Coherent Anti-Stokes Raman Scattering (CARS) for Quantitative Temperature and Concentration Measurements in a High-Pressure Gas Turbine Combustion Test Rig

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Motivation

• To demonstrate dual-pump CARS measurements of CO$_2$, N$_2$ and temperature in the gas turbine combustor over a wide range of simulated supersonic flight conditions.

• To obtain high-quality data in the reacting flow field downstream of the NASA lean direct injection array for comparison with advanced computational models.
Outline of the Presentation

• Optically Accessible Gas Turbine Combustor Facility
• Dual-Pump CARS Measurements: Challenges and Optical System
• Temperature Measurements: PDFs, Mean Profiles, Standard Deviation Profiles
• Conclusions and Accomplishments
• Future Work
Purdue Gas Turbine Combustion Facility (GTCF)

<table>
<thead>
<tr>
<th>High Pressure Lab System</th>
<th>Maximum Flow Capacity</th>
<th>Max Operating Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas Heated High Pressure Air</td>
<td>9 lbm/sec</td>
<td>700 psi / 500 deg C</td>
</tr>
<tr>
<td>Electric Heated Air or Nitrogen</td>
<td>1 lbm/sec</td>
<td>600 psi / 600 deg C</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>2 to 5 lbm/sec</td>
<td>1,500 psi</td>
</tr>
<tr>
<td>Liquid Aviation Fuel (Kerosene)</td>
<td>1 lbm/sec/tank (2 tanks)</td>
<td>1,500 psi</td>
</tr>
<tr>
<td>Cooling Water</td>
<td>40 gpm</td>
<td>400 psi</td>
</tr>
</tbody>
</table>
NASA 9-Point LDI Assembly (Top-Hat)

• Nine simplex injectors arranged at throats of nine converging-diverging venturis in a 3 x 3 arrangement.

• Axial swirlers with helical vanes at 60° impart swirl to incoming heated air.

• Only central injector used for testing.
Window Assembly Details

Stagnant Air Gap

3"x3" Inner Cross Section
Coherent Anti-Stokes Raman Scattering (CARS)

- Conventional “Single-Pump” CARS
- Noninvasive
- Coherent Laser-Like Signal
- Spatially and Temporally Resolved
- Excellent Gas Temperature Data (especially at higher temperatures)
Dual-Pump CARS of N\textsubscript{2}/CO\textsubscript{2}

\[ \omega_{as} = \omega_{p1} - \omega_s + \omega_{p2} \]

\( v=1,J \)

\( v=0,J \)

\( 2300 \text{ cm}^{-1} \)

\[ \omega_{p1} \quad \omega_s \quad \omega_{p2} \]

\[ \omega_{p2} \quad \omega_s \quad \omega_{p1} \]

\[ \omega_{as} = \omega_{p2} - \omega_s + \omega_{p1} \]

\( v=1,J \)

\( v=0,J \)

\[ 1300 \text{ cm}^{-1} \]
CARS System for GTCF Measurements

A: Aperture
BD: Beam Dump
CL: Camera Lens
IF: Interference Filter
L: Lens
\(\lambda/2\): Half-wave-plate
Pol: Polarizer
S: Shutter
TS: Translation Stage
ZL: Zoom Lens
Optical Arrangement for Laser Beam Generation

- **Seeded Nd:YAG**: Input source for laser beam generation.
- **BBDL**: Beam block device
- **ECDL**: External Cavity Diode Laser
- **BS**: Beam Splitter
- **PDA 1**: Polarization Dependent Attenuator
- **PDA 2**: Polarization Dependent Attenuator
- **Mirror**: Reflecting surface for beam redirection
- **OPO**: Optical Parametric Oscillator
- **To Purdue GTCF**: Path for laser beam output to external facility
Dual-pump CARS System
Measurement Challenges in GTCF

