UTSR Workshop 2016
Flow and Heat Transfer Characterization of Lean Premixed Combustor Systems

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

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

Calculate heat flux into the liner from the normal temperature gradient

Estimate HTC based on reference gas temperature

Heat conduction equation for the quartz liner

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

Energy balance at the inner surface

\[ -k \frac{\partial T}{\partial r} \bigg|_{r=r_0} = h(T_{r=r_0} - T_{\infty}) \]
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°C

Use another filter for the IR camera.

Schott KG glasses

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

KG1

- Reduces overall IR radiance received by camera
- More aggressive for $\lambda > 2.7\mu$m where the quartz liner emits!

IR camera range

Quartz emission

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

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

0.6 Eq ratio- 50k Re
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).
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

LBO

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

LBO event is identified by pressure measurements

Current Status: Experiments are being conducted at various conditions.
Lean Blow Out (LBO) – Preliminary Studies

POD - Mode 1 shows Blowout

POD - Mode 2 shows Re-ignition.

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.

• 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
Reacting PIV under different conditions – Outline

Goal
- Examine reacting flow fields under different combustor operating conditions
  - \( \phi \) (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 1-2\( \mu \)m seeding particle

Test conditions – Total 9 cases
- 3 pilot fuel ratios
  - Varied: Pilot 6%, 4%, 0%
  - Fixed: \( \phi \) 0.65, Re 50 k
- 3 equivalence ratios
  - Varied: \( \phi \) 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%, \( \phi \) 0.65 (or \( \phi \) 0.58)

<table>
<thead>
<tr>
<th>Case</th>
<th>Pilot %</th>
<th>( \phi )</th>
<th>Re # ((\times 10^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>0.65</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>0.65</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0.65</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>0.78</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>0.55</td>
<td>50</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>0.65</td>
<td>75</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>0.55</td>
<td>110</td>
</tr>
</tbody>
</table>
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

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: \( \text{Re} \# = 50,000, \text{Pilot}: 6\% \)

- \( \phi : 0.55 \)
- \( \phi : 0.65 \)
- \( \phi : 0.78 \)

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 : $\phi$: 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%

<table>
<thead>
<tr>
<th>Re #</th>
<th>φ</th>
</tr>
</thead>
<tbody>
<tr>
<td>50,000</td>
<td>0.65</td>
</tr>
<tr>
<td>75,000</td>
<td>0.65</td>
</tr>
<tr>
<td>110,000</td>
<td>0.58</td>
</tr>
</tbody>
</table>

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

- 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**

<table>
<thead>
<tr>
<th>Case</th>
<th>Pilot %</th>
<th>$\phi$</th>
<th>Re #</th>
<th>$x/D_N$</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR1</td>
<td>-</td>
<td>-</td>
<td>50 k</td>
<td>1.34</td>
<td>-</td>
</tr>
<tr>
<td>NR2</td>
<td>-</td>
<td>-</td>
<td>50 k</td>
<td>1.32</td>
<td>-</td>
</tr>
<tr>
<td>R1</td>
<td>6</td>
<td>0.65</td>
<td>50 k</td>
<td>1.18</td>
<td>+1.9 %</td>
</tr>
<tr>
<td>R2</td>
<td>4</td>
<td>0.65</td>
<td>50 k</td>
<td>1.23</td>
<td>+6.2 %</td>
</tr>
<tr>
<td>R3</td>
<td>0</td>
<td>0.65</td>
<td>50 k</td>
<td>1.17</td>
<td>+1.0 %</td>
</tr>
<tr>
<td>R4</td>
<td>6</td>
<td>0.78</td>
<td>50 k</td>
<td>1.10</td>
<td>-5.0 %</td>
</tr>
<tr>
<td>R5</td>
<td>6</td>
<td>0.55</td>
<td>50 k</td>
<td>1.01</td>
<td>-12.8 %</td>
</tr>
<tr>
<td>R6</td>
<td>6</td>
<td>0.65</td>
<td>75 k</td>
<td>1.25</td>
<td>+7.9%</td>
</tr>
<tr>
<td>R7</td>
<td>6</td>
<td>0.55</td>
<td>110 k</td>
<td>1.17</td>
<td>+1.0 %</td>
</tr>
</tbody>
</table>

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

- 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

- 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

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

Axial locations of measurement (from fuel nozzle)
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
- **3D sector**
- **3D cylinder**

### Turbulence Models
- **RANS** (Steady-state)
- Scale Resolved Models: (Transient)
  - **SAS (in progress)**

### Premixed Models
- **Zimont Flamelet model**
  (Ongoing for modified test set-up)

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- **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
Approximate (lacking vane profile/turning angles)

CFD model of nozzle

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

Industrial fuel nozzle (1.5 lb./s air)
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

Simulation schemes:
Steady state, RANS computations
Pressure based solver
SIMPLE, Coupled P-V scheme
2\textsuperscript{nd} order spatial discretization
Least square based gradients

BCs
Inlet: Velocity profiles, k, e, w
Liner wall: constant heat flux 2500 W/m\textsuperscript{2}
Side faces: Rotationally periodic
Outlet: Pressure outlet (atm), 75% TI, IRZ size
Turbulence model effects: Re 50000 flow (non-reacting)

- 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

- Rankine vortex behavior
- Larger gradients near liner

Outside IRZ - RANS predicts better

Inside IRZ – RANS predictions fail
Effect of turbulence models on liner HT predictions

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

Peak Liner HT compilation v/s Expts

<table>
<thead>
<tr>
<th>Model</th>
<th>Magnitude (%)</th>
<th>Location (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expt</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>k-ε (WT)</td>
<td>-16</td>
<td>-21</td>
</tr>
<tr>
<td>Real</td>
<td>-8.7</td>
<td>-18</td>
</tr>
<tr>
<td>RNG</td>
<td>-2</td>
<td>-8</td>
</tr>
<tr>
<td>SST</td>
<td>+27</td>
<td>-12</td>
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Realizable model chosen for future computations based on better velocity predictions (compared to other models)

RNG although offers better predictions, has convergence issues !!

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*)

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<thead>
<tr>
<th></th>
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<tr>
<td>50k</td>
<td>-8</td>
<td>-18</td>
</tr>
<tr>
<td>100k</td>
<td>3.8</td>
<td>-7</td>
</tr>
<tr>
<td>180k</td>
<td>13</td>
<td>-2</td>
</tr>
</tbody>
</table>

**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 $y^+ \sim 1$ mesh)

**Graphs:**
- Convective HTC [W/m²K]
- Reynolds Number
- X/Dₜ
Unsteady SAS simulation capabilities - Re 50k

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

- Coherent vortices captured well with SAS

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

Unsteady Axial velocity contours (m/s)

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

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</tr>
<tr>
<td>SST</td>
<td>+27</td>
<td>-12</td>
</tr>
<tr>
<td>SAS</td>
<td>+25</td>
<td>-9</td>
</tr>
</tbody>
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- 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
Current simulations (steady state) are performed for CFD domain (90° 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

- 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
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:


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)*
In Preparation

2. Kedukodi, S., Ramirez, DG., Ekkad, S et al., ‘Effect of combustor geometry modifications on liner heat transfer’, IJHMT
Acknowledgements

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