Project Update: Flow and Heat Transfer Characterization of Lean Pre-mixed Combustor Systems

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Department of Energy
Solar Turbines, Inc.

Taurus 65 and Taurus 70 Turbines
Courtesy of Solar Turbines Inc.
Virginia Tech - Combustion Team

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- Current Affiliation: Schlumberger
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- Ph.D student in Mechanical Engineering
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- Current research: Experiment in flow field and heat transfer measurement

Yongbin Ji (Went back to China - Sep. 2017)
- Visiting scholar from Shanghai Jiao Tong University, China (PhD student)
- Experience: Experimental investigation on flow field and cooling of effusion cooled multi-nozzle combustor
Optical Combustor Rig

Updates on combustor test rig at Virginia Tech
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

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.
Axial swirl type premixed fuel nozzle

Industrial fuel nozzle by Solar Turbines Inc.

Input ports
- Air
  - Small % to pilot nozzle
  - Most to main nozzle
- Main fuel
- Pilot fuel

Output ports
- Main nozzle: air + main nozzle
- Pilot nozzle: air + pilot nozzle

Features
- Overall fuel air ratio
  - $\frac{\text{main fuel} + \text{pilot fuel}}{\text{total air}}$
- Pilot flow increases stability
Rig Upgrade – Test section

Added parts
- Exhaust connection
  - Transition piece
  - Water cooled jacketed pipe
  - Quenching system
- Double liner add-on piece
- Integrated dome plate
  - Air-cooling
  - Pressure transducer
  - Thermocouple
  - Built-in ignition
Rig Upgrade – Control and acquisition

Upgradation of the control and acquisition system

• Flow rate drift was removed by PID control
  Peak-to-peak error was reduced from 4.3% to 1.4 % (0.003 to 0.001 lb/s)
• DAQ upgrade to PXI system
• Wire connections are re-organized in an electrical box
• Integrated LabVIEW control
Rig Upgrade – Fuel supply system

- Control valves: Alicat mass flow controllers
  - Fast, precise measurement and control
  - Mass flowmeter + control
  - Max P : 145 psig
Liner Wall Heat Transfer

Non-intrusive infrared thermographic camera measurement on reacting combustor
Combustor liner heat transfer

Previous work validated the technique

Goal
• Investigate interaction between flow field and heat transfer on the liner wall
• Compare heat transfer characteristics on combustor liner with PIV flow field inside liner

Liner wall coating
• black paint spray, 5 coats
  • Inner wall coat: whole area in the view
  • Outer wall coat: a section in the view

Combustor operating condition
• Re 50k, $\phi = 0.65$, pilot 6-7%
• Geometry: Closed combustor downstream (previously done with open combustor)

Measurement setup
• FLIR SC6700 + KG2 filter glass
• Frame rate: 5 Hz rate
• Duration: ~180 s
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

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

\[ -k \frac{\partial T}{\partial r} \bigg|_{r=r_0} = h(T_{r=r_0} - T_\infty) \]
Inner and outer wall temperature measured in time

Combustor set point
- Re : 50 k
- $\phi$ : 0.65
- Pilot: 6%

Measurement
- FLIR SC6700
- Fps : 5 Hz
- KG2 filter
- Duration: 180 s

- Calibrated temperature of inner and outer liner surface
- Pilot flame was on at $t<0$, Main flame started at $t=0
Liner wall temperature axial profile

- Peak temperature location found at $x = 1.5\, D_N$ from the fuel nozzle.
- Maximum measured temperature:
  - 912 K (639 C) at inner wall
  - 880 K (607 C) at outer wall
Combustor liner heat flux measurement

- High heat transfer at low liner temperature
- Peak location moves downstream, from \( x/D = 1.8 \) \((t=20)\) to \( x/D = 2.4 \) \((t=180)\)
- Heat transfer at steady state at \( t > 160 \)
- Heat transfer peak is 23 kW/m\(^2\) at \( x/D_N \approx 2.3 \) at steady state
- Increase of heat flux at \( 0.9 \leq x/D_N \leq 2.3 \) due to heat release in reacting flow attached to liner wall
Combustor liner heat flux measurement

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Heat flux axial distribution in time

Axial distribution of heat flux on hot side (inner wall) in time

• Initially (0 < t < 3 s) peak heat flux reached higher than 200 kW/m²
• When liner is cold (t < 80s), peak heat flux was about 50-60 kW/m²
• After liner warmed up (t > 80 s), heat flux reduces below 40 kW/m²
• Peak heat load location moved from upstream (x/D_N = 1.8) to downstream (x/D_N = 2.4)
Reacting Flow Field

2D velocity field measurement with PIV (Particle Image Velocimetry) to study swirl flow field structure
PIV experimental setup at combustor rig

