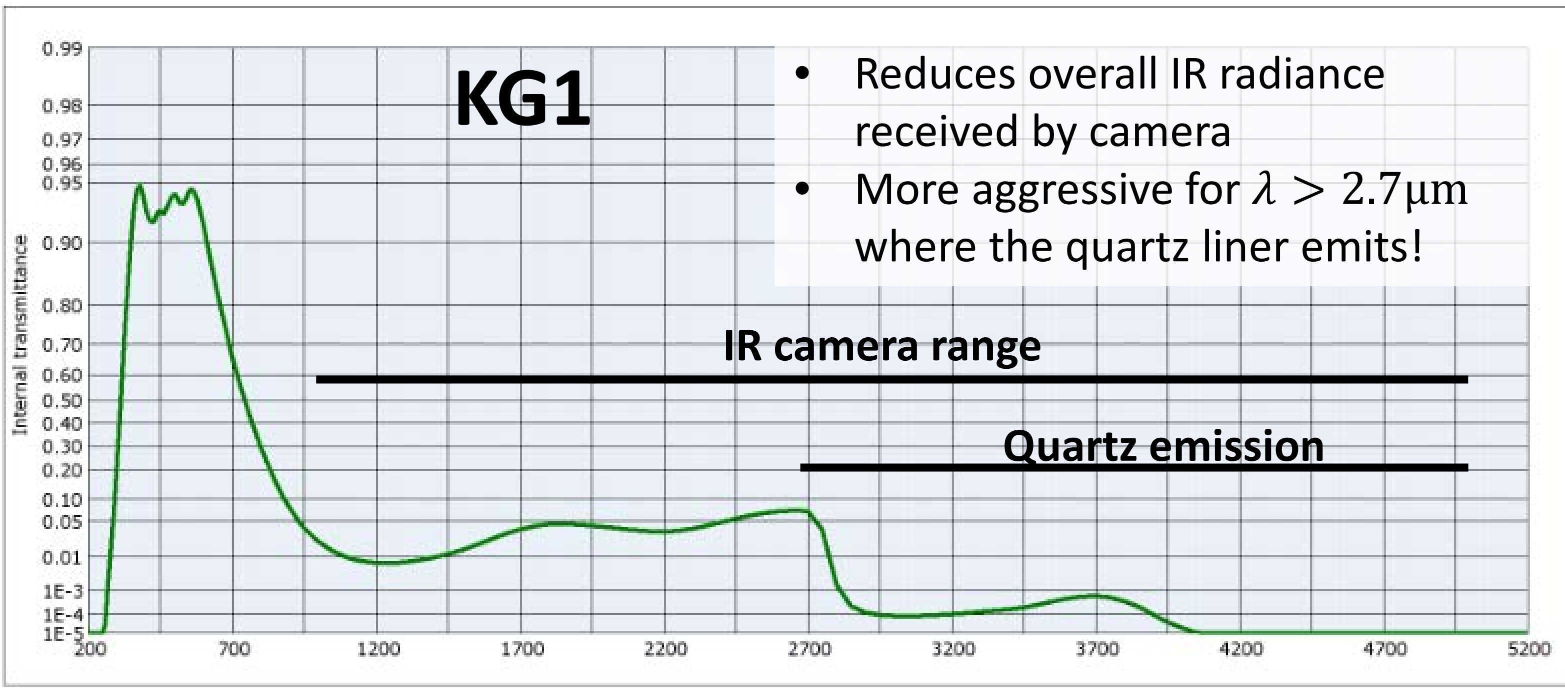
Reynolds number

(Non-reacting)

Extending the Temperature Range Beyond 300^{0}C

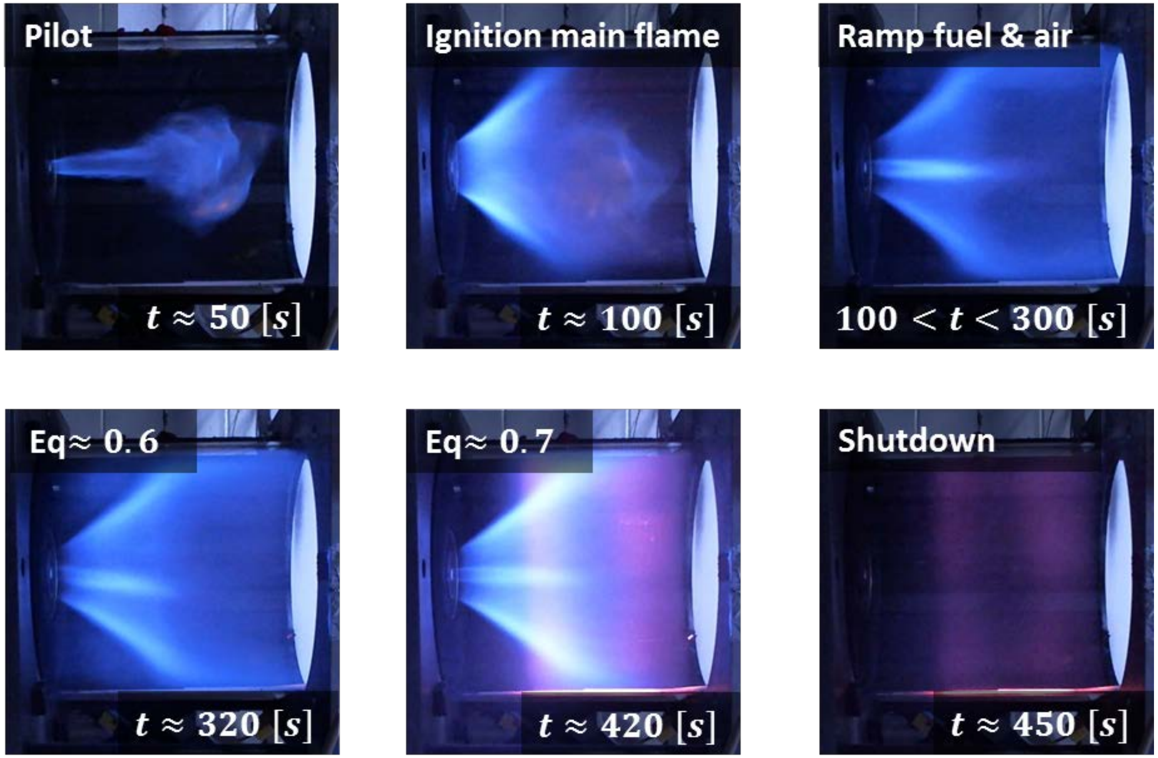
Use another filter for the IR camera. → **Schott KG glasses**

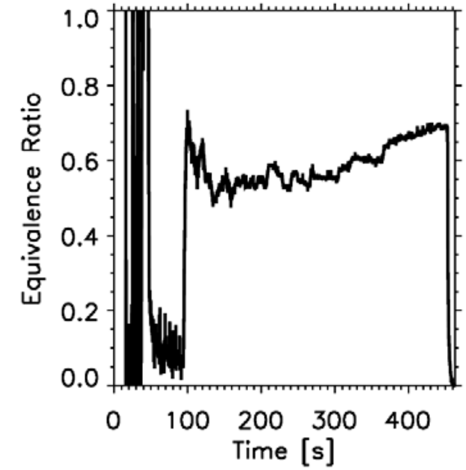
Disadvantage: No access to low temperatures (filter dominates the signal)

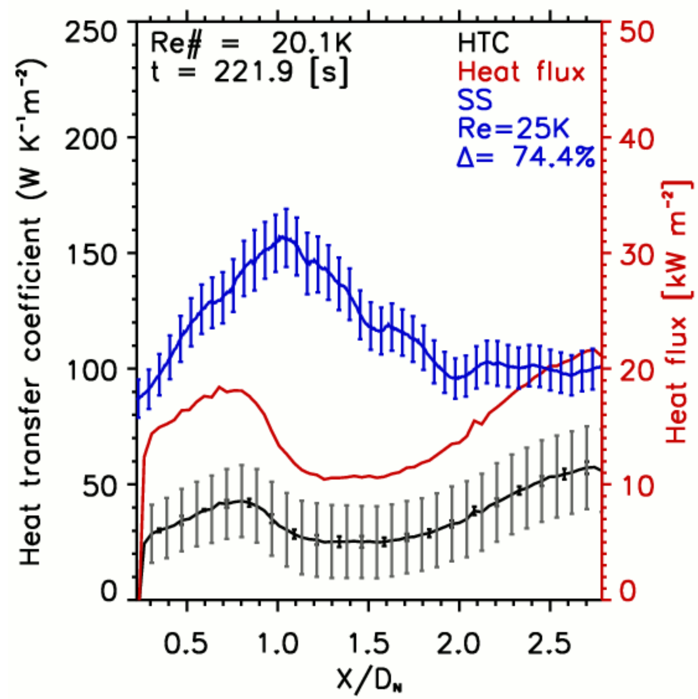


http://www.galvoptics.co.uk/datasheets/56esgu1ds6yq628/4eh4vyyck1fyjxd/schott%20KG1%20shortpass%20filter.pdf

Heat Transfer Measurement: 24,000 Reynolds# Case







Time dependent measurements suggests heat transfer coefficient peak location, $X/D_N \approx 1$

Compared to non-reacting steady state results, the axial decay of HTC is low and shows trends of waviness at high Re#

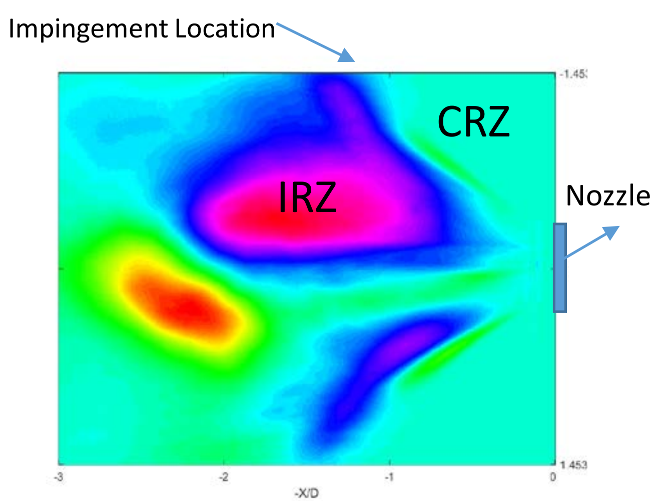
After shutdown the Non-Reacting values are recovered!

High Speed Imaging

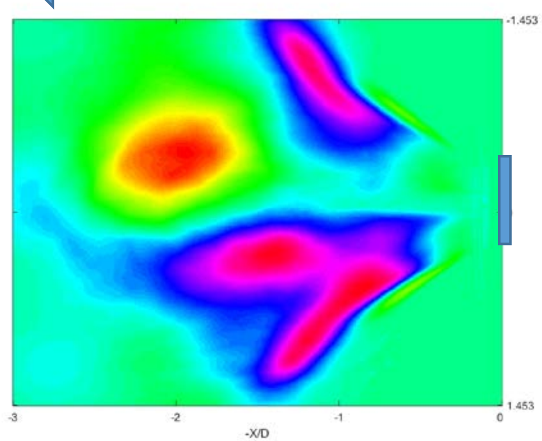
Objective: To observe flame features using high speed imaging

Proper Orthogonal Decomposition (POD) on flame images → Reduced order model give **dominant structures** in the flames as different modes → Temporal information (coefficients) from POD gives information about the **oscillations** in the flame → Observation of **Combustion oscillations**

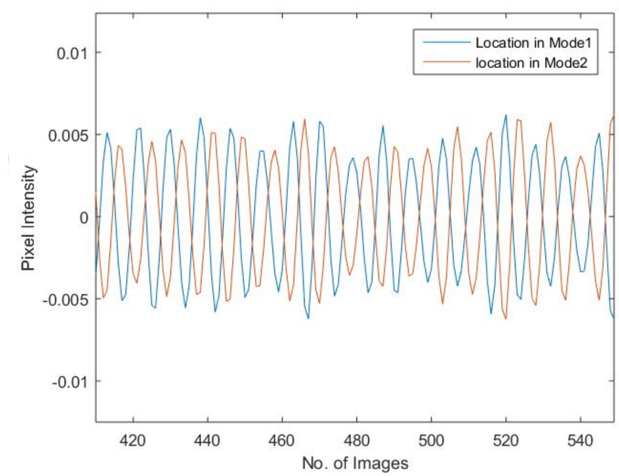
Flow Direction



Mode 1



Mode 2



Filtered Pixel intensity at specified locations obtained from reconstructed data from mode 1 and mode 2

