University Turbine Systems Research Program
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Improving NOx Entitlement with Axial Staging
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Background, Why Axial Staging

- Firing temperature is main parameter to increase efficiency of ground-based gas turbine powerplants.
- \( \text{NO}_x \) is an exponential function of firing temperature.
- Need to minimize time at peak firing temperature.

Axial staging increases the peak firing temperature with a short residence time.
- Obtain axial stage data at industry relevant conditions.
- Develop reacting jet in crossflow correlation and validate CFD for axial stage modeling.
Tasks

- Task 2: Develop moderate pressure axial stage test rig
  - Tune headend to provide similar NO\textsubscript{x} curve as current engines

- Task 3: CH4-air axial stage conditions
  - Pressure effects
  - Level of axial premixing and preheating
  - Reacting and non-reacting jets
  - PIV, Chemiluminescence, exit emissions
  - Rig heat loss and test section inlet conditions
  - Axial jet mixture fraction profile

- Task 4: CH4-air/diluent axial stage conditions
  - Reacting and non-reacting jets
  - PIV, Chemiluminescence, exit emissions

- Task 5: Axial stage modeling
  - Develop reacting jet in crossflow correlation
  - Validate CFD
Experimental Facility and Diagnostics
5.4 atm combustion facility
- Concentric dump style headend combustor run at lean conditions
- Jet injector diameter = 12.7 mm and 4 mm
- Optically accessible test section for optical diagnostics with variable air heaters
- Contoured nozzle exit that is adjustable in length
- Perforated screen and 6-inch section to improve axial stage boundary conditions
- Increased exit length to improve CO burnout before emissions sampling

Experimental Facility – Overview

Test section
- 3.5” tall
- 3.0” wide
- 4.0” window length
- 0.5” axial jet diameter
- Jet starts 0.5” from window
Particle Image Velocimetry (PIV)
- Double pulse Nd:YAG Evergreen 200, 15 Hz repetition rate
- Andor Zyla 5.5 sCMOS Camer
- 530 ± 10 nm filter
- 3 μm Al$_2$O$_3$ particles used for seeding both jet and crossflow
- Vector resolution: 600 μm/vector, $\ell_f = 1500$ micron (3-4 vectors across flame)

High Speed CH* Chemiluminescence
- Photron fastcam SA1.1
- 430 nm filter
- 20,000 fps
- Spatial resolution: 270 μm/pix

Temperature Measurements
- Exposed bead B-type thermocouple
- High temperature c-type thermocouple

Emissions
- E-Instruments BTU 4500 Combustion Analyzer
Headend conditions to match real-world gas turbines:

- Headend $\Phi$: 0.58-0.72
- Temperature: 1350-1650ºC
- Velocity: 50 to 80 m/s
- Pressures: 1 to 5.4 atm
- NO levels: 5-25 ppmVol
- Relatively uniform velocity profile prior to axial stage
- Velocity and turbulence intensity profiles follow a 4th order fit function
- Temperature profile follows an approximate 2nd order function

- Velocity and turbulence intensity were measured at 5.4 atm.
- Temperature was measured at 1 atm.
CH4-air axial stage conditions

Pressures Effects
Premixing Effects
Preheating Effects
Non-Reacting Jets
Rig Heat Transfer

Test Conditions

- Pressure Range: 1 - 5.4 atm
- Headend $\Phi$: 0.58
- Axial Jet $\Phi$: 0.75
- Total $\Phi$: 0.60
- Momentum Flux Ratio: 15
- Firing Temperature: 1730K
- Axial Jet Diameter: 12.7mm
- Fuel: Premixed methane/air for crossflow and axial jet

Uniform normalized incoming velocity profiles with pressure

Decrease in turbulence intensity at elevated pressure

CFD profile extrapolation to 2nd dimension based on PIV data

PIV Velocity Profile
Extrapolation for CFD
Pressure Effects

- Decrease in flame lift off height with pressure
- Increase ignition delay time (shorter chemical timescales)
- Increased jet penetration with elevated pressure due to increase in heat release resulting in lower entrainment
- Trajectories underpredicted with literature correlations

Noticeable difference between 5 and 1-4 atm.
**Emissions**

- NO$_x$ levels increase with pressure in a single stage combustor
- Single stage combustor has longer length leading to increased thermal NO
- Benefits of axial staging are greater at higher pressures
- Shear burning flame (low pressure) seen to contribute to NO$_x$ production greater than core burning flame (high pressure) attributed to lower hot zones at higher pressures