PIV measurement, (a) flame luminosity, (b) seeding particle injection, (c) laser sheet

PIV measurement experimental setup at combustor rig
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.
- Axial position of zero axial velocity at the liner wall indicates jet impingement location.
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 under different conditions
Impingement locations with 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**
2D Flow Temperature

Thermocouple probe scanning measurement on reacting flow
Temperature measurement

- 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

Diagram of temperature mapping setup in reacting flow
Temperature measurement

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Temperature measurement – Primary zone mapping

Combustor reacting conditions
- Re : 50000
- Equivalence ratio: 0.65
- Pilot fuel ratio: 6%
- Open combustor (without transition piece)

TC r-x plane scan setting
- Resolution: r - 5 mm, x - 10 mm
- Number of averaged samples : 3
- Time between samples : 0.5 s
- STD of samples : < 0.5%
- Number of nodes : 20 * 16
- Area : 0 < r_{ND} < 1.36, 0.14 < x_{ND} < 2.29
Temperature measurement – Primary zone mapping

- Highest temperatures were found at two locations
  - Shear layer between main flame and central recirculation
  - Center of recirculation zone, downstream of pilot flame
- Lower near wall temperature at $x_{ND} \approx 1.2$ was due to impingement of fresh mixture
- Near wall fluid temperature increases as the attached flow reacts continuously at downstream of impingement location
- Temperature at central recirculation was relatively uniform

Temperature profiles in reacting combustor
Temperature measurement – Axial line scans

- Temperature ranged 1000 K to 1500 K except flame jet region.
- Maximum and minimum in reacting flame jet region (0.2 < x/D < 1, r/D=0.71) were 1600 K and 400 K (at cold fuel air mixture and flame front).
- Near wall (r/D=1.36) temperature was higher at x/D > 1.7 due to continuous heat release of reacting flow attached on the wall.

**Conditions**
- Axial resolution: 5 mm (0.0714 D)
- Number of averaged samples: 3
- STD of samples: < 0.5%
- Number of nodes: ~300
- Number of repeat: 2 (1 for r/D = 0)

**Temperature profiles in axial scanning**

Inside combustor liner

![Graph showing temperature profiles in axial scanning inside combustor liner.](image)

**Schematic (top)**

- **Nozzle**
- **Liner**
- **r/D =1.45 at wall**
- **r/D=0**
- **r/D=0.71**
- **r/D=1.36**

**Legend**

- Blue line: r/D = 1.36
- Orange line: r/D = 0.71
- Yellow line: r/D = 0

**Graph Details**

- X-axis: x/D
- Y-axis: T (K)
- Color codes:
  - Blue: r/D = 1.36
  - Orange: r/D = 0.71
  - Yellow: r/D = 0
Flame IR Radiation

Infrared thermographic camera measurement on reacting flow
Infrared radiation of reacting flow in combustor

Instantaneous snapshots of flame IR radiation
- 7.5 Hz rate, 60 s duration
- Length scale was normalized with the fuel nozzle diameter, $D_N$
- Strong radiation around the axis
- Turbulent behavior of the flow was observed
Reconstruction of the flame infrared radiation

Averaged flame IR radiant energy density
- Line-of-sight averaged Two shear layers were observed (not visible in visible luminosity image)
- High intensity at hot metal surfaces, but not at quartz glass surfaces

Abel transformation
- Line-of-sight averaged radiant density projection was observed (left)
- Tomographic inversion for axisymmetric geometry
- Projection images are reconstructed to represent planar distributions
Infrared radiant energy density in axial-radial plane.

- The inner structures of swirl flame are more distinct.
- Flow structures shown better than the projection.
- Flame front between incoming fresh mixture and central recirculation zone.
- The flame front divides the image into two zones:
  1) main jet and corner recirculation, 2) central recirculation.
- The highest intensity: near the nozzle.
- The lowest intensity: incoming fresh mixture at main jet.
High Speed Imaging

To observe flame features using high speed direct light imaging
High Speed Imaging – Setup

Objective: To observe flame features using high speed direct light imaging

Experimental Setup showing High-Speed Camera

Photron Fastcam SA4 – High speed camera

Test Section – Quartz Liner

Test Section – Images taken in X-Y plane
Objective: To observe flame features using high speed direct light 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

Spatio-Temporal dynamics of the flame images are decomposed into constituent POD modes.

Highest POD mode represent the maximum spatial variance observed. Other POD modes shows spatial variance according to mathematical significance.

Spatial variance in flame images is because of the flame dynamics.
POD Modes - Stable Flame

50K Re | 6% pilot | 0.75 Eq ratio

Mean Image and Top 5 POD Modes
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).