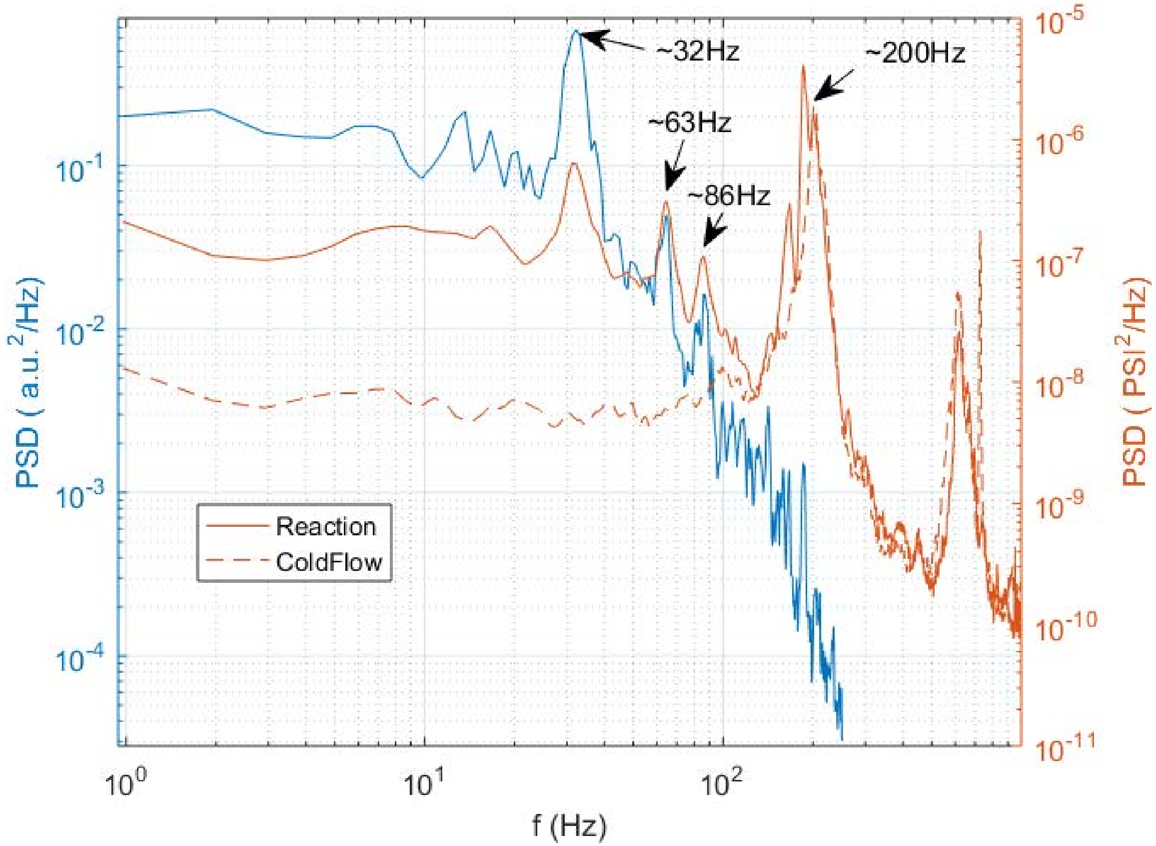
0.6 Eq ratio- 50k Re

POD on Flame Images

Top POD modes obtained from high speed imaging replicates the pressure PSD (some peaks) below 100Hz

200Hz frequency oscillations are due to coolant air (separate testing has been done to validate)

Mode 2 of POD was used for this plot which corresponds to 5% of energy (mode 1 is 7% for comparison).



50K Re | 6% pilot | 0.65 Eq ratio

Lean Blow Out (LBO) – Preliminary Studies

Objective: To compare different effects of pilot fuel mass flows, Reynolds numbers on LBO and observe the instabilities as LBO is approached.

Experiment Procedure

Stable conditions → Fuel flow rate reduced gradually to **decrease Equivalence ratio** as LBO approaches

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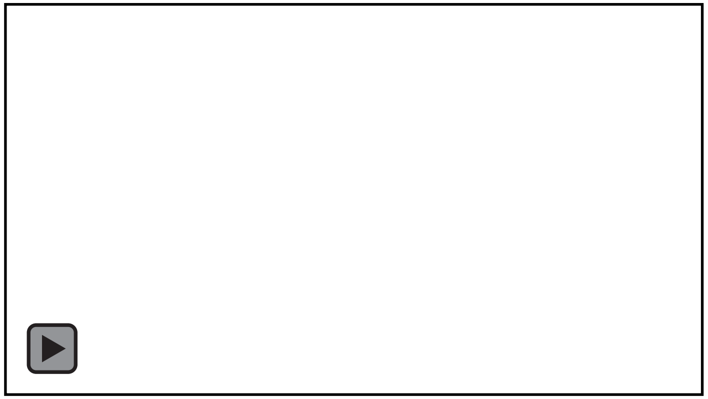
LBO ← High Speed Imaging and pressure measurement as **instabilities** due to LBO happen

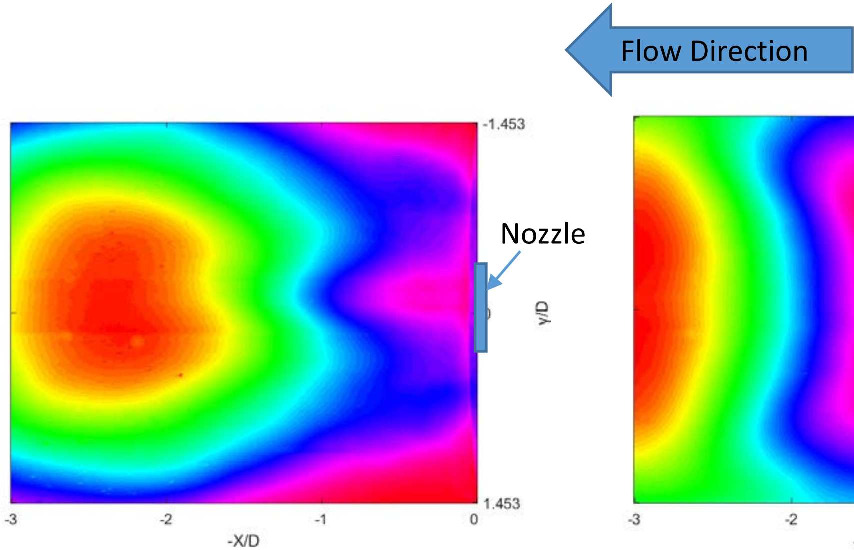
Current Status: Experiments are being conducted at various conditions.

LBO event is identified by pressure measurements

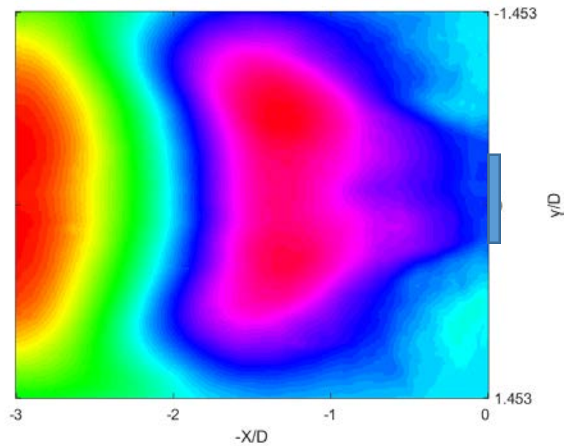


Blowout and re-ignition as LBO approaches

Lean Blow Out (LBO) – Preliminary Studies

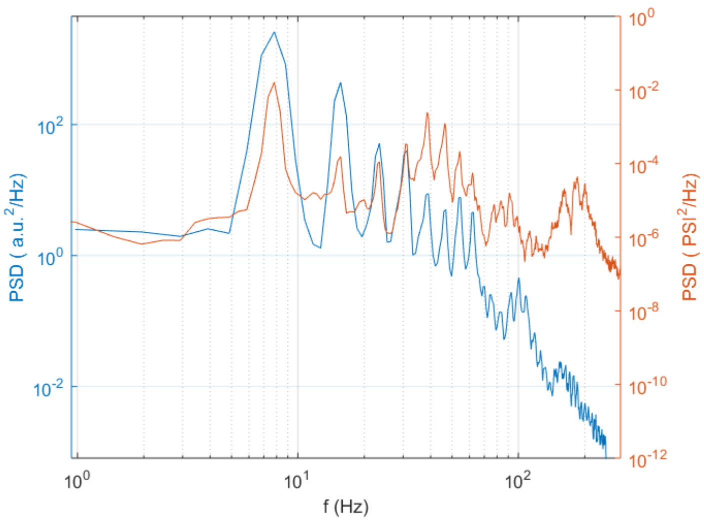


POD -Mode 1 shows Blowout



POD -Mode 2 shows Re-ignition.

- 50K Re – Fixed Pilot fuel Mass flow (0.12E-3 lb./s)
- LBO at 0.4 Eq ratio



POD predicting instabilities due to LBO as well

POD Modes of flame images show the dominant structures of the flame.

Mode 1 and Mode 2 show blowout and re-ignition as observed in the images above.

POD on flames images was able to predict the pressure oscillations.

Reacting PIV under different conditions – Outline

Goal

- Examine reacting flow fields under different combustor operating conditions
  -> **ϕ (equivalence ratio), pilot fuel ratio, Reynolds number**
- Will the **flow field change** for the same combustor geometry?

Resources

- PIV system : 532 nm double pulse laser + PIV camera (bandpass filter)
- Titanium oxide 1-2μm seeding particle

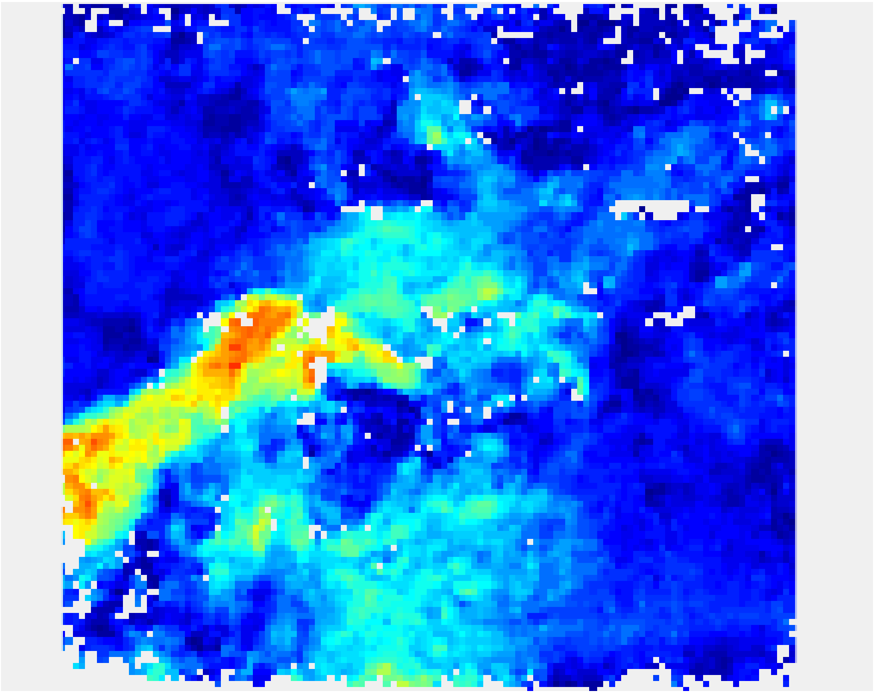
Test conditions – Total 9 cases

- 3 pilot fuel ratios
  - Varied: Pilot 6%, 4%, 0%
  - Fixed: ϕ 0.65, Re 50 k
- 3 equivalence ratios
  - Varied: ϕ 0.55 0.65 0.78
  - Fixed: pilot 6%, Re 50 k
- 3 Reynolds numbers (w.r.t. nozzle dia.)
  - Varied: Re 50 k, 75 k, 110 k
  - Fixed: pilot 6%, ϕ 0.65 (or ϕ 0.58)

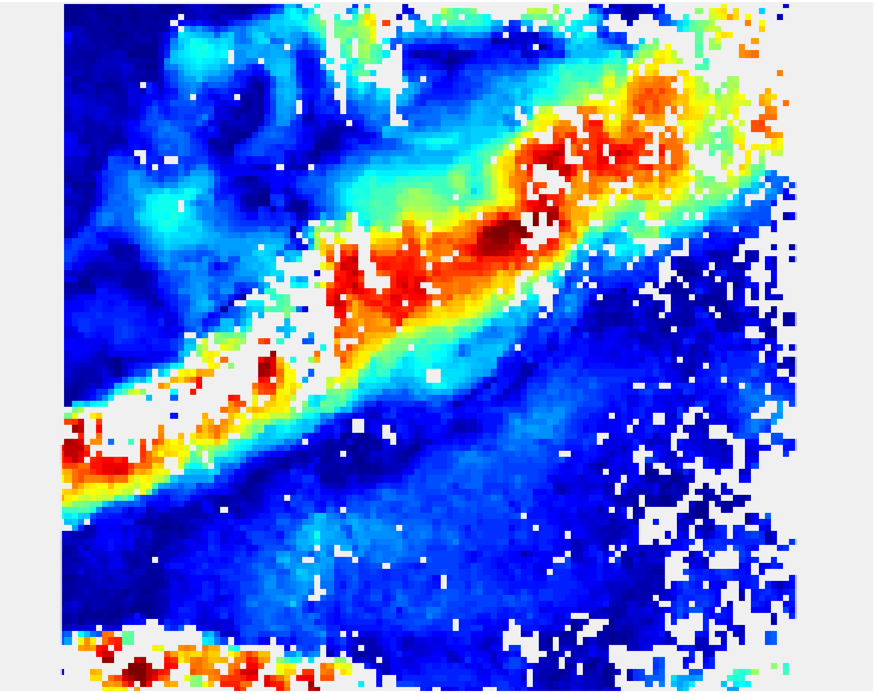
Case	Pilot %	ϕ	Re # ($\times 10^3$)
1	6	0.65	50
2	4	0.65	50
3	0	0.65	50
4	6	0.78	50
5	6	0.55	50
6	6	0.65	75
7	6	0.55	110