**Important to test at a minimum of 5 atm for industry**
CH4-air axial stage conditions

- Pressure Effects
- Premixing Effects
- Preheating Effects
- Non-Reacting Jets
- Rig Heat Transfer

Effect of Premixing at Two Fuel Splits

- Fully and partially premixed flames look similar and ignite further upstream
- 15% fuel split burns mainly in viewing window, richer jet continues burning out of viewing window
- Non-premixed burns significantly further downstream for both fuel splits
- Total air/fuel fixed, phi=0.73, 1650 C overall temperature
Effect of Premixing at Two Fuel Splits

- Contours are vorticity from PIV, dashed line CH*
- Fully and partially premixed flames ignite in leeward shear region
- $\Phi = 1.07$ jet spreads to core while $\Phi = 1.78$ remains mainly in leeward shear layer
- Both non-premixed cases ignite in core
- Flame stabilization function of jet and crossflow equivalence ratio
Jet Centerline Trajectories

- The Holdeman correlation predicts more penetration for both fully premixed cases.
- The Holdeman correlation slightly overpredicts the non-premixed due to the strong windward entrainment.
- Max CH* intensity plotted at each $x/d_j$ to give an idea of flame strength at each location along the centerline.

![Graphs showing variation in penetration and CH* intensity for different equivalence ratios (ϕ = 1.07 and ϕ = 1.78).]
Flame Liftoff and Emissions

- Non-premixed flame lifted significantly compared to fully premixed with HE temperature 1,580 C
- Non-premixed flames liftoff similar independent of jet equivalence ratio
- Liftoff increases for fully premixed flames as jet equivalence ratio increases
- Non-premixed cases need more time to mix the fuel and air plus mix with the hot cross stream
- Non-premixed flames have lower NOx emissions compared to fully premixed attributed to the enhanced pre-flame mixing with increased liftoff
CH4-air axial stage conditions

Pressure Effects
Premixing Effects
Preheating Effects
Non-Reacting Jets
Rig Heat Transfer

Liftoff Variance

- The 25°C case was noticeably less stable than the 150°C and 300°C cases with HE temperature 1,580°C.
- Here the leeward flame ignites and propagates upstream, then back downstream for one of the 300°C and 25°C cases.
- The 25°C case propagates further downstream and at a slower rate than the 300°C case.
- This is seen across multiple cases: the 300°C cases dampen instabilities in the jet and are less susceptible to these large-scale fluctuations.
Emissions

\[ \tau_{\text{ign}} = \frac{LO}{v_{\text{jet}}} \]

- \( \tau_{\text{ign}} \) is used to quantify pre-flame mixing, where LO is liftoff height and \( v_{\text{jet}} \) is jet injection velocity
- Increasing jet preheat temperature hinders pre-flame mixing
- This leads to increased NO\(_x\) compared to non-preheated jets

Increasing jet temperature
Premixing vs. Preheating

- The non-premixed and non-preheated jets increased ignition delay and showed a NO$_x$ benefit compared to the fully premixed, preheated jet with HE temperature 1,580°C, jet equivalence ratio 1.8 and J=3.5.

- Three configurations were run at the same conditions and compared:
  - Fully premixed $T_{jet} = 300°C$
  - Fully premixed $T_{jet} = 25°C$
  - Non-premixed $T_{jet} = 25°C$

- Although the non-premixed provided the greatest ignition delay, the non-preheated provided the best NO$_x$ reduction.

- Attributed to the fully premixed jet mitigating hot regions compared to the non-premixed jet.
CH4-air axial stage conditions

Pressure Effects
Premixing Effects
Preheating Effects
Non-Reacting Jets
Rig Heat Transfer
Flow-field Comparisons

- Non reacting vs reacting for $J = 5.5$ instantaneous $u$, $v$, and $\omega$

- $J = 5.5$, $\Phi_{jet} = 1.62$ (for reacting), $\Phi_{HE} = 0.75$, $v_{HE} = 74$ m/s, $v_{jet} = 72$ m/s

- Reacting case shows a more coherent windward shear region than the non-reacting case

- Vorticity magnitude stronger for the reacting case

- Same headend conditions
Centerline Jet Trajectories

- Non-reacting vs non-reacting for \( J = 5.5 \) and \( J = 7 \) time-averaged jet centerlines