- Translation of probe volume inside the flame zone.
- Installation of pin-hole for spatial overlap of CARS beams not possible, must use reference leg alignment.
- Measurement of non-resonant signal in the reference leg for spectral normalization of CARS signal.
- Safety of thin window, CARS beams are focused tightly in the middle of the test section.
CARS Probe Volume Translation
DP-CARS Detection Optics
Operating Conditions, Measurement Locations and Sample DP-CARS Spectra

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Φ = 0.4</th>
<th>Φ = 0.59</th>
<th>Φ = 0.80</th>
<th>Φ = 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 psia</td>
<td>■</td>
<td>■</td>
<td>■</td>
<td>■</td>
</tr>
<tr>
<td>125 psia</td>
<td>■</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150 psia</td>
<td>■</td>
<td></td>
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</tbody>
</table>

- **Burner Inlet**
  - Temperature: 850 °F (725 K)
- **Fuel**: Jet-A
- **Normalized injector pressure drop** = 4%

**Note**: Distance between points along the centerline is 5 mm

\[ Φ = 0.6 \]
\[ P = 100 \text{ psi} \]
\[ ΔP/P = 4\% \]

**Comb. Pr. = 100 psia, Eq. Ratio = 0.8**

- **T = 1325 K**
- **CO₂/N₂ = 0.079**

**Data**
**Theory**
**Residual**

**PURDUE UNIVERSITY**
Purdue GTCF in Operation

Central injector operation

$\Phi = 0.45, \ P_{\text{comb}} = 120 \ \text{psia}, \ T_{\text{inlet}} = 780^\circ \text{ F}$
Flame Characteristics @ 100 psia

Φ = 0.4
Φ = 0.59
Φ = 0.8
Φ = 1.0
Data Analysis

- 1000 to 2000 spectra collected at each measurement location.
- Spectra with low average $N_2$ signal counts and droplet interferences rejected.
- Square-root of background corrected normalized CARS spectra analyzed using Sandia CARSFT code in the batch processing mode.
- $N_2$ spectra analyzed for optimal temperature, horizontal and vertical shift, instrument function etc.
- Spectra with low peak $CO_2$ counts rejected. $CO_2$ part of the spectrum analyzed for $CO_2/N_2$ concentration ratio.
Data Processing

Raw Image → Restring → Beam Image → Corrected Non-Resonant Signal → Final Corrected Image
Combustor Pressure: 104 psia, Equivalence Ratio: 0.4

Temperature PDF: Z = 10 mm, R = 0 mm
Mean Temp. = 2020 K
Std. Dev. = 370 K

Temperature PDF: Z = 15 mm, R = 0 mm
Mean Temp. = 1820 K
Std. Dev. = 340 K

Temperature PDF: Z = 25 mm, R = 0 mm
Mean Temp. = 1595 K
Std. Dev. = 267 K

Temperature PDF: Z = 50 mm, R = 0 mm
Mean Temp. = 1340 K
Std. Dev. = 180 K
Temp PDFs at Different Locations

Combustor Pressure: 104 psia., Equivalence Ratio: 0.4

- **Temperature PDF: Z = 10 mm, R = 6 mm**
  - Mean Temp. = 1835 K
  - Std. Dev. = 340 K

- **Temperature PDF: Z = 10 mm, R = 9 mm**
  - Mean Temp. = 1760 K
  - Std. Dev. = 410 K

- **Temperature PDF: Z = 20 mm, R = 6 mm**
  - Mean Temp. = 1520 K
  - Std. Dev. = 235 K

- **Temperature PDF: Z = 20 mm, R = 9 mm**
  - Mean Temp. = 1405 K
  - Std. Dev. = 265 K
Mean Temperature & Temperature Standard Deviation Profiles

Combustor Pressure: 104 psia

Equivalence Ratio: 0.4
Mean Temperature Profiles

$Z = 20 \text{ mm}, 150 \text{ psia}, \Phi = 0.4$

Graph showing the mean temperature profile with vertical distance (mm) on the x-axis and mean temperature (K) on the y-axis.
Temperature and CO$_2$/N$_2$ PDFs