PIV flow field – Non-reacting vs. Reacting

Non-reacting



Reacting



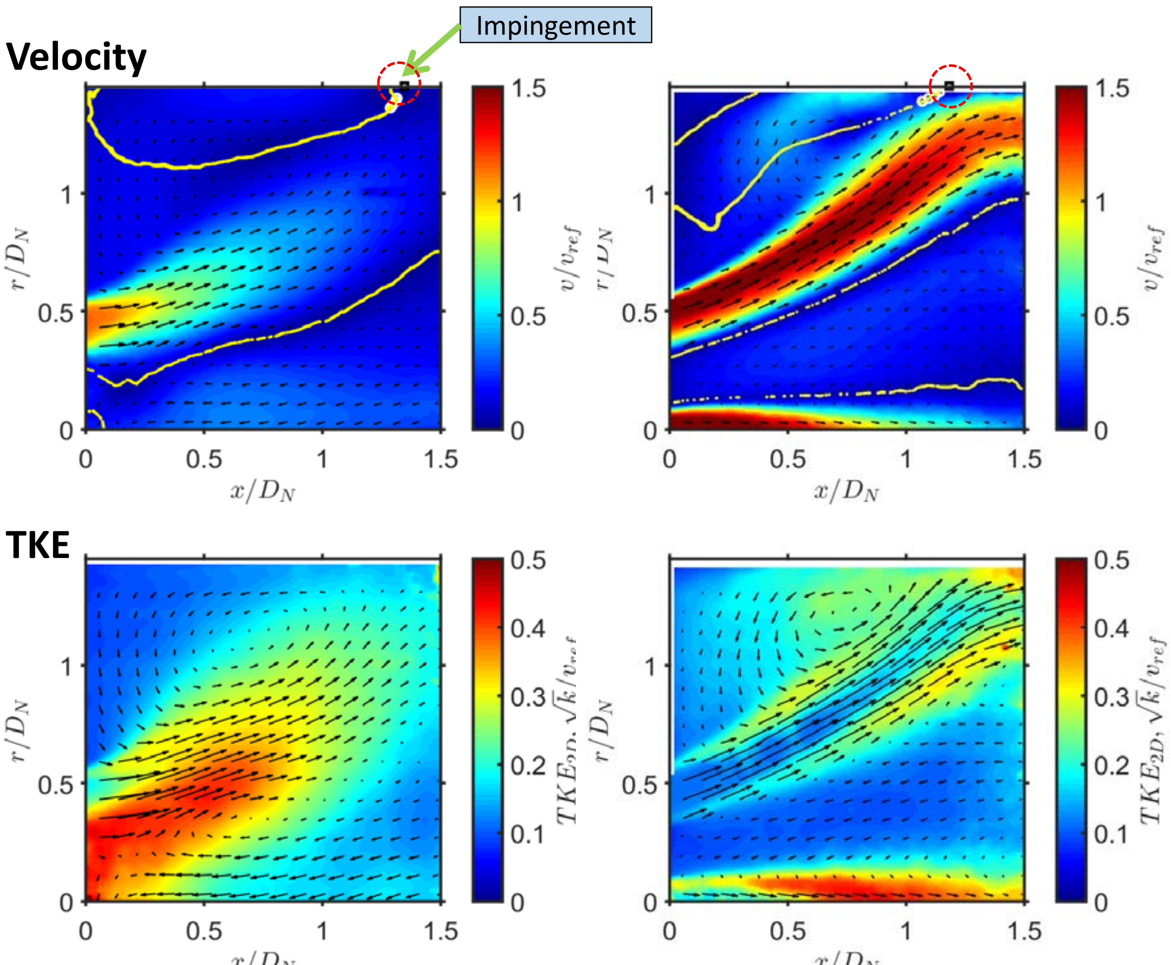
Velocity field snapshots of non-reacting and reacting flows measured with PIV

- Data acquisition frequency : 7.4 Hz
- Average of the 400 snapshots are used for each mean vector field

PIV flow field – Non-reacting vs. Reacting

Fixed: Re #: 50,000

Non-reacting | **Reacting (ϕ : 0.65, Pilot: 6%)**

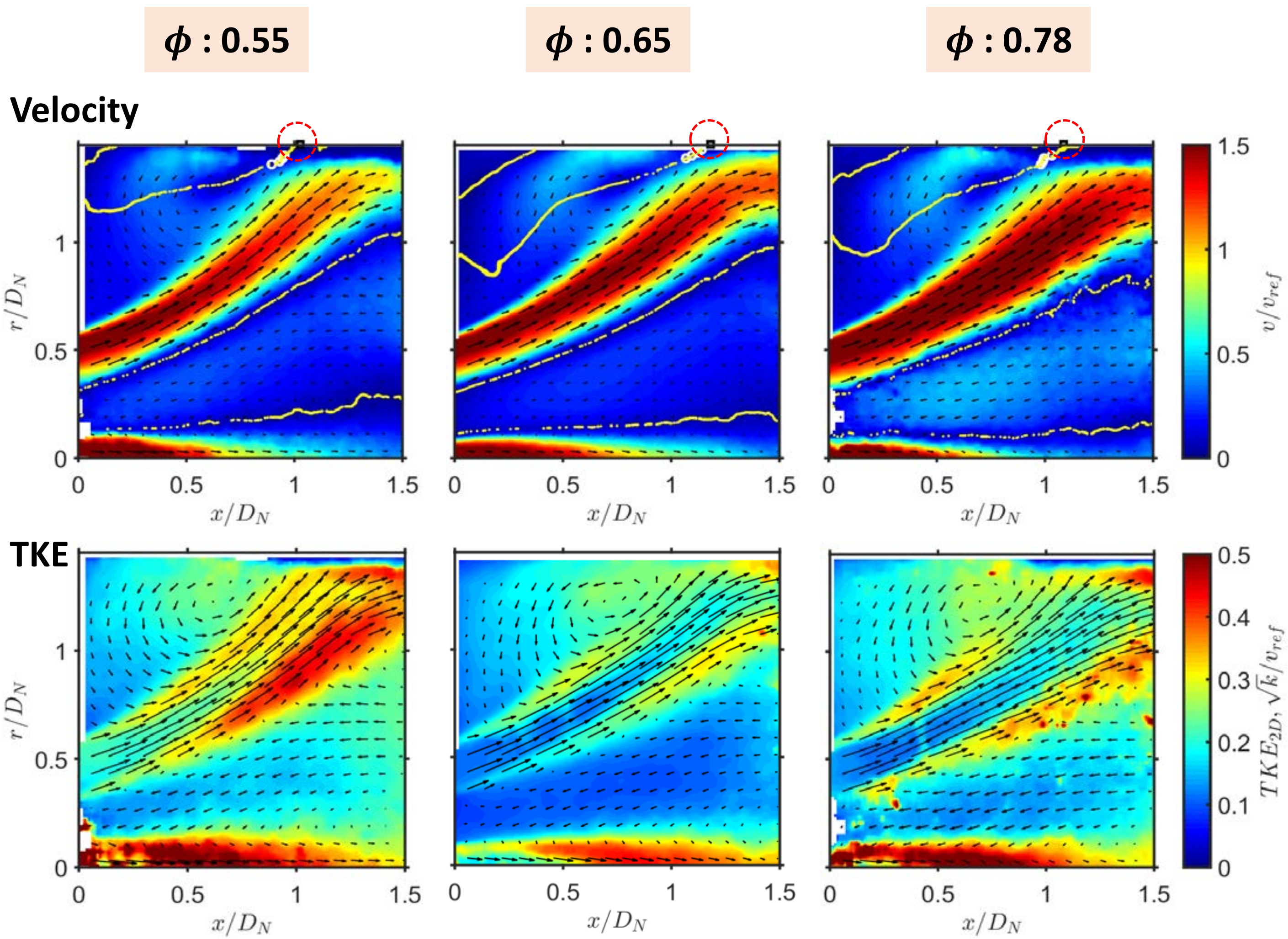


Flow field characteristics in reacting flow are distinctly different from non-reacting flow

- ***Maximum velocity in the jet is higher in reacting flow because of flow energization***
- **High turbulence regions lie on shear layers for reacting case**
- Pilot flame interacts with central recirculation zone
- Axial position of **zero axial velocity** at the liner wall indicates **jet impingement location**

Self-similarity in reacting flow – Equivalence ratios

Fixed : Re #: 50,000, Pilot: 6%



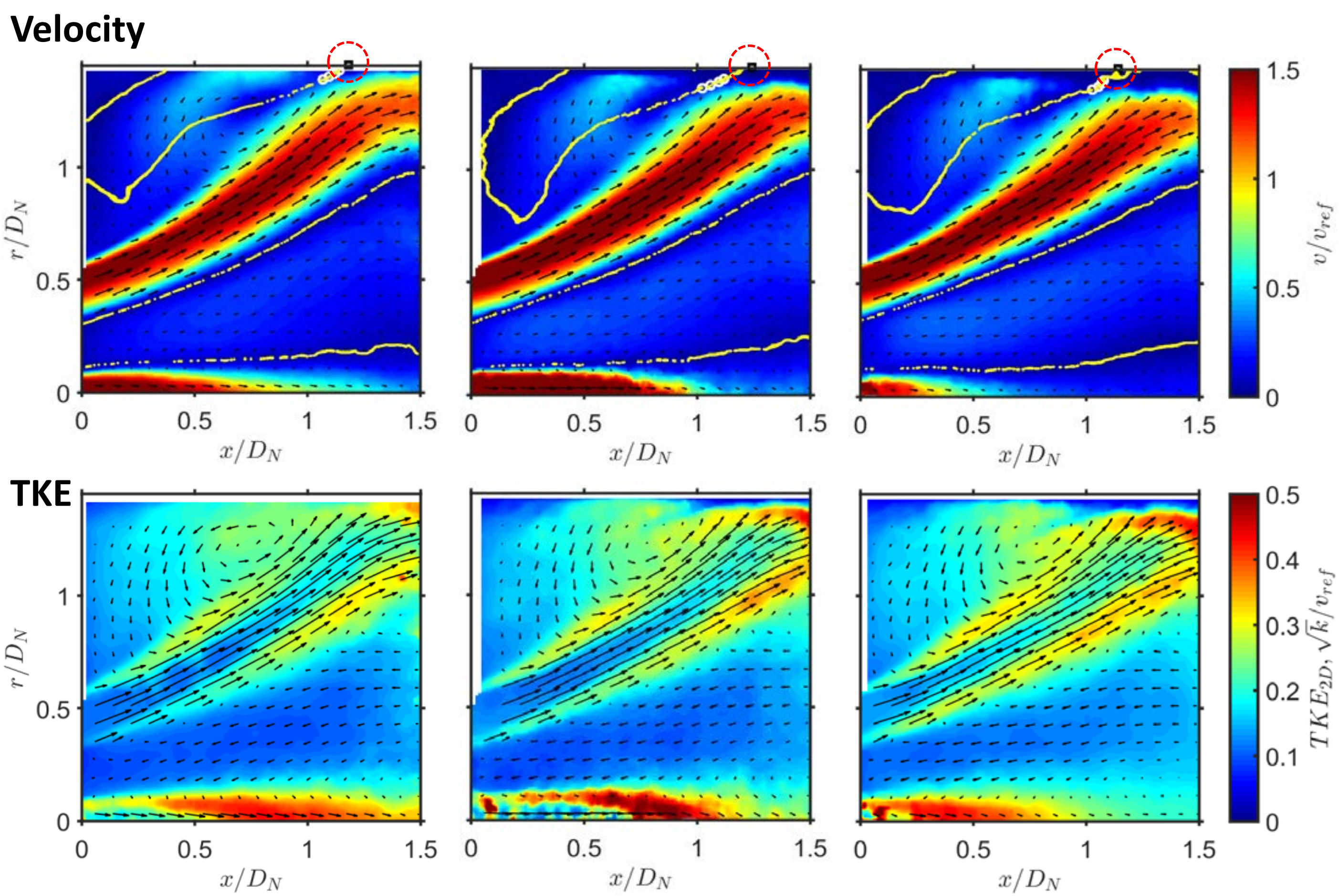
Self-similarity observed with different eq. ratios

- Flow expansion in main flame is higher for higher equivalence ratios
- Flame zone is **wider** with high equivalence ratio
- **TKE decreases with eq. ratio** because of damped vortices
- Nevertheless, the **impingement** locations and distribution of high turbulence regions are **similar**

Self-similarity in reacting flow – Pilot fuel ratios

Fixed : ϕ: 0.65, Re #: 50,000

Pilot: 6% **Pilot: 4%** **Pilot: 0**



Self-similarity observed with different pilot ratios

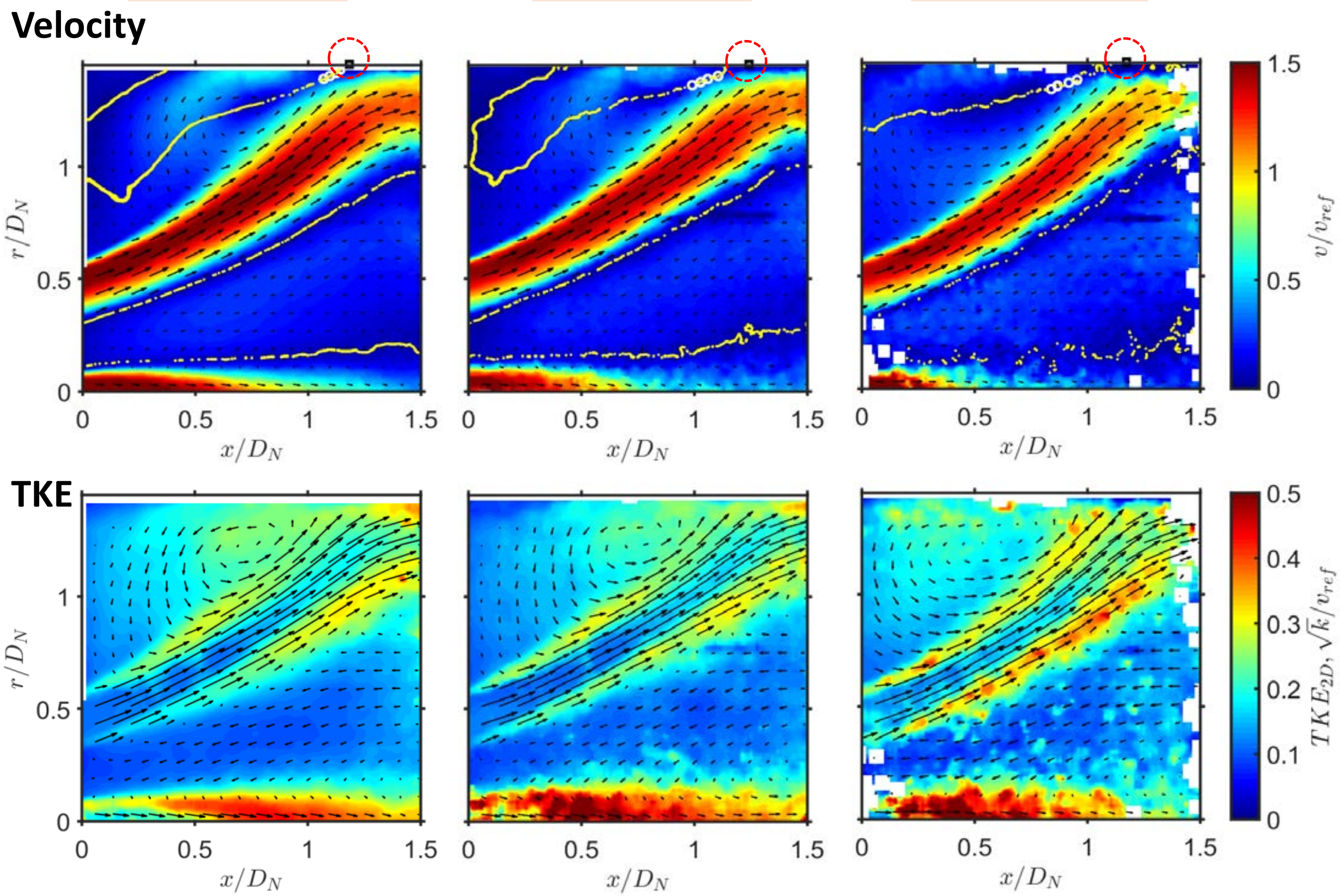
Minor changes in pilot ratio

- Less effect on main flow
- Do not change the impingement location
- Small amount of air flows through pilot nozzle when pilot fuel is zero