- For \( J = 7 \), \( \Phi_{\text{jet}} = 0.95 \) (for reacting), \( \Phi_{\text{HE}} = 0.66 \), \( v_{\text{HE}} = 69 \) m/s, \( v_{\text{jet}} = 77 \) m/s
  - Max penetration: 3.5 \( D_j \) for reacting
  - Max Penetration: 2.7 \( D_j \) for non-reacting

- For \( J = 5.5 \), \( \Phi_{\text{jet}} = 1.62 \) (for reacting), \( \Phi_{\text{HE}} = 0.75 \), \( v_{\text{HE}} = 74 \) m/s, \( v_{\text{jet}} = 72 \) m/s
  - Max penetration: 3.1 \( D_j \) for reacting
  - Max Penetration: 2.8 \( D_j \) for non-reacting

- A larger difference in trajectories is seen for the \( \Phi_{\text{jet}} = 0.95 \) compared to \( \Phi_{\text{jet}} = 1.62 \) because the heat release for the leaner jet occurs earlier in the trajectory
CH4-air axial stage conditions

Pressure Effects
Premixing Effects
Preheating Effects
Non-Reacting Jets
Rig Heat Transfer
Experimental Setup

- Sampled with NI-9174 DAQ at 75 Hz to obtain transient period
- Inner wall flush thermocouple mounted at inlet of test section where jet would be injecting
- Simultaneously measure temperature on the inside and outside of the rig to backout heat flux
Heat Transfer Results

- Temperature results for each case
  - Headend was varied between 1266-1600°C
  - The outer wall temperature increased throughout the campaign, but did not vary much during each individual run

<table>
<thead>
<tr>
<th>P (atm)</th>
<th>Φ_{global}</th>
<th>T_{global} (°C)</th>
<th>T_{inner} (°C)</th>
<th>T_{outer} (°C)</th>
<th>ΔT (°C)</th>
<th>q'' (kW/m²²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.684</td>
<td>1564</td>
<td>44</td>
<td>226</td>
<td>182</td>
<td>91</td>
</tr>
<tr>
<td>5</td>
<td>0.517</td>
<td>1266</td>
<td>52</td>
<td>168</td>
<td>116</td>
<td>58</td>
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<tr>
<td>5</td>
<td>0.597</td>
<td>1400</td>
<td>55</td>
<td>212</td>
<td>158</td>
<td>78</td>
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<tr>
<td>5</td>
<td>0.649</td>
<td>1500</td>
<td>58</td>
<td>261</td>
<td>203</td>
<td>101</td>
</tr>
<tr>
<td>5</td>
<td>0.706</td>
<td>1600</td>
<td>62</td>
<td>286</td>
<td>224</td>
<td>111</td>
</tr>
</tbody>
</table>
Outer Wall Temperature

- Recorded after 40 back-to-back runs
- Quasi steady-state
- Taken with infrared thermometer
CH4-air/diluent axial stage conditions
Testing Conditions

- Mass Flow Rate: 0.5kg/s
- Pressure: 5atm
- HE equivalence ratio : 0.70
- Diluent gas: CO₂ and N₂
- Diluent %: 0 to 50 (replace air in axial stage)
- Axial equivalence ratio: 1.75 to 3.5
- Fuel mass remain constant
- Momentum flux ratio: 5 and 8 without diluent
- Premixed Methane/Air Crossflow and Axial Jet
Diluents – Liftoff and Emissions

- Increased diluent leads to an increased axial jet equivalence ratio
- This in turn leads to increased liftoff
- Increased diluent leads to a decrease in overall NO$_x$ of combustor
- CO$_2$ provided slightly better NO$_x$ reduction compared to N$_2$
Reacting Jet-in-Crossflow Correlation
Jet Centerline and Max Trajectory Correlation

- MATLAB algorithm written to create correlation accurate within 1.8%

- Correlation holds for jets where there is sufficient heat release prior to deflection into crossflow (fully premixed vs. non-premixed)

- Three different equivalence ratios were run: 0.73, 1.07, and 1.78. Valid for P = 1-5.4 atm

\[
\frac{y_c}{d_j} = 1.13 J^{0.68} \left( \frac{x}{d_j} J^{-0.23} \right)^{0.59} P^{0.12}
\]

\[
\frac{y_{max}}{d_j} = 0.73 J^{0.68} P^{0.12}
\]
Jet Centerline and Max Trajectory Correlation

