University Turbine Systems Research Program
Annual Meeting 18 November, 2020

Improving NOx Entitlement with Axial Staging

DE-FE0031227

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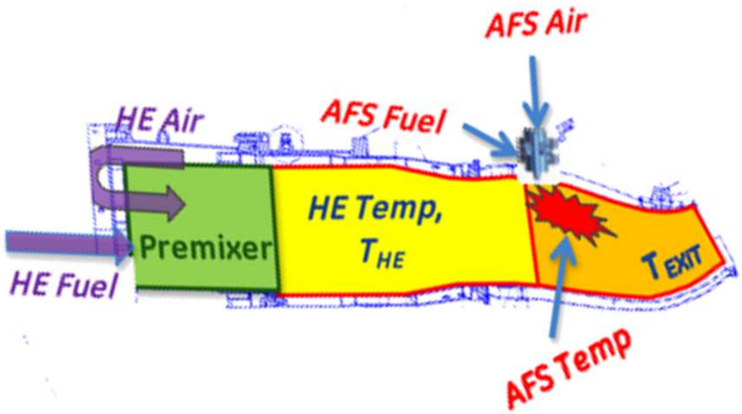
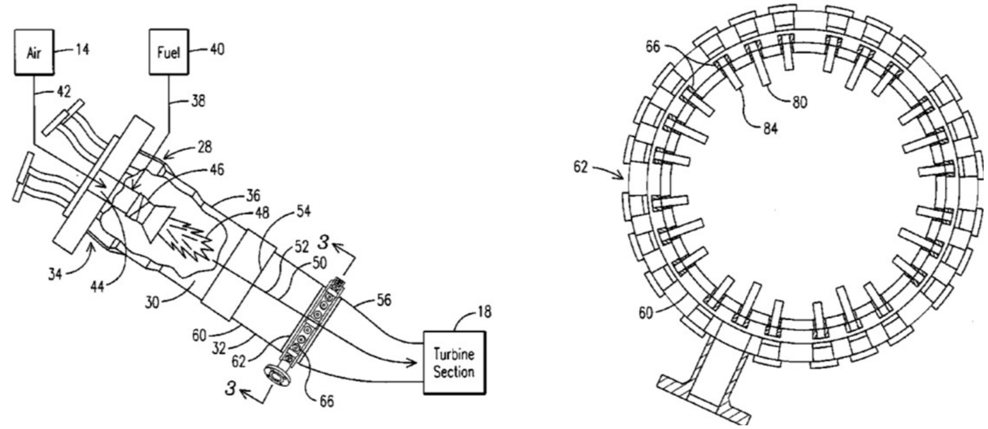
Outline

- Introduction
- Motivation of Study
- Objectives
- Completion of years 1-3 tasks
- Year 4 tasks

Axial Stage Combustion System



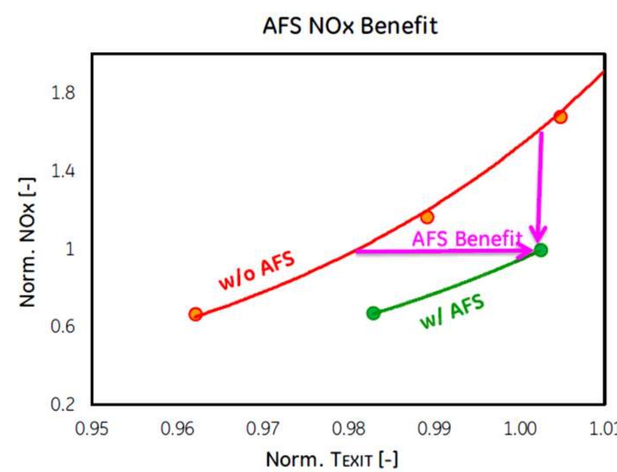
H.Karim *et al.* **GE power**, TurboExpo 2017



Martin et al., **Siemens Energy**, U.S. Patent 8,387,398, 2013

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

Minimize NO_x with increasing turbine inlet temperature



H.Karim *et al.* GE power, TurboExpo 2017

Motivation of Study

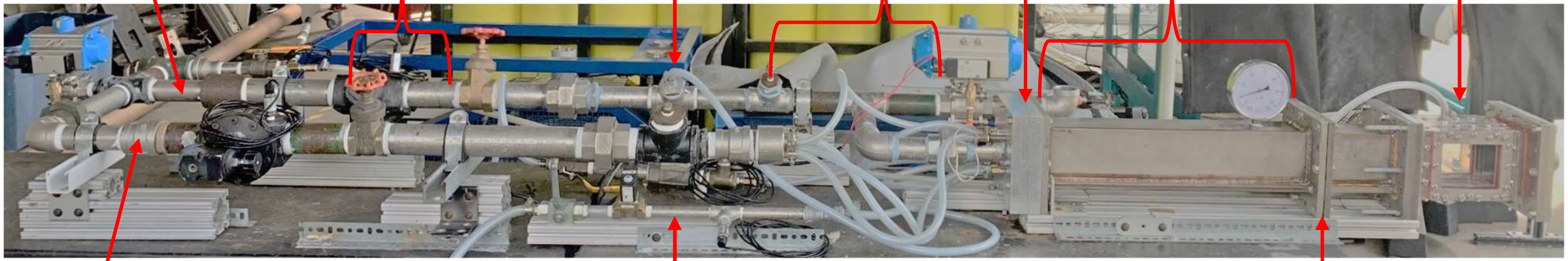
- Increase gas turbine efficiency by increasing turbine inlet temperature with minimal NO_x production
- Challenge: Overcome strong effect between temperature and NO_x
- Enhance current gas turbine designs to provide low NO_x over wide range of operational loads by axial staging
  - Axial Staging: Two step combustion process involving additional fuel injected close to combustor exit for increase temperature, giving shorter residence time and minimal NO_x formation
  - OEM unable to obtain detail information of reacting jet behavior during full scale testing