Self-similarity in reacting flow – Reynolds numbers

Fixed : Pilot 6%

Re #: 50,000 ϕ : 0.65	Re #: 75,000 ϕ : 0.65	Re #: 110,000 ϕ : 0.58

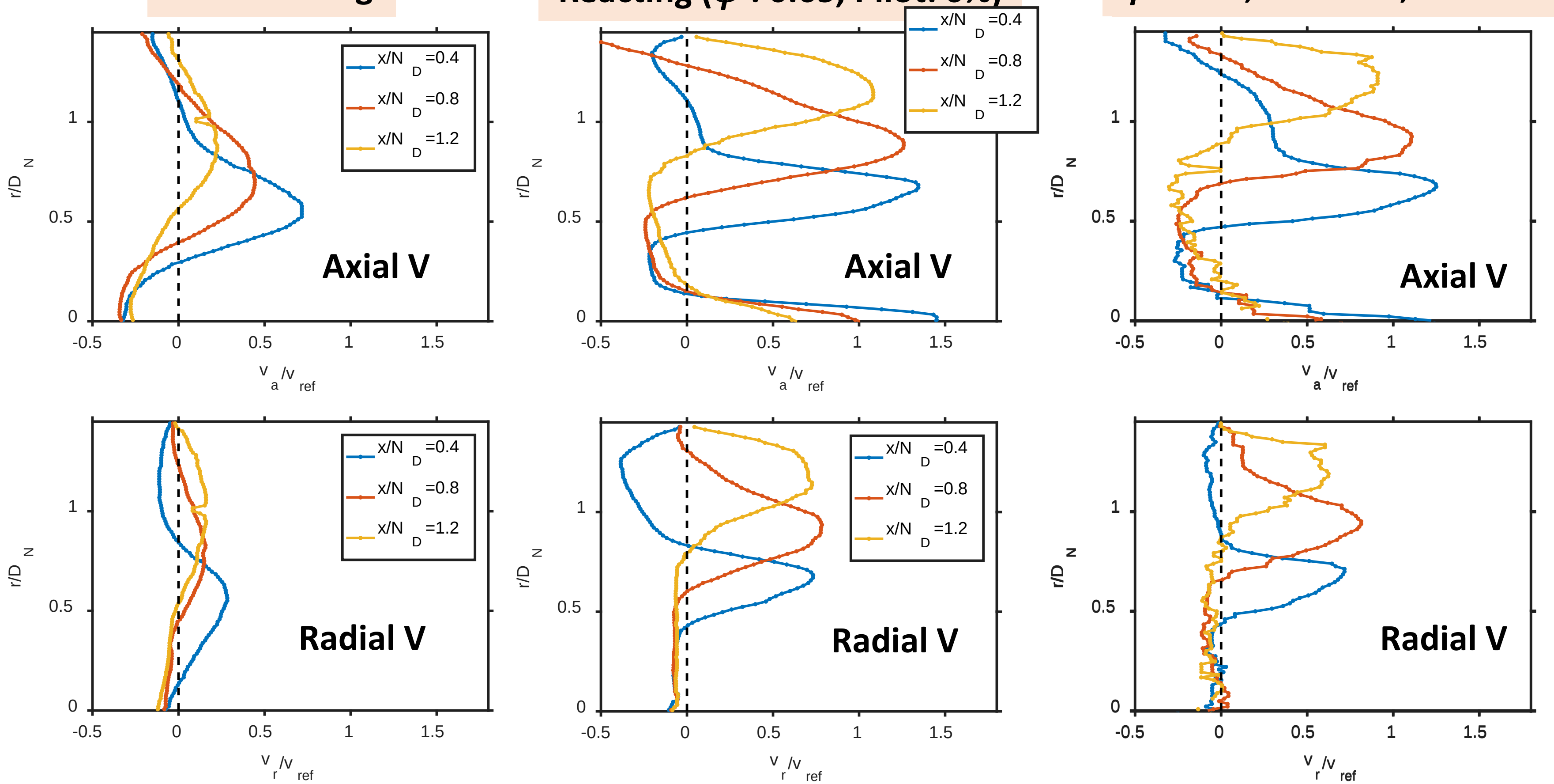


Self-similarity observed with different Re numbers

- Peak main flow velocity increases.
  18.4 -> 26.5 -> 37.7 m/s
- Normalized velocity fields and regions of high TKE are similar

Profile comparison of PIV flow fields

Non-reacting | **Reacting (ϕ : 0.65, Pilot: 6%)** | **ϕ : 0.65, Pilot: 6%, Re 110 k**



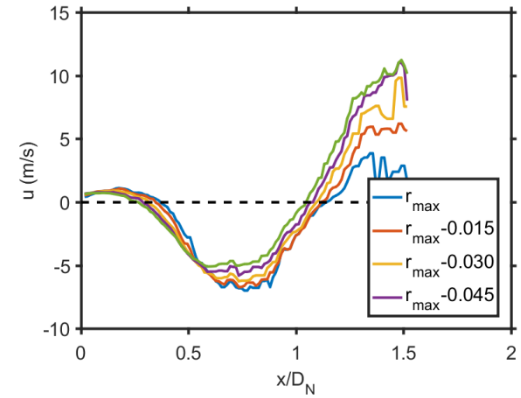
- Main jet in non-reacting decays as it moves downstream
- Self-similarity observed in velocity profiles in reacting flows
- The peak location and shape of the main flame are consistent

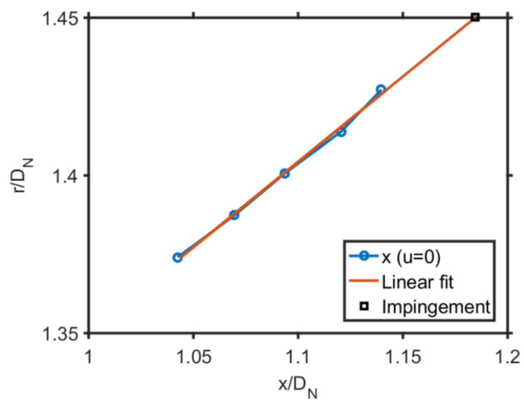
Impingement locations in different conditions

Impingement locations on the liner wall

Case	Pilot %	ϕ	Re #	x/D_N	Deviation
NR1	-	-	50 k	**1.34**	**-**
NR2	-	-	50 k	**1.32**	**-**
R1	6	0.65	50 k	**1.18**	**+1.9 %**
R2	4	0.65	50 k	**1.23**	**+6.2 %**
R3	0	0.65	50 k	**1.17**	**+1.0 %**
R4	6	0.78	50 k	**1.10**	**-5.0 %**
R5	6	0.55	50 k	**1.01**	**-12.8 %**
R6	6	0.65	75 k	**1.25**	**+7.9%**
R7	6	*0.55*	110 k	**1.17**	**+1.0 %**

For reacting cases:
Mean x/D_N: **1.16**, STD: 0.08 (**7%**)





- Impingement location of the flame on the wall is located approximately $x/D_N \sim 1.16$
- Measurement error (alignment, noise, etc.) might have caused minor differences, but **the impingement locations appear consistent for all reacting cases**

Temperature profile measurement configuration

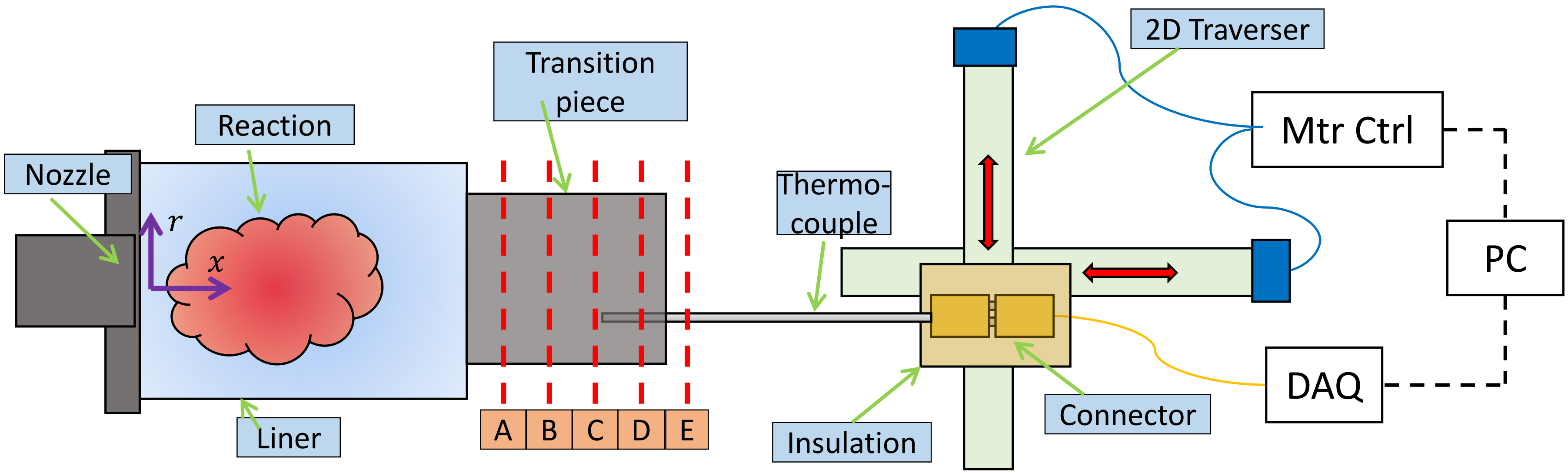
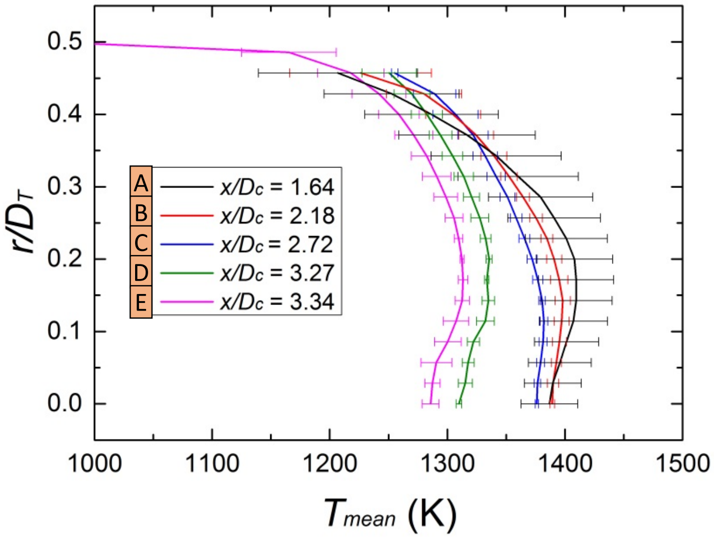


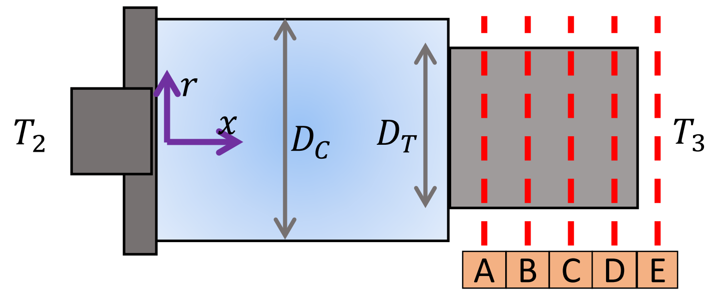
Diagram of temperature mapping setup in reacting flow

- Temperature distribution in 2-D plane of reacting flow for:
  - ✓More accurate **heat transfer** characterization
  - ✓Better understanding of the **combustion process**

- Thermocouple was installed on 2-D linear motorized traversers
- A probe with B type thermocouple was used in the reacting flow
- Connections were protected by insulation casing
- For initial study, measurements were done in transition piece

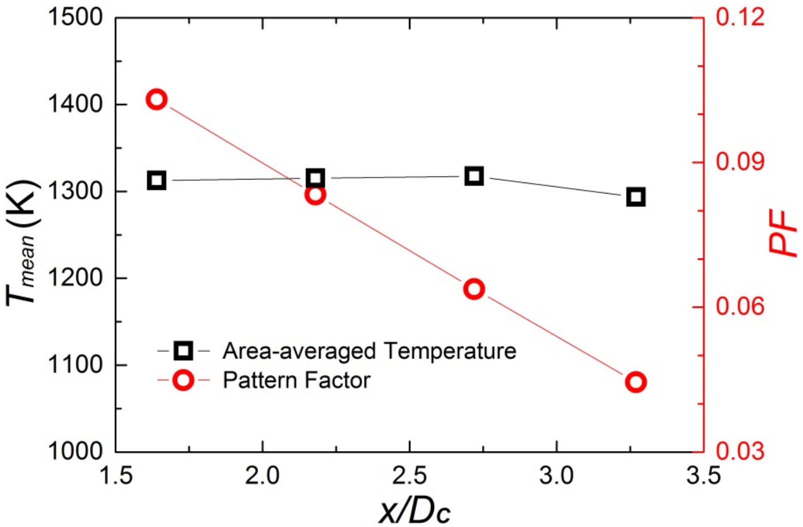
T profile and pattern factor at transition piece





Axial locations of measurement (from fuel nozzle)

Pattern factor (PF): $\frac{T_{max} - T_3}{T_3 - T_2}$



- Temperature at different axial locations inside transition piece
- Errors within 5%
- As the axial location moves downstream,
  - Average temperature: ~ 1300 K
  - PF decreases due to mixing in transition piece

Accomplishment summary in 2015-2016

Experimental side:

Accomplishment summary

- Experimental setup for reaction conditions at atmospheric conditions is completed.
- Cold flow transient state method validated.
- Experimental method for reaction conditions validated.
- Effect of equivalence ratio, Reynolds number on flow in reaction condition was studied.
- A method was developed to study flame dynamics using high speed imaging.
- Preliminary study of Lean Blow Out (LBO) conditions is studied.
- Experimental setup to measure temperature field in combustor chamber using thermocouple is prepared.