- Comparing to literature and industry-based correlations
- Holdeman and Lefebvre underpredict jet trajectory
- Recent Wagner investigation in a low Reynolds number reacting flow
- Non premixed case under-penetrates current correlation. CH* signal not seen until jet has already been swept into crossflow
- Level of premixing needs to be in the correlation
CFD-based, exp. validated

Traditional sqrt-trajectory description

\[ \frac{y}{d} = a \ast J^b \ast \left( \frac{x}{d} \right)^c \]

<table>
<thead>
<tr>
<th>sqrt-type</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lefebvre [33]</td>
<td>0.82</td>
<td>0.5</td>
<td>0.33</td>
</tr>
<tr>
<td>Holdeman [34]</td>
<td>0.89</td>
<td>0.47</td>
<td>0.36</td>
</tr>
<tr>
<td>Demuren [32]</td>
<td>0.7-1.3</td>
<td>0.36-0.52</td>
<td>0.28-0.40</td>
</tr>
</tbody>
</table>

Approximate 12.7mm jet data with quarter-Ellipse

\[ \frac{y}{d} = \sqrt{\frac{2 \alpha J^b \ast \left( \frac{x}{d} \right)^\beta - \left( \frac{x}{d} \right)^2}{\sqrt{J^\gamma}}} \]

<table>
<thead>
<tr>
<th>Ellipse</th>
<th>α</th>
<th>β</th>
<th>γ</th>
</tr>
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<tbody>
<tr>
<td>(a)</td>
<td>1.0</td>
<td>0.88</td>
<td>1.0</td>
</tr>
<tr>
<td>(b)</td>
<td>1.65</td>
<td>0.82</td>
<td>1.76</td>
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CFD Validation
### Operating Conditions

<table>
<thead>
<tr>
<th>Headend conditions</th>
<th>Axial jet conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main air flow</strong></td>
<td>Air flow</td>
</tr>
<tr>
<td>0.290 kg/s</td>
<td>0.03618 kg/s</td>
</tr>
<tr>
<td><strong>Main CH4 flow</strong></td>
<td>CH4 flow</td>
</tr>
<tr>
<td>0.010 kg/s</td>
<td>0.002104 kg/s</td>
</tr>
<tr>
<td><strong>By-pass air flow, total</strong></td>
<td>Inlet temperature</td>
</tr>
<tr>
<td>0.071 kg/s</td>
<td>573 K</td>
</tr>
<tr>
<td><strong>Hydrogen pilot flow, total</strong></td>
<td>Inlet density</td>
</tr>
<tr>
<td>0.00048 kg/s</td>
<td>3.364 kg/m^3</td>
</tr>
<tr>
<td><strong>Products velocity</strong></td>
<td>CH4 mass fraction</td>
</tr>
<tr>
<td>49 m/s</td>
<td>0.05517</td>
</tr>
<tr>
<td><strong>Products density</strong></td>
<td>O2 mass fraction</td>
</tr>
<tr>
<td>1.125 kg/m^3</td>
<td>0.2202</td>
</tr>
<tr>
<td><strong>Products temperature</strong></td>
<td>N2 mass fraction</td>
</tr>
<tr>
<td>1545 K</td>
<td>0.72463</td>
</tr>
<tr>
<td><strong>Pressure</strong></td>
<td>Turbulence intensity</td>
</tr>
<tr>
<td>5.4 atm.</td>
<td>17 %</td>
</tr>
<tr>
<td><strong>CO₂ mass fraction, exit</strong></td>
<td>Turbulence length</td>
</tr>
<tr>
<td>0.0761 -</td>
<td>0.0012 m</td>
</tr>
<tr>
<td><strong>H₂O mass fraction, exit</strong></td>
<td>Axial jet diameter</td>
</tr>
<tr>
<td>0.07378 -</td>
<td>12.7 mm</td>
</tr>
<tr>
<td><strong>N₂ mass fraction, exit</strong></td>
<td>J</td>
</tr>
<tr>
<td>0.74468 -</td>
<td>10.0</td>
</tr>
<tr>
<td><strong>O₂ mass fraction, exit</strong></td>
<td>T increase</td>
</tr>
<tr>
<td>0.10544 -</td>
<td>100 K</td>
</tr>
<tr>
<td><strong>Turbulence intensity</strong></td>
<td></td>
</tr>
<tr>
<td>5 %</td>
<td></td>
</tr>
<tr>
<td><strong>Turbulence length scale</strong></td>
<td></td>
</tr>
<tr>
<td>0.004 m</td>
<td></td>
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</tbody>
</table>
CFD Methodology