Tasks

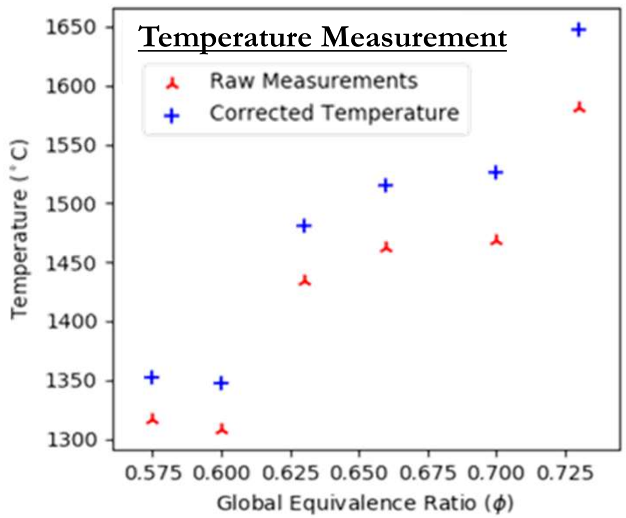
- Task 1: Project management and planning
- Task 2: Modify UCF high pressure test facility for axial stage and tune to match OEM engines
- Task 3: Fuel and air axial mixtures
  - Premixed and non-premixed jets
- Task 4: Fuel and diluent axial mixtures
  - Premixed jets
- Task 5: Axial stage modeling
  - Reacting JiC correlation and validate existing CFD

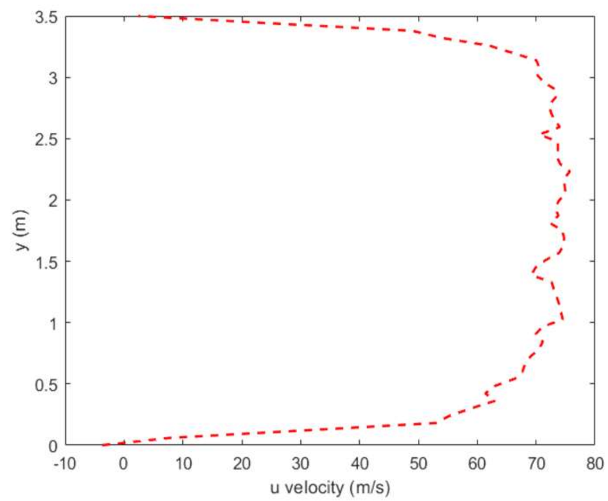
Task 2: Experimental Facility

- Headend
  - Mass flow rates: 0.5 kg/s
  - Temperature Range: 1623 - 1923 K
  - Operating Pressure: 5atm
  - Premixed Methane/Air
  - 4 air bypass lines
  - Backward facing step combustor design for simplified uniform crossflow
  - Straight exit geometry
- Axial Jet
  - Diameter: 12.7mm
  - Fuel: Air/Methane

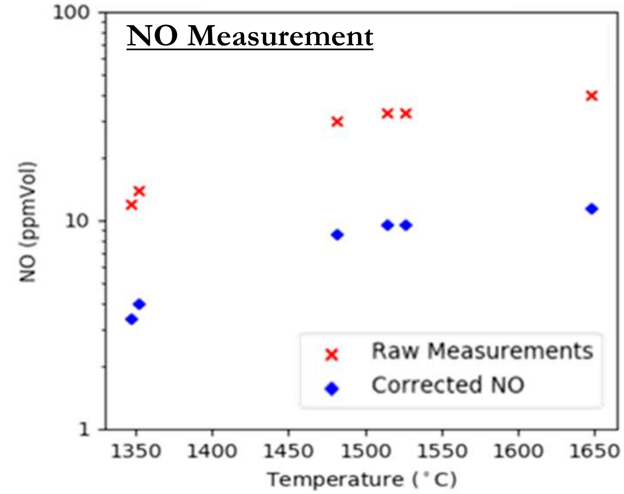


- **Tuned headend conditions:**
  - Headend Φ: 0.58-0.72
  - Temperature : 1350-1650 C
  - Velocity: 50 to 80 m/s
  - Pressures: 1 to 5 atm
  - NO levels: 5-12 ppm Vol
  - Uniform velocity profile prior to secondary stage