Moving forward :

- Reacting PIV at different cross sections to map velocity in radial-azimuthal direction.
- Lean Blow Out (LBO) studies at various conditions.
- Temperature field measurement using Thermocouple at various reacting conditions.
- Heat transfer on the liner wall at various reacting conditions.
- Heat transfer on the liner wall during LBO conditions.
- Temperature mapping in the combustion chamber using optical measurement (IR thermography etc.).

Computational investigation approach

Objective:

Numerically characterize heat transfer along the combustor liner for industrial burner to

- **Identify peak heat transfer location** along the liner
- ***Non-reacting and reacting conditions*** for the combustor test set up

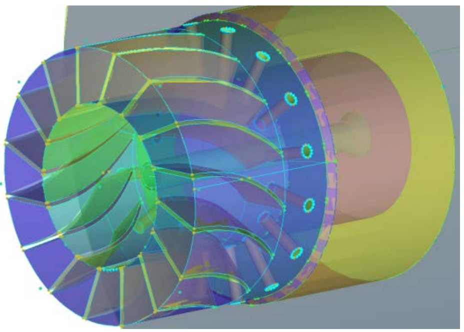
CFD DOMAIN	TURBULENCE MODELS	PREMIXED MODELS
3D sector ✓ ***3D cylinder*** ✓	RANS (Steady-state) ✓ Scale Resolved Models: (Transient) - ***SAS (in progress)*** ✓	Zimont ✓ ***Flamelet model*** ✓ ***(Ongoing for modified test set-up)***

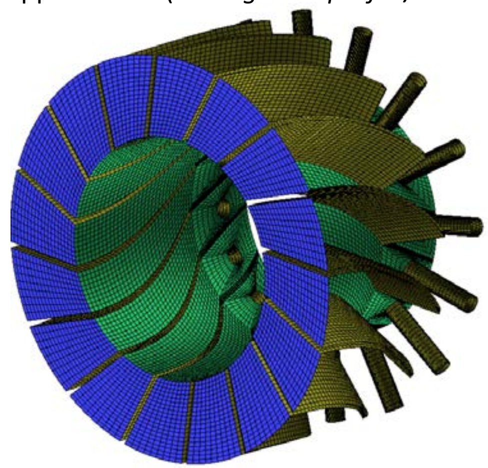
- **Preliminary studies** are performed on previous test cases of **Patil *et al.(2014-2015)***
- Flow and HT studies performed on **experimental combustor set up (without transition piece) (2015-2016) – (Turbulence models and flow profiles assessed for non-reacting flow cases)**
- Non-reacting and **reacting simulations being performed on modified test set-up with transition piece (2016)**

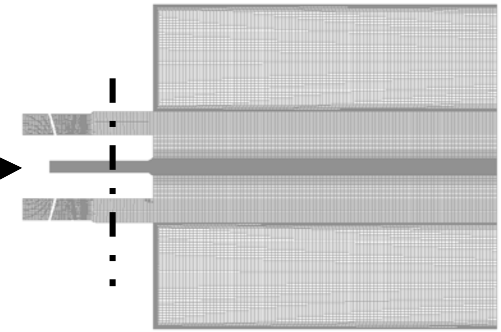
Industrial nozzle model and mesh development

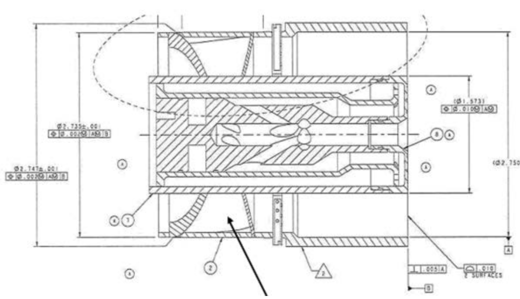
Proprietary fuel nozzle design → **Attempted CAD of the nozzle based on design cross-section** → **CFD model of nozzle**

Approximate (*lacking vane profile/turning angles*)







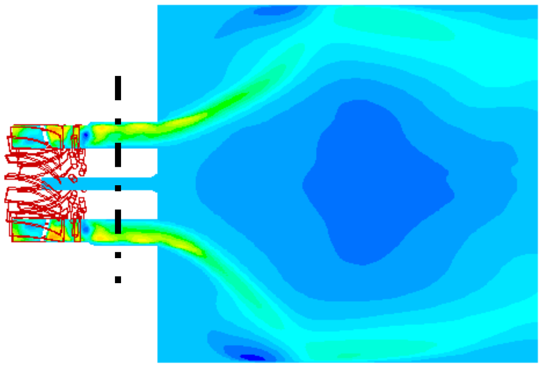


Industrial fuel nozzle (1.5 lb./s air)

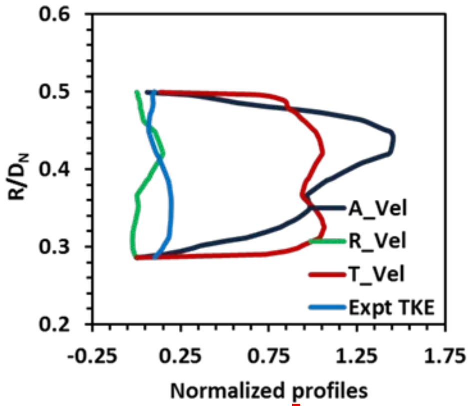
Simplified modeling methodology
- Step 1: Swirler + combustor
- Step 2: 90^0 sector alone

Inlet conditions for 90° combustor sector

- Downstream velocity profiles obtained from Step 1
- Velocity profiles applied as inlet BC for Step 2
- TKE is derived from experiments



Step 1

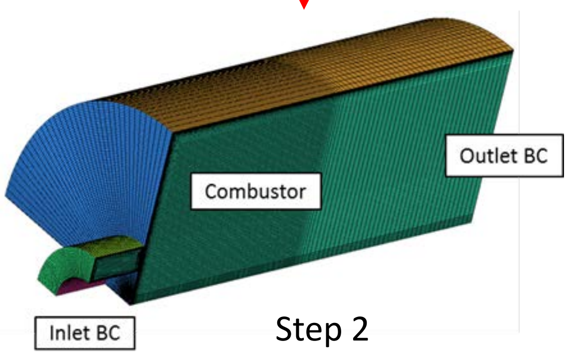


Simulation schemes:

Steady state, RANS computations
Pressure based solver
SIMPLE, Coupled P-V scheme
2nd order spatial discretization
Least square based gradients

BCs

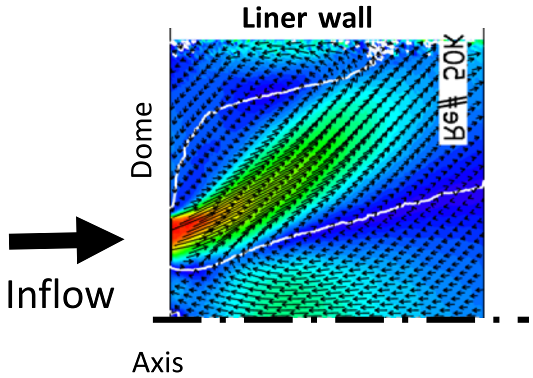
Inlet: Velocity profiles, k, e, w
Liner wall: constant heat flux 2500 W/m²
Side faces: Rotationally periodic
Outlet: Pressure outlet (atm), 75% TI, IRZ size

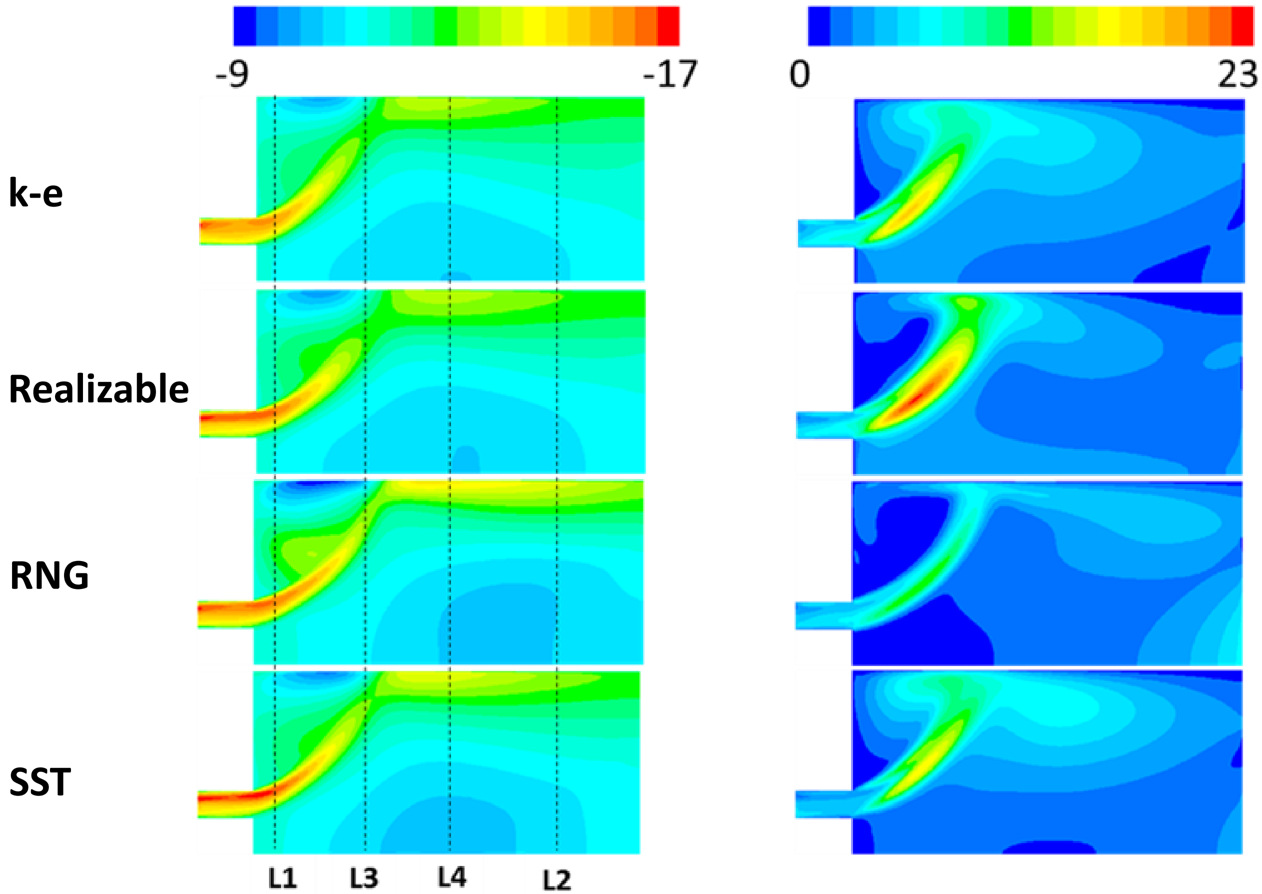


Step 2

Turbulence model effects: Re 50000 flow(non-reacting)

Expt Re 50k





Axial velocity (m/s)

TKE (m^2/s^2)

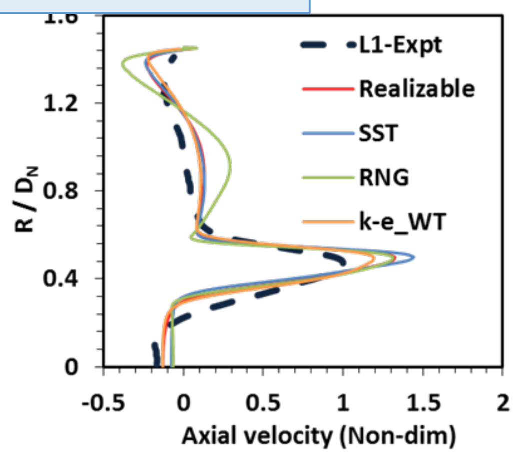
- ***Peak liner HT location varies with IRZ size***

