University Turbine Systems Research
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Improving NOx Entitlement with Axial Staging
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Outline

• Introduction
• Objectives
• Experimental Facility
• Fuel Only Jet Preliminary Results
• Premixed Jet Preliminary Results
• PIV and TDLAS Measurements
• Modeling
• Year 3 Work
INTRODUCTION
Axial Stage Combustion System

- Lean premixed combustion for the headend
- Axially staged fuel injection with short residence time
- Higher firing temperature

Minimize NOx with increasing turbine inlet temperature

H. Karim et al. GE power, TurboExpo 2017

D. Winkler et al. GPPS Journal 2017
Gas Turbine OEM’s are under pressure to increase efficiency without increasing emissions.

Increasing turbine inlet temperature is one method to increase efficiency, but NO$_x$ increases rapidly.

NO$_x$ is a function of peak flame temperature and residence time.

By injecting some of the fuel late in the combustor (axial staging) it burns with a shorter residence time, minimizing the NO$_x$ penalty.

OEM’s have tested full size axial staging designs at engine conditions, but are unable to obtain detailed measurements of the reacting jet-in-crossflow.

**Axial Stage Combustion System Applications**

- Power Generation
- Potential for Aircraft Engines
S. Martin et al., Siemens Energy, Orlando, FL
U.S. Patent 8,387,398, 2013

• Apparatus and method for controlling the secondary injection of fuel.
• Adds multiple fuel nozzles in the transition.
• Can be used to improve temperature pattern factor entering the turbine.
Recent Investigation - 2017

H. Karim et al., GE power, Greenville, SC
ASME Turbo Expo, 2017

- Lean-lean two stage combustion system
- Development testing in FA and HA class gas turbine
- Validation testing for 7HA.01 engine
- Premixers in a can (PM) vs Axial Fuel Staging (AFS)
OBJECTIVES
Develop a high pressure axial stage combustion test facility and explore novel configurations to implement axial staging with direct involvement of original equipment manufacturers (OEMs).

- Conduct experiments using a high pressure combustion facility.
- Tune rig headend to give similar NOx curve as current engines.
- Axial stage testing with Fuel/Air and Fuel/Diluent axial mixtures with various levels of premixing.
- Obtain detailed measurements of the burning jet to understand the design space and model validation.
- Axial Stage Modeling: Develop reacting jet-in-crossflow correlation and validate existing CFD capabilities.
EXPERIMENTAL FACILITY
Three optical access windows for imaging diagnostics
Interchangeable top plate for different jet geometries
Wall flush jet injector
4 mm and 12.7 mm jet injectors
Pressure 5 atm.
Air flow rate 0.5 kg/s
Fuel Only Jet Preliminary Results
Optical Diagnostics

- High-Speed CH* Chemiluminescence
  - 10,000 frames per second
  - FOV = 4.9 x 3.5 in
  - 430 nm filter (used for methane jet)

Axial Stage Conditions

- Methane non-premixed jet
  - J = 10-115
  - $\Phi_{\text{inlet}} = 0.48-0.72$
  - $T_{\text{inlet}}$: 1260-1650°C

- Hydrogen non-premixed jet
  - J = 10-115
  - $\Phi_{\text{inlet}} = 0.58-0.72$
  - $T_{\text{inlet}}$: 1350-1650°C
Flame Stabilization – Hydrogen Non-premixed Jet

- Crossflow Equivalence Ratio
  - Lower temperature inlet conditions burn further upstream and wider
  - Leeward and windward flames
- Leaner crossflow provides more oxygen

J is momentum flux ratio
Flame Stabilization – Hydrogen Non-premixed Jet

- Momentum flux ratio
  - Crossflow $\Phi = 0.58$
  - All flames lifted
  - Lower momentum flux ignites the same and burns slower

- Higher momentum flux leads to better oxygen entrainment

- $J = 115$
  - $\Phi_{inlet} = 0.58$
  - $T_{inlet} = 1350 \, \text{C}$

- $J = 50$
  - $\Phi_{inlet} = 0.58$
  - $T_{inlet} = 1350 \, \text{C}$

- $J = 10$
  - $\Phi_{inlet} = 0.58$
  - $T_{inlet} = 1350 \, \text{C}$
Flame Stabilization – Methane Non-premixed Jet