CONVERGE 3.0 URANS & LES
Sage laminar combustion model with full GRI 3.0 kinetic mechanism
Adiabatic wall BC’s
Modeled full width of rig from test section entrance to choke plate exit

**URANS**
RNG turbulence
4.5 M cell mesh
4 mm base mesh with embedding and AMR
0.025 s of statistics

**LES**
Dynamic Smagorinsky SGS turbulence
11.2 M cell mesh
2.5 mm base mesh with embedding, no AMR
0.03025 s of statistics
170 hrs on 360 cores
### Emissions Data

<table>
<thead>
<tr>
<th>Emissions</th>
<th>Data</th>
<th>LES probe</th>
<th>LES area average</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>6.5</td>
<td>6.1</td>
<td>6.1 % Vol dry</td>
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<tr>
<td>CO</td>
<td>4.1</td>
<td>1.9</td>
<td>1.6 ppm dry 15% O₂</td>
<td></td>
</tr>
<tr>
<td>NOₓ</td>
<td>5.9</td>
<td>0.8</td>
<td>0.9 ppm dry 15% O₂</td>
<td></td>
</tr>
</tbody>
</table>

Note: CFD O₂ and H₂O from equilibrium calculation
Averaged axial velocity and PIV centerline trajectory

LES

URANS

BAR_U: 0 10 20 30 40 50 60 70
# URANS Axial Stage Results

## Simulation cases

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
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<tbody>
<tr>
<td>Turbulence model</td>
<td>-</td>
<td>k-epsilon</td>
<td>RNG</td>
<td>k-epsilon</td>
<td>k-epsilon</td>
<td>k-epsilon</td>
</tr>
<tr>
<td>Inlet velocity</td>
<td>-</td>
<td>Case a</td>
<td>Case a</td>
<td>Case b</td>
<td>Experiment</td>
<td>Uniform</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>-</td>
<td>Case a</td>
<td>Case a</td>
<td>Case b</td>
<td>Case a</td>
<td>Uniform</td>
</tr>
<tr>
<td>Inlet turbulence</td>
<td>-</td>
<td>Case a</td>
<td>Case a</td>
<td>Case b</td>
<td>Experiment</td>
<td>Uniform</td>
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</table>

## Emissions

<table>
<thead>
<tr>
<th></th>
<th>15% O2</th>
<th>15% O2</th>
<th>15% O2</th>
<th>15% O2</th>
<th>15% O2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO(_x) (ppmv)</td>
<td>5.9</td>
<td>6.3</td>
<td>14.1</td>
<td>3.5</td>
<td>5.9</td>
</tr>
<tr>
<td>CO (ppmv)</td>
<td>4.1</td>
<td>1.1</td>
<td>1.5</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>CO(_2) (vol frac dry)</td>
<td>0.065</td>
<td>0.060</td>
<td>0.060</td>
<td>0.060</td>
<td>0.060</td>
</tr>
</tbody>
</table>

**Cases 1, 4 & 5 give best NO\(_x\) match**

## Headend CFD results

Adiabatic case a  
Peak T=2,405 K  
Average T=1,545 K

Non-adiabatic case b  
Peak T=2,280 K  
Average T=1,430 K
Lefebvre jet penetration correlation

\[ \frac{y}{d_j} = 0.82 J^{0.5} \left( \frac{x}{d_j} \right)^{0.33} \]

Momentum flux ratio

\[ J = \frac{(\rho v^2)_{jet}}{(\rho v^2)_{crossflow}} = 10 \]

Cases 1, 3 & 4 give best penetration match
- Substitute between 0 and 50% of axial jet air with either CO$_2$, or N$_2$ diluent
- CO$_2$ dilution reacts slower than with N$_2$
- Higher Lift-off for CO$_2$ relative to N$_2$
- Chemiluminescence vs. CFD simulation
- Detailed chemistry with GRI 3.0 RANS CFD with half-width symmetric model 5M cells validated with experimental flame position (axial flame lift-off captured within 8% deviations)
Axial Profiles along downstream coordinate show the decrease of reacting progress with increased diluent content.

CO$_2$ reacts slower than N$_2$.

High Coupling between temperature and NO emission profiles.

Decrease in NO emission with more diluent (model validated experimental data within 3%).

Increase in CO emission with more diluent (model validated experimental data within 9%).

Same CFD conditions as previous slide.

12d downstream


Thank you!

Questions?