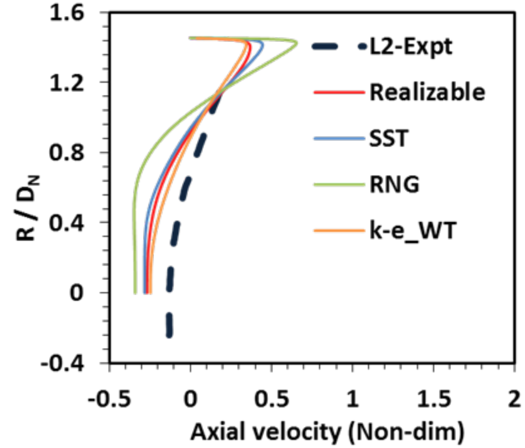
Inner Recirculation zone region and TKE predictions are different for different turbulence models

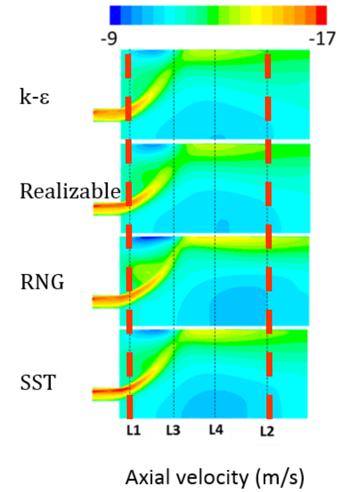
Axial velocity contours for Re 50000 flow

Outside IRZ- RANS predicts better

- Jet peak location well predicted

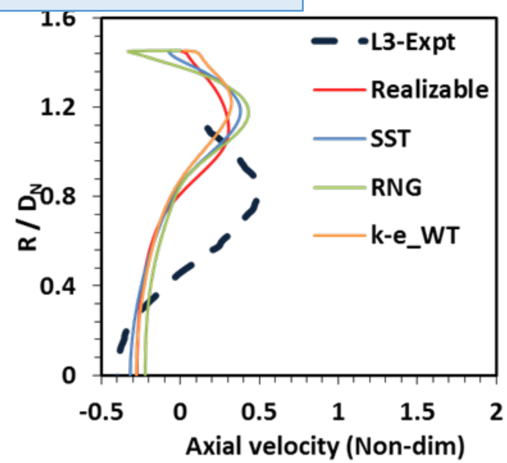


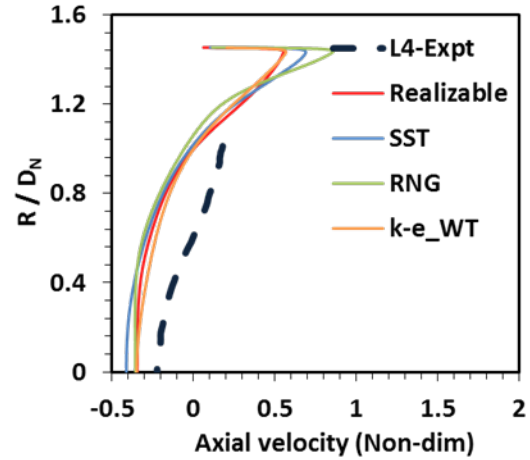


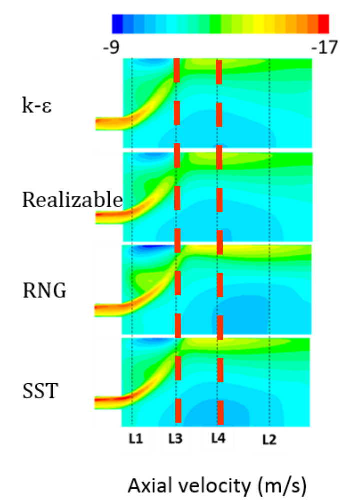


Inside IRZ – RANS predictions fail

- RANS limitations observed within IRZ
- Larger IRZ



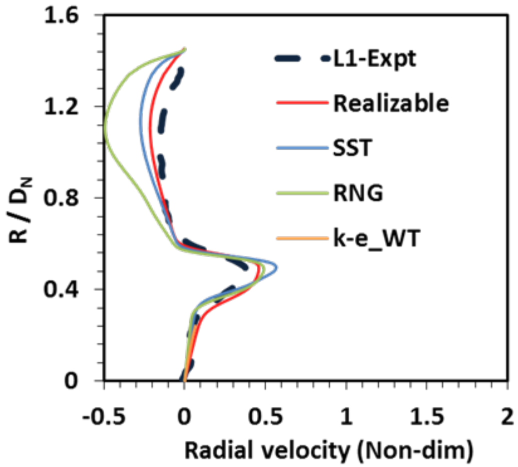


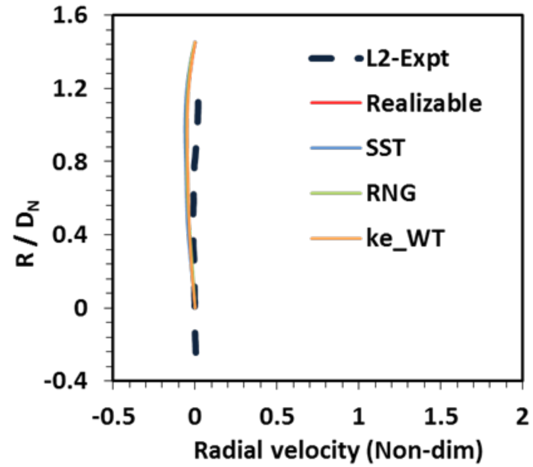


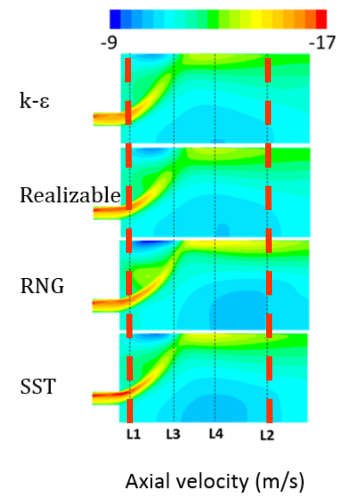
Radial velocity contours for Re 50000 flow

Outside IRZ- RANS predicts better

- RNG over-predicts Corner Vortex strength

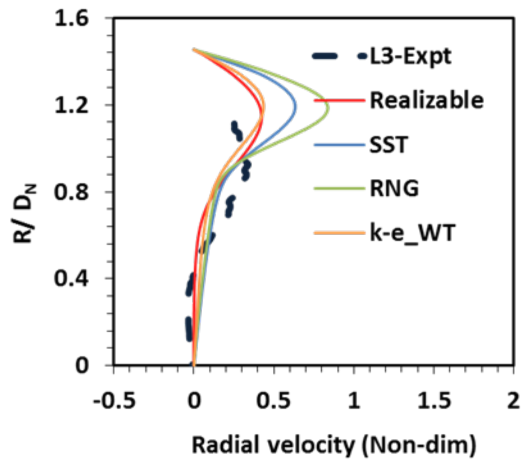


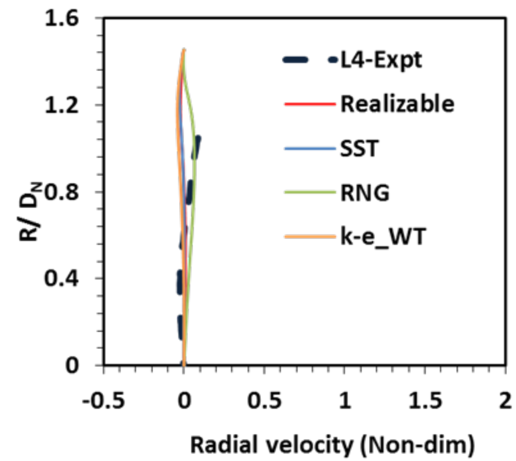


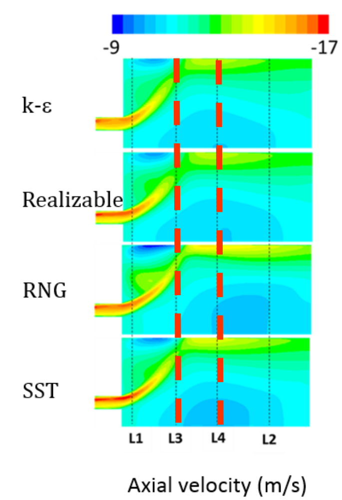


Inside IRZ – RANS predictions fail

- Larger gradients near liner



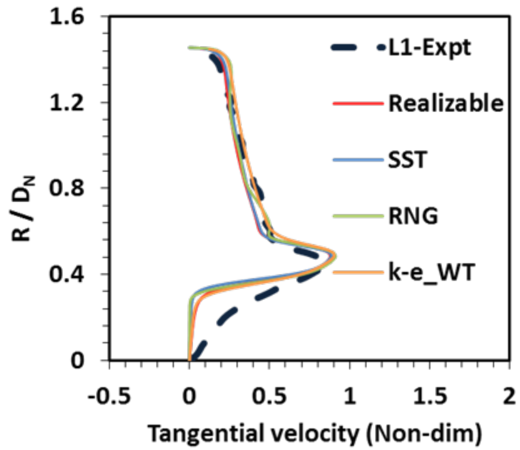


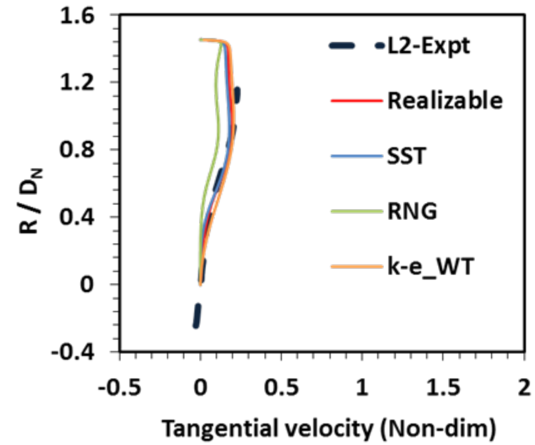


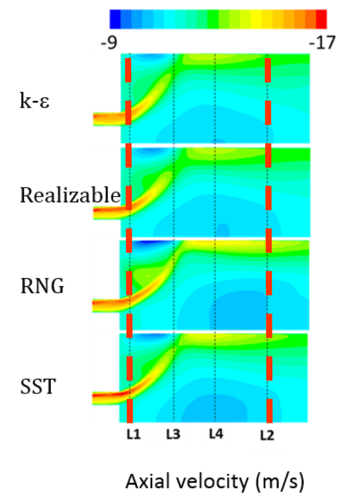
Tangential velocity contours for Re 50000 flow

Outside IRZ- RANS predicts better

- Rankine vortex behavior

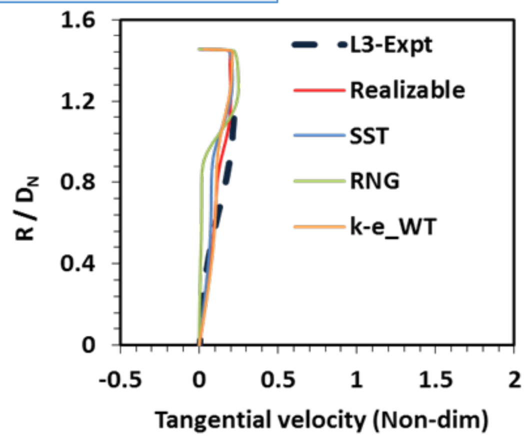


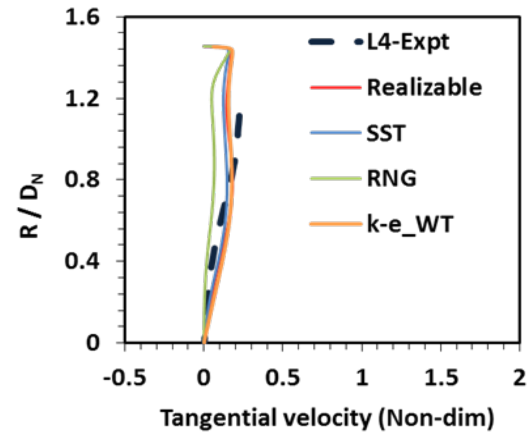


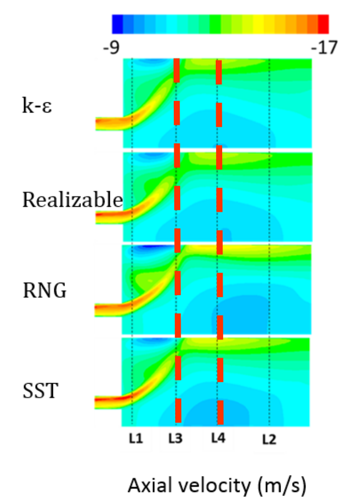


Inside IRZ – RANS predictions fail

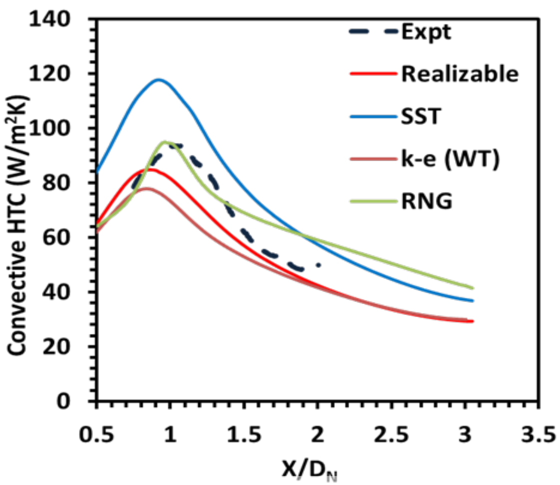
- Larger gradients near liner







Effect of turbulence models on liner HT predictions

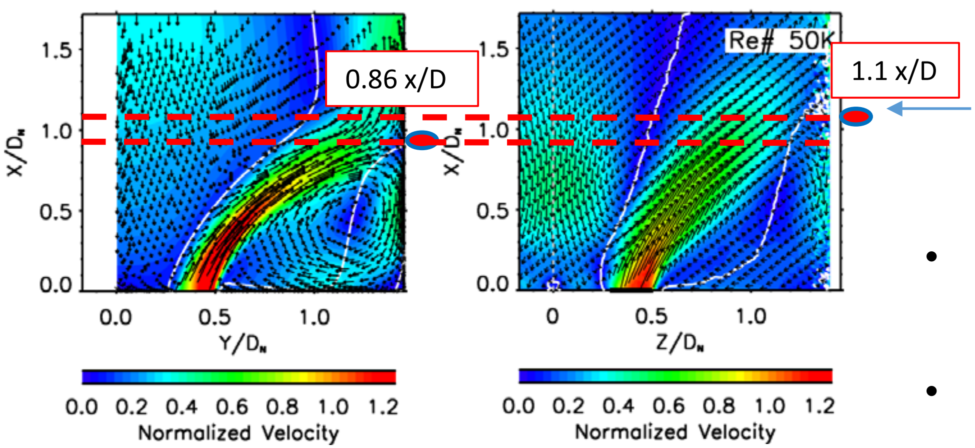


$$h = \frac{Q}{(T - T_{inlet})}$$

Peak Liner HT compilation v/s Expts

	Magnitude (%)	Location (%)
Expt	0.0	0.0
k-ε (WT)	-16	-21
Real	-8.7	-18
RNG	-2	-8
SST	+27	-12