- Crossflow Equivalence Ratio
  - J = 115 (top) J = 10 (bottom)
  - Leaner flame burns further upstream
  - Leeward shear layer flames

- Leaner crossflow provides better oxygen entrainment
Flame Stabilization – Methane Non-premixed Jet

- Momentum flux ratio
  - Crossflow $\Phi = 0.58$
  - Wall jet does not burn in leeward side but on windward side
  - Wall jet not stable experiences blow-off

- Higher momentum flux entrains enough oxygen on both sides to remain lit
Jet Centerlines

- Leanest Crossflow - Methane
  - Leaner crossflow burned in shear layer on leeward side of jet

$T_{\text{inlet}} = 1350 \, \text{C}$

Experimental $\Phi_{\text{inlet}} = 0.58, T = 1350$

OH* CFD Centerline, $\Phi_{\text{inlet}} = 0.58, T = 1350$

Non-reacting Lefebvre correlation
Jet Centerlines

- **Richest Crossflow – Methane**
  - Richest crossflow – flame burned downstream of viewing section
  - Jet trajectory matches non-reacting correlation

![Jet Centerlines Diagram](image)

- Experimental $\Phi_{\text{inlet}} = 0.72$, $T = 1650$
- OH* CFD Centerline, $\Phi_{\text{inlet}} = 0.72$, $T = 1650$
- Non-reacting Lefebvre correlation

**$T_{\text{inlet}} = 1650 \, \text{C}$**
Leaner crossflow entrains more oxygen

Higher velocity gradients (large $J$) entrain oxygen better and burn further upstream

Two flames observed: stabilized jet with flame kernels constantly forming and flame propagation

RJIC penetrates further due burning in the wake relative to non-reacting
Premixed Jet Preliminary Results
Testing Conditions

- Mass Flow Rate: 0.5 kg/s
- Pressure: 5 atm
- Premixed Methane/Air Crossflow and Axial Jet
Crossflow Temperature: 1352° C

Jet $\phi = 4$

Jet $\phi = 8$
Rich jet approaches non-premixed jet behavior.
Results: Ignition Process

- Crossflow Temperature: 1352° C

**Jet \( \phi = 4 \)**

- Increasing Time

**Jet \( \phi = 8 \)**

- Increasing Time
Lefebvre jet trajectory correlations:

\[
\frac{y}{d_j} = 0.82 J^{0.5} \left(\frac{x}{d_j}\right)^{0.33} \quad \text{Where } J = \frac{\rho_j U_j^2}{\rho_m U_m^2}
\]
CFD of Premixed CH₄ Flames, 4mm Jet

Local CH* occurrence (φₑ = 1.1)
- CFD Centerplane w(CH*) φ(crossflow) = 0.73
- CFD Centerplane w(CH*) φ(crossflow) = 0.575
- Filtered CH*, I/Imax = 0.65-0.67

φₑ = 0.73
φₑ = 1.1

Thermal delay

x/d = 3.5
x/d = 4
x/d = 4.5
x/d = 5
An increase of crossflow temperature reduces ignition time and flame liftoff.

Autoignition process occurs on the leeward side of flame followed by flame propagation.

Reacting jet in crossflow at higher pressure over penetrate compared to non-reacting jet.
PIV AND TDLAS MEASUREMENTS
Began PIV setup
- Achieved proper seed density
- Set delta T between laser beams
- Finalize optical lens setup

Start Formaldehyde PLIF setup
- Timing
- Optical lens setup
Crossflow $\varphi = 0.575$

Velocity profile at inlet of test section
<table>
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<tr>
<th>Thermocouple</th>
<th>Baseline</th>
<th>Total Mass</th>
<th>Total Main Air</th>
<th>Total Fuel</th>
<th>Total Air</th>
<th>Global Phi</th>
<th>Local Phi</th>
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<table>
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<th>Pressure (PSIG)</th>
<th>Split %</th>
<th>Axial Air</th>
<th>Main Air</th>
<th>Seeder Air</th>
<th>Bypass Air</th>
<th>Axial Air ROU</th>
<th>Main Air ROU</th>
<th>Bypass Air ROU</th>
<th>Seeder ROU</th>
<th>Axial PSIG</th>
<th>Seeder PSIG</th>
<th>Bypass PSI</th>
<th>J</th>
<th>Y(1n)</th>
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<td>0.341</td>
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<td>0.341</td>
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<td>0.091</td>
<td>0.22</td>
<td>0.5625</td>
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<td>151</td>
<td>398</td>
<td>151</td>
<td>15</td>
<td>2.1</td>
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Beer-Lambert Law for Species Detection

\[ \alpha = - \ln \left( \frac{I}{I_0} \right) = \sum_i \sum_j S_{ij}(T)X_jPL\phi_{ij}\left(\nu - \nu_{0ij}\right) \]

- \( I \) = Transmitted Intensity \( \left( \frac{W}{cm^2srHz} \right) \)
- \( I_0 \) = Incident Intensity \( \left( \frac{W}{cm^2srHz} \right) \)
- \( S_{ij} \) = Linestrength \( \left( \frac{cm^{-2}}{atm} \right) \)
- \( T \) = Static Temperature (K)
- \( X_j \) = Mole Fraction
- \( P \) = Static Pressure (atm)
- \( L \) = Path Length (cm)

\( \phi_{ij} \) = Lineshape Function (cm)
\( \nu \) = Optical Frequency (Hz)
\( \nu_{0ij} \) = Line Center Optical Frequency (Hz)
\( i \) = Quantum Transition
\( j \) = Atomic/Molecular Species
Initial measurements (top image) utilized a **fixed-wavelength, direct absorption** approach to measure water & temperature.

Two wavelength multiplexed, pitched through combustor, then demultiplex in the catch box using diffraction gratings.

Entire system required continuous purge with dry $N_2$ and cooling, so the equipment did not overheat (outside measurements).

New approach (bottom image) will utilize **wavelength-modulation-spectroscopy (WMS)**.

This approach simplifies demultiplexing, eliminates the number of optical surfaces (for water to condense on), and requires only one detector. The system is smaller, simpler, and less sensitive to noise.

Thermal electric coolers (TECs) will be employed to regulate equipment temperatures.
MODELING
• Symmetric jet-in-crossflow axial stage geometry
• Structured, locally refined mesh with (1–50) E6 cells
• Computational Cost: 1000-5000 datacenter hours

• Reactive Domain:
  A) Detailed Chemistry
  B) Flamelet Approach
    • Non-premixed: Steady Laminar Flamelet
    • Partially Premixed: FGM with Turbulent Flame Closure
    • Premixed: FGM with Coherent Flame Model
Axial Stage: NO\textsubscript{x} Emission
CFD prediction and comparison with literature data

Preferred: Detailed Chemistry Model
Poor: Flamelet + Thermal NO\textsubscript{x} Model
Unheated 4mm jet, control parameters to *accelerate* local flame ignition:

<table>
<thead>
<tr>
<th>Windward branch</th>
<th>Lee-side branch</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\dot{m}_{CH4}^{crossflow}$ ↓</td>
<td>$T_{crossflow}$ ↑</td>
</tr>
<tr>
<td>$w_{O2}^{crossflow}$ ↑</td>
<td>$w_{O2}^{crossflow}$ ↑</td>
</tr>
</tbody>
</table>

Combustion instabilities visible in the windward flame branch
$w_{CH^*} @ z=0$ [CFD] and CH* Chemi [Exp.]

Closed flames

Divided flame

Jet Penetration

Local CH* occurrence ($\phi_{preflow} = 0.575, \phi_{jet} = 4$)
- CFD Centerplane w(CH*)
- Filtered CH*, I/Imax = 0.65-0.92

Local CH* occurrence ($\phi_{preflow} = 0.73, \phi_{jet} = 4$)
- CFD Centerplane w(CH*)
- Filtered CH*, I/Imax = 0.84-0.99

Local CH* occurrence ($\phi_{preflow} = 0.575, \phi_{jet} = 8$)
- CFD Centerplane w(CH*)
- Filtered CH*, I/Imax = 0.82

Local CH* occurrence ($\phi_{preflow} = 0.73, \phi_{jet} = 8$)
- CFD Centerplane w(CH*)
- Filtered CH*, I/Imax = 0.8
Year 3 Work Tasks

- Perform flow field analysis using particle image velocimetry (PIV)
- Study flame structure through PLIF
- Vary levels of partially premix in axial jet
- Explore pressure effect on NO\(_x\)
- Obtain NO and CO emissions with Tunable diode laser absorption spectroscopy (TDLAS)
Questions