Combustor Pressure: 104 psia, Equivalence Ratio: 0.4

Temperature PDF: Z = 25 mm, R = 0 mm

- Mean Temp. = 1595 K
- Std. Dev. = 267 K

CO$_2$/N$_2$ Conc. Ratio PDF: Z = 25 mm, R = 0 mm

- Mean CO$_2$/N$_2$ = 0.0625
- Std. Dev. = 0.0212

Temperature PDF: Z = 30 mm, R = 3 mm

- Mean Temp. = 1515 K
- Std. Dev. = 205 K

CO$_2$/N$_2$ Conc. Ratio PDF: Z = 30 mm, R = 3 mm

- Mean CO$_2$/N$_2$ = 0.0546
- Std. Dev. = 0.019
Temperature and $\text{CO}_2/\text{N}_2$ Scatter

Combustor Pressure: 104 psia., Equivalence Ratio: 0.4

Temp. vs $\text{CO}_2/\text{N}_2$ Correlation: $Z = 25 \text{ mm}, R = 0 \text{ mm}$

Temp. vs $\text{CO}_2/\text{N}_2$ Correlation: $Z = 30 \text{ mm}, R = 3 \text{ mm}$
Accomplishments and Conclusions

- GTCF has been operated at wide range of simulated supersonic flight conditions. The optically accessible GTCF has been operated up at pressures up to 150 psia, single-shot dual-pump CARS measurements obtained at all operating conditions.

- Approximately 500,000 single-shot spectra were acquired in a test campaign conducted during the summer of 2009. These spectra are being processed to obtain temperature and CO\(_2/N_2\) concentration ratio values at various equivalence ratios at multiple axial and vertical positions downstream of the LDI injector.
Accomplishments and Conclusions

- A new OPO/PDA system was used to generate the 560-nm pump beam in the dual-pump CARS system. Considerable care in alignment was required for all beams to obtain good beam quality in the combustor test cell.

- The Zaber translation stages performed well, alignment was maintained over the entire spatial region of interest during the test.

- The reference leg was invaluable for alignment and for frequent recording of the nonresonant signal. Alignment was maintained before and after translation of the large 2-inch prisms.
Data analysis is still in progress. Filtering techniques to remove spectra with signals that were too low have been developed and are still being optimized.

Experimental results will be compared with computational results obtained from, for example, the National Combustion Code (NCC). The data will be provided in a form decided in collaboration with NASA personnel.
Accomplishments and Conclusions

- Estimated uncertainty in temperature measurements:
  - Accuracy: 1-2%
  - Precision: 2-3%

- Uncertainty in CO$_2$/N$_2$ ratio measurements:
  - Very dependent on CO2 concentration and on the temperature, approximately 10% relative standard deviation in the range of 5% CO2 concentration around 1500 K.

- Probe volume dimensions:
  - 500 μm along the laser propagation direction.
  - 50 μm perpendicular to the laser direction.


Typical Dual-Pump CARS spectra

Pressure: 100 psia. @ Φ = 1.0, 40 mm Center-line
Modified Combustor Window Assembly (CWA) for RRC Injector

- Cross section increased from 3"x3" to 4.2"x4.2". The modified CWA is fabricated from Hastelloy-X instead of stainless steel. Brazing has been eliminated. Film cooling air passages are incorporated in the injector assembly rather than in the CWA. Thermal barrier coatings are being applied to the window assembly inner surfaces.

- Upstream spool section has been redesigned to accommodate the larger injectors and to ensure uniform flow into the injector.

- Downstream spool sections redesigned for larger flow cross section.
Modified Combustor Window Assembly (CWA) for RRC Injector
Modified Combustor Window Assembly (CWA) for RRC Injector