CFD **Experiment**



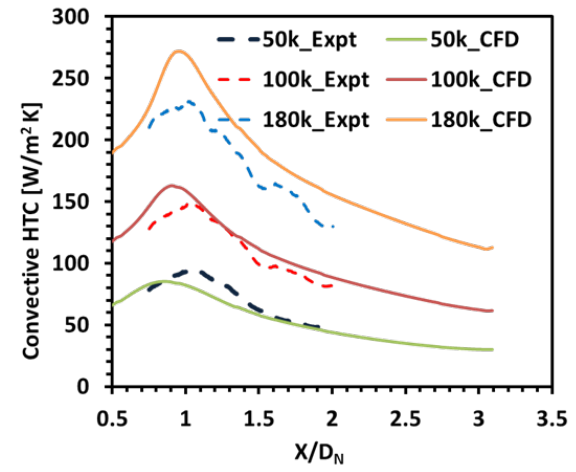
Impingement location

- **Realizable model chosen for future computations** based on better velocity predictions (compared to other models)
- RNG although offers better predictions, has convergence issues !!

Heat transfer predictions (High Re cases)

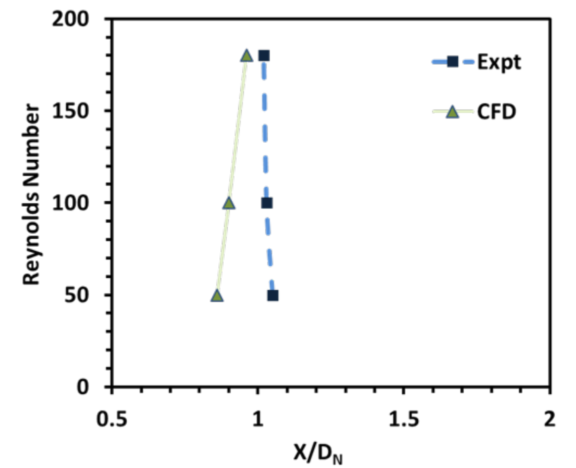
- Experiments show no change in peak HT location for High Re
- CFD predicted peak HT location moves downstream with Re until invariance is reached
- CFD magnitude predictions increase with simulated Re (*RANS limitations*)

	Magnitude (%)	Location (%)
50k	-8	-18
100k	3.8	-7
180k	13	-2

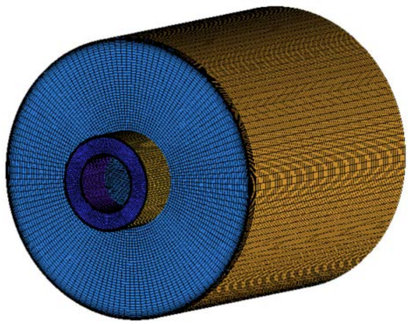


Issues with RANS and mitigation:

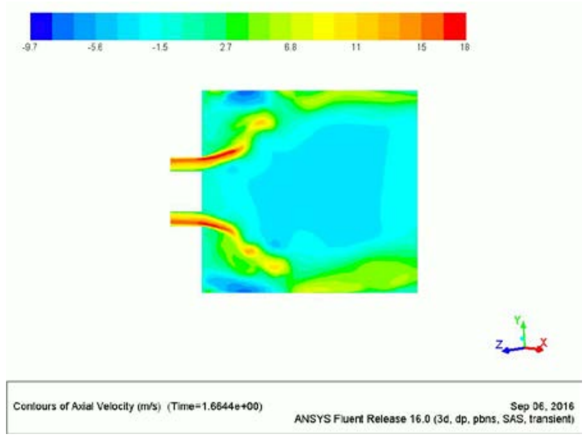
- Swirling flow has anisotropy due to vortex stretching (not captured well in RANS due to isotropy assumptions)
- Resolving vortex scales in the simulations may improve peak heat transfer characteristics
- Scale Resolved Simulations → SAS (unsteady) is the next step
  - 2 equation, transient set up with modified length scale equation (modified SST equations)
  - resolves large coherent scales based on new length scale (Von-karman scales)
  - 4 times less expensive than LES (needs y^+ ~1 mesh)



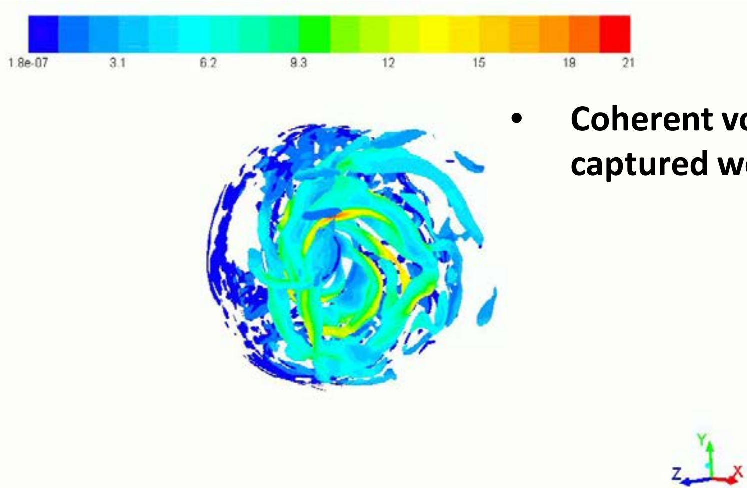
Unsteady SAS simulation capabilities- Re 50k



- Full 3D combustor domain used for SAS simulations (to capture vortex effects occupied in the entire domain)

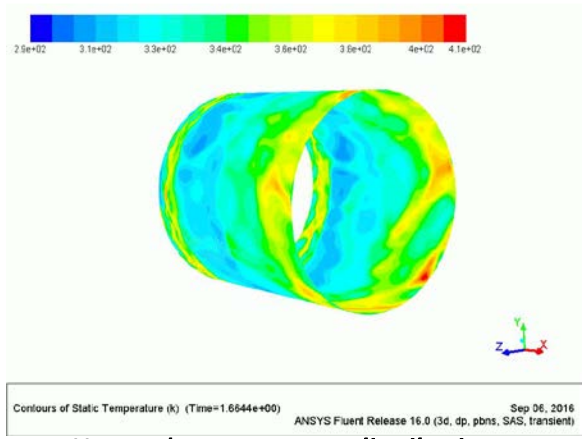


Unsteady Axial velocity contours (m/s)



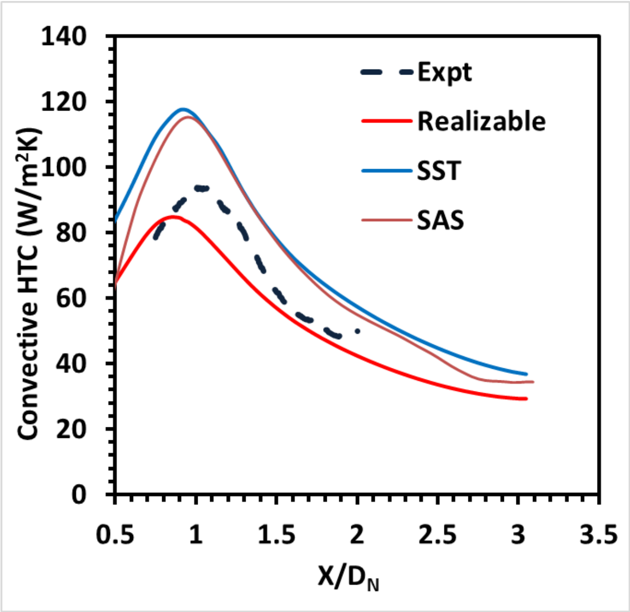
- **Coherent vortices captured well with SAS**

TKE on iso-contours of Q-criterion (SAS-SST unsteady solution)



Unsteady temperature distribution (K) along the liner wall (simulation yet to reach convergence)

Unsteady SAS simulation results- Re 50k



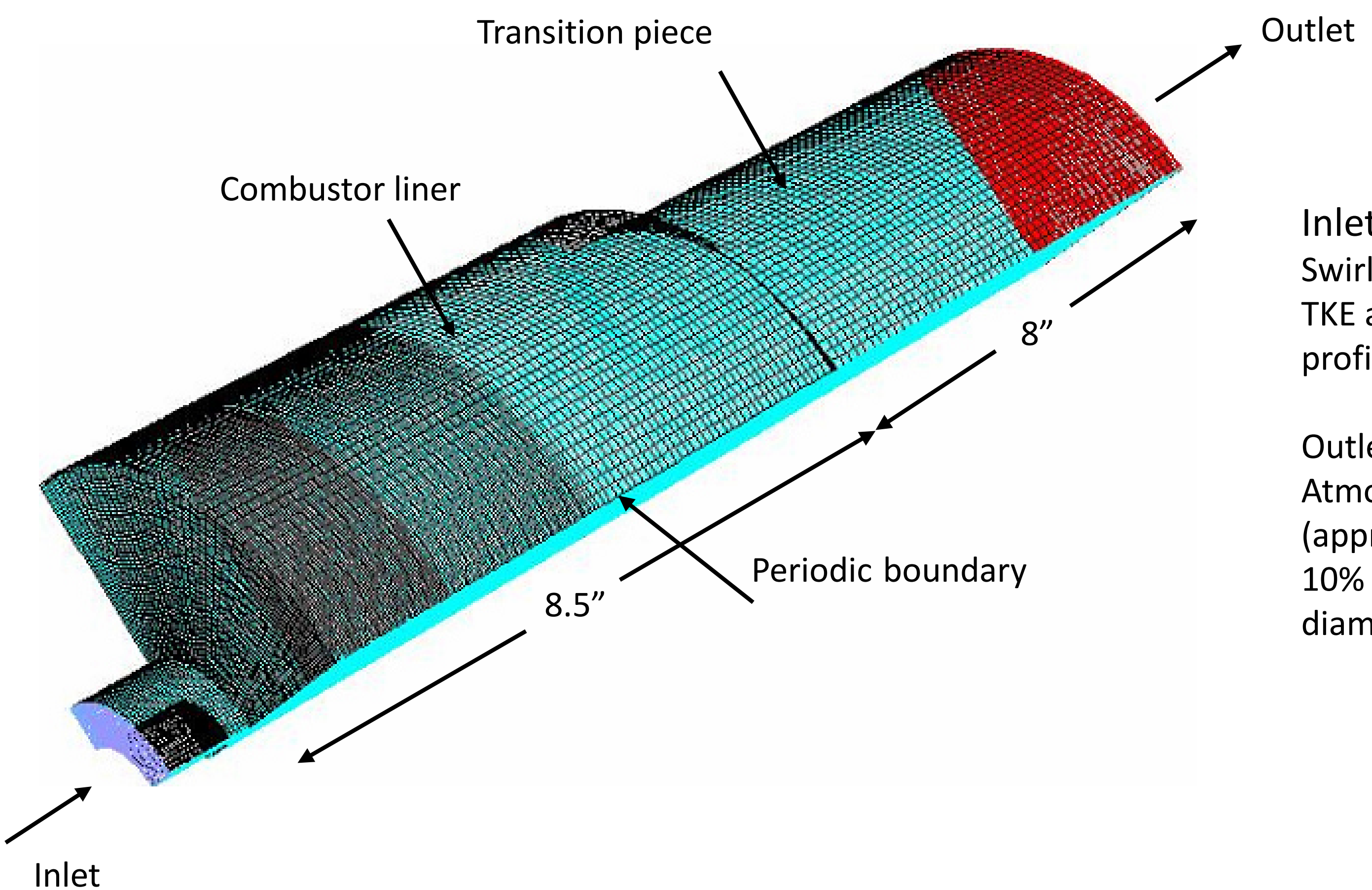
Peak Liner HT compilation v/s Expts

	Magnitude (%)	Location (%)
Expt	0.0	0.0
k-ε (WT)	-16	-21
Real	-8.7	-18
RNG	-2	-8
SST	+27	-12
SAS	+25	-9

- **SAS-SST qualitatively predicts the coherent vortices within the combustor**
- **Predicts Liner impingement location better for Re 50k**
- **Over-predicts the HTC magnitude similar to SST model**

Sector model (with transition piece) for reacting/non-reacting simulations - ongoing

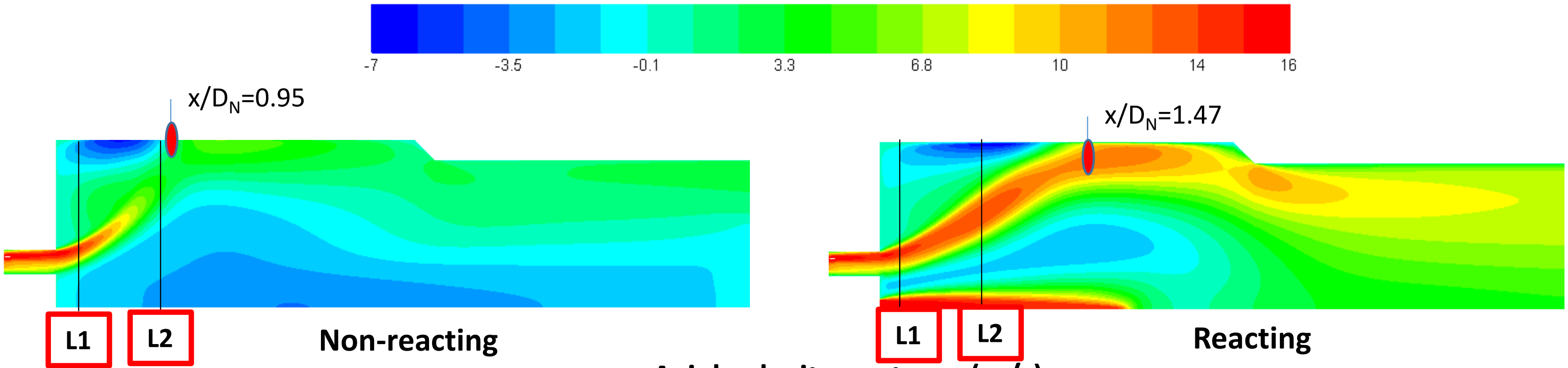
Current simulations (steady state) are performed for CFD domain (90^0 sector) that also includes transition piece (8” length which is ½ of its total length)



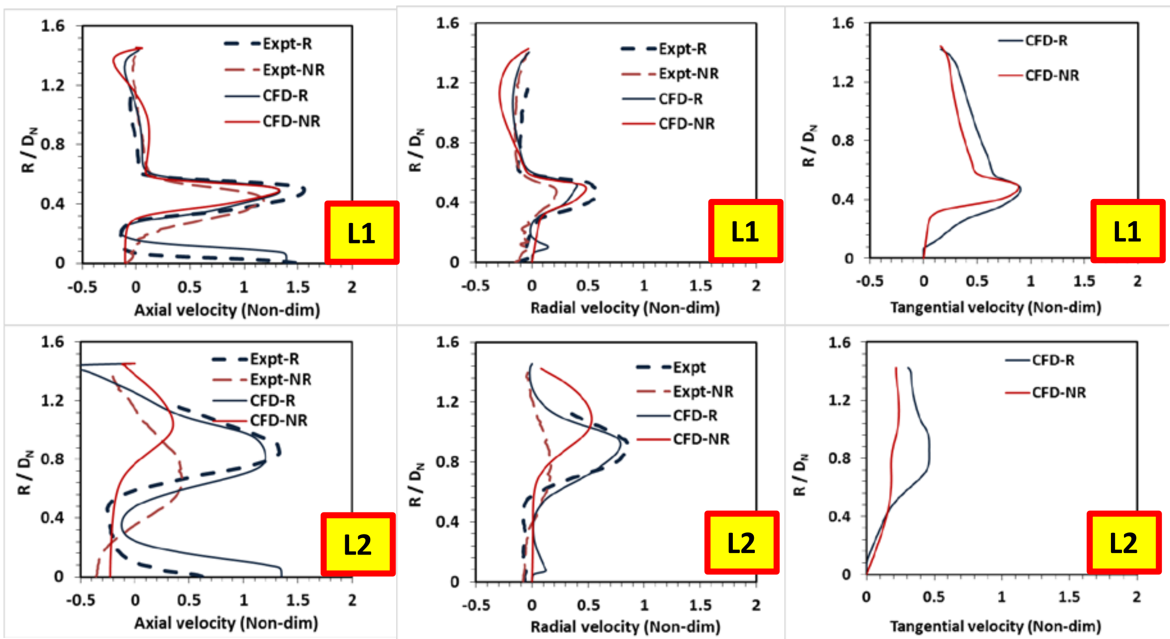
Inlet BC:
Swirler velocity profiles
TKE and dissipation rates profile

Outlet BC:
Atmospheric pressure (approximated.)
10% TI and Hydraulic diameter

Flow profiles with and without reaction: Re 50000

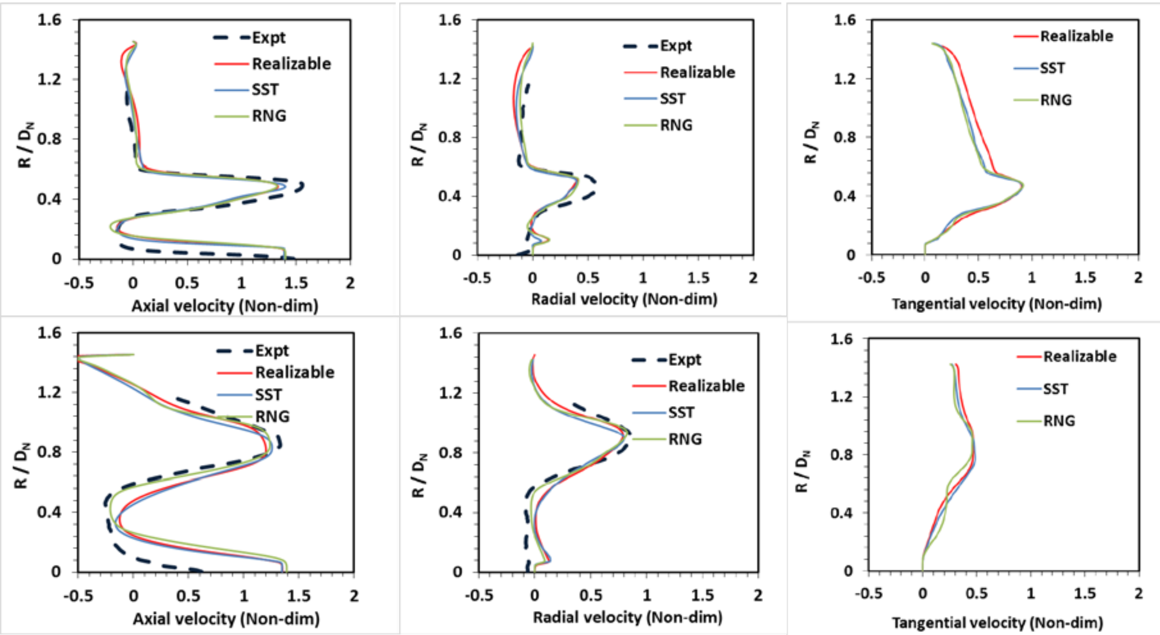


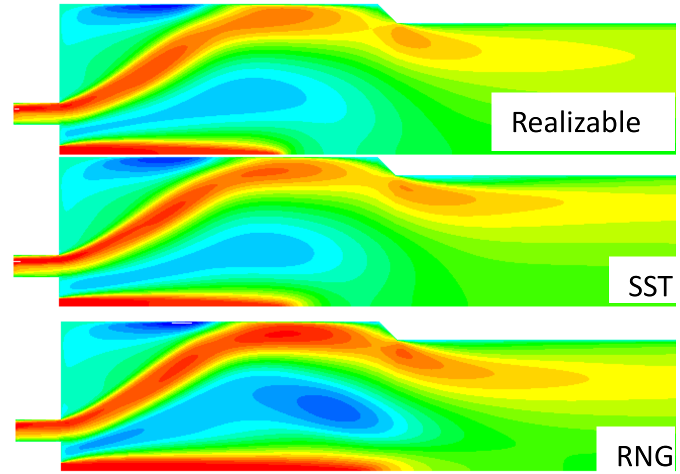
Axial velocity contours (m/s)



- Flow profiles well predicted for reacting case
  - IRZ strength damped
- IRZ extends into transition case (for non-reacting case)
- Reduced IRZ size pushes liner impingement location downstream (50%) (for reacting case)

Turbulence model impact on flow profiles: Re 50000





- Turbulence models show negligible impact on reacting flow profiles inside combustor

Accomplishment summary in 2015-2016, targets till Dec 2016, future goals

Computational side:

Accomplishment summary

- Isothermal flow CFD studies with RANS compared with in-house test data (k-e Realizable model chosen)
- **Experimental v/s RANS computational results** compared for various Reynolds numbers (Liner HT)
- **Effect of inlet swirl** was studied v/s liner impingement location
- **Unsteady SAS simulations** being performed for low Re case to investigate liner HT features

Moving forward (till Dec 2016):

- SAS simulations (non-reacting) for low Reynolds numbers
- Flow analysis under reacting conditions for various Re using RANS model (k-e Real)
  - v/s equivalence ratios
  - v/s Re
- Parametric studies (for various combustor diameters- isothermal)

Future Goals (beyond Dec 2016):

- SAS simulations (isothermal and reacting) for high Reynolds numbers
- Liner Heat transfer analysis under reacting conditions for various Re using SAS/LES models
  - v/s equivalence ratios
  - v/s Re Nos

- Parametric studies (for reacting conditions)

Peer reviewed publications related to this work

Published/under review:

1. **Kedukodi, S**., Ekkad, S., Moon, H K., Srinivasan, R., Kim, Y., 'Numerical investigation of effect of geometry changes in a model combustor on swirl dominated flow and heat transfer', Proceedings of ASME Turbo Expo 2015 (Montreal, Canada), No. GT2015-43035
2. **DG Ramirez,** V Kumar, SV Ekkad, D Tafti, Y Kim, HK Moon, R Srinivasan, " Flow field and Liner Heat Transfer for a Model Annular Combustor Equipped with Radial Swirlers"
3. **D Gomez-Ramirez**, D Dilip, BV Ravi, S Deshpande, J Pandit, SV Ekkad et al., "Combustor Heat Shield Impingement Cooling and its Effect on Liner Convective Heat Transfer for a Model Annular Combustor With Radial Swirlers", ASME Turbo Expo 2015
4. **Kedukodi, S**., Ekkad, S., 'Effect of downstream contraction on liner heat transfer in a gas turbine combustor swirl flow', ASME Gas Turbine India Conference 2015, No. GTINDIA2015-1206 **(Recommended for Journal and Honors)**
5. **D Gomez-Ramirez**, SV Ekkad, BY Lattimer, HK Moon, Y Kim, R Srinivasan., "Separation of Radiative and Convective Wall Heat Fluxes Using Thermal Infrared Measurements Applied to Flame Impingement ", ASME IMECE 2015
6. **Kedukodi, S**., Ramirez, DG., Ekkad, S., Moon, H K., Srinivasan, R., Kim, Y., 'Analysis on impact of turbulence parameters on isothermal gas turbine combustor flows', ASME 2016 Summer Heat Transfer Conference, No. HT2016-7134
7. **Ramirez, DG.,** Kedukodi, S., Gadiraju, S., Ekkad, S et al., 'Gas turbine combustor rig development and initial observations at cold and reacting conditions', Proceedings of ASME Turbo Expo 2016, No. GT2016-57825
8. **D Gomez-Ramirez**., "Heat Transfer and Flow Measurements in an Atmospheric Lean Pre-Mixed Combustor". PhD Dissertation
9. **David Gomez-Ramirez,** Sandeep Kedukodi, Srinath V. Ekkad, Hee-Koo X. Moon, Yong Kim, Ram Srinivasan., 'Investigation of isothermal convective heat transfer in an optical combustor with a low-emission swirl fuel nozzle ', Applied thermal engineering **(Under review)**
10. **David Gomez-Ramirez,** Srinath V. Ekkad, Hee-Koo Moon, Yong Kim, Ram Srinivasan., 'Isothermal coherent structures and turbulent flow produced by a gas turbine combustor lean pre-mixed swirl fuel nozzle ', Experimental Thermal and Fluid Science **(under review)**

Peer reviewed publications related to this work

In Preparation

1. **Kedukodi, S.,** Ramirez, DG., Ekkad, S et al., 'Effect of two-equation turbulence models on liner heat transfer and combustor flow', IJHMT
2. **Kedukodi, S.,** Ramirez, DG., Ekkad, S et al., 'Effect of combustor geometry modifications on liner heat transfer', IJHMT
3. **Kedukodi, S.,** Ramirez, DG., Ekkad, S et al., 'Comparison of combustor flow and liner heat transfer predictions using RANS and SAS turbulence models ', IJHMT
4. **Kedukodi, S.,** Park, S., Gadiraju, S., Ekkad, S et al 'Experimental and Numerical Investigations for Flow Fields under Non-Reacting and Reacting Conditions through a Lean Premixed fuel nozzle', IGTI 2017 ***(abstract submitted)***
5. **Gadiraju, S.,** Park, S., Ekkad, S et al 'Characterization of Lean Blow Out Limits and Sensing of Precursor Events for an Industrial Premixed Swirl Stabilized Nozzle', IGTI 2017 ***(abstract submitted)***
6. **Gadiraju, S.,** Park, S., Ekkad, S et al 'Application of Proper Orthogonal Decomposition to the Flame Chemiluminescence to Observe Flame Structure And Dynamics', IGTI 2017 ***(abstract submitted)***
7. **Park, S.,** Gadiraju, S., Kedukodi, S., Ramirez, DG., Ekkad, S., et al., 'Effects of Conditions on Reacting Flow in a Lean Premixed Swirl Stabilized Combustor at Atmospheric Pressure', IGTI 2017 ***(abstract submitted)***
8. **Park, S.,** Gadiraju, S., Kedukodi, S., Ramirez, DG., Ekkad, S., et al., 'Temperature Distribution Measurement on Reacting Flow in a Lean Premixed Swirl Stabilized Combustor' ', IGTI 2017 ***(abstract submitted)***

Acknowledgements

Robin Ames (DOE, NETL)
Hee-Koo Moon, Yong Kim, Ram Srinivasan (Solar Turbines Inc.)

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Thank you!