Power Spectral Density of POD Time Coefficient and Pressure Measurement show similar frequency peaks.
POD Time Coefficients Comparison - Other Stable Cases

50K Re | 6% pilot | 0.65 Eq ratio

50K Re | 4% pilot | 0.65 Eq ratio

50K Re | 0% pilot | 0.65 Eq ratio

75K Re | 6% pilot | 0.65 Eq ratio
High Speed Imaging - Near Blowout Oscillations

Objective: To observe flame features and oscillations using high speed imaging

Animation shows high Speed Images acquired during near blowout Oscillations. The objective is to study these oscillations using the snapshots obtained from high speed imaging.
Near Blowout Oscillations - POD Modes

High Speed images were obtained at 500 Hz

POD Modes indicate flame extinction and re-ignition
POD Time Coefficients and Pressure Measurements similarity

POD was able to replicate the same frequencies as that of pressure fluctuations - 7.8 Hz.
POD Reconstruction Example

<table>
<thead>
<tr>
<th>Instantaneous Snapshots are not sufficient to understand the flame structure.</th>
<th>POD reconstruction shows statistically dominant flame structures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Near Blowout - POD Reconstruction

Mean Image of a Stable case

Compared to stable case, the flame spread even in the corner recirculation zone.

The Flame oscillation observed here correspond to the same 7.8 Hz observed in the pressure measurement.
Liner Wall Heat Transfer During Oscillations

Heat load on liner wall During Near Blowout Oscillations
Heat Flux Oscillations - Same as POD Temporal Coefficients

Transient Heat load measurements using IR-Thermography.

High magnitude fluctuations in heat flux were observed
Heat Flux Oscillations - Same as POD Temporal Coefficients

Amplitude of Heat Flux fluctuation is huge

Spectra shows 7.8 Hz frequency same as that of pressure oscillations and POD Temporal Coefficients.
Summary

Swirl flow field and heat transfer measurement

- Flow field structure and impingement locations were not sensitive to combustor operating parameters
- Temperature field inside combustor was measured in combustor primary zone
- Axial distribution of hot side heat flux on combustor liner wall was measured
- Moving maximum heat flux location was observed
- Feasibility of IR thermographic camera to measure thermal properties of turbulent reacting flows was demonstrated.

High Speed Imaging and Heat Transfer – Unstable combustion

- POD on High Speed imaging: Reconstruction and Phase averaging gave insight to flame oscillations
- Heat Transfer during near blowout oscillations showed huge fluctuation in liner heat transfer.
Project Accomplishments

• Development of optically accessible combustion test rig.
• Characterization of liner wall heat transfer and flow field in non-reacting conditions.
• Development of heat transfer technique for liner wall heat transfer in reacting conditions.
• Flow field characterization using PIV in reacting conditions.
• RANS based simulations with FGM model was able to predict combustor flow field numerically.
• Liner wall heat transfer in reacting condition.
• Demonstration of IR flame radiation measurements.
• Direct flame temperature measurements.
• Liner wall heat transfer during instabilities.
• Study of flame structures using high speed imaging.

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”**


Publications


Publications under review

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Thank you!
Sensitivity of POD modes on the Ensemble chosen

A correlation coefficient is defined as

\[ E(I) = \sqrt{\phi_A^I \cdot \phi_B^I} \]

Top few modes have most of the energy

First few modes are ensemble independent

Sensitivity analysis was performed to check the ensemble dependency

Two random ensembles A and B chosen from actual data set and POD was applied
Proper Orthogonal Decomposition - Snapshot Method

Arrange fluctuating part of images for the N snapshots as:

$$X = [x^1 \ x^2 \ \ldots \ x^N] = \begin{bmatrix} x_1^1 & \cdots & x_1^N \\ \vdots & \ddots & \vdots \\ x_m^1 & \cdots & x_m^N \end{bmatrix}$$

Calculate the covariance as:

$$C = X^TX$$

$C$ is a symmetric matrix and the Eigen value problem can be solved as:

$$CA_i = \lambda_i A_i$$

Eigen Vectors are representative of POD modes while Eigen values are representation of POD Mode energy

$$\lambda_1 > \lambda_2 > \lambda_3 > \ldots > \lambda_n = 0$$

POD modes are now found as:

$$\phi^i = \frac{\sum_{n=1}^{N} A_n x^i n}{\|\sum_{n=1}^{N} A_n x^i n\|}$$

With POD modes arranged as:

$$[\phi^1 \ \phi^2 \ \ldots \ \phi^N]$$

POD coefficients $a^i$ can be found for the snapshot $i$ as:

$$a^i = [\phi^1 \ \phi^2 \ \ldots \ \phi^N]^T x^n$$

A snapshot (fluctuating part) can be reconstructed as:

$$X_{n,Rec} = \sum_{i=1}^{N} \phi^i \ a^i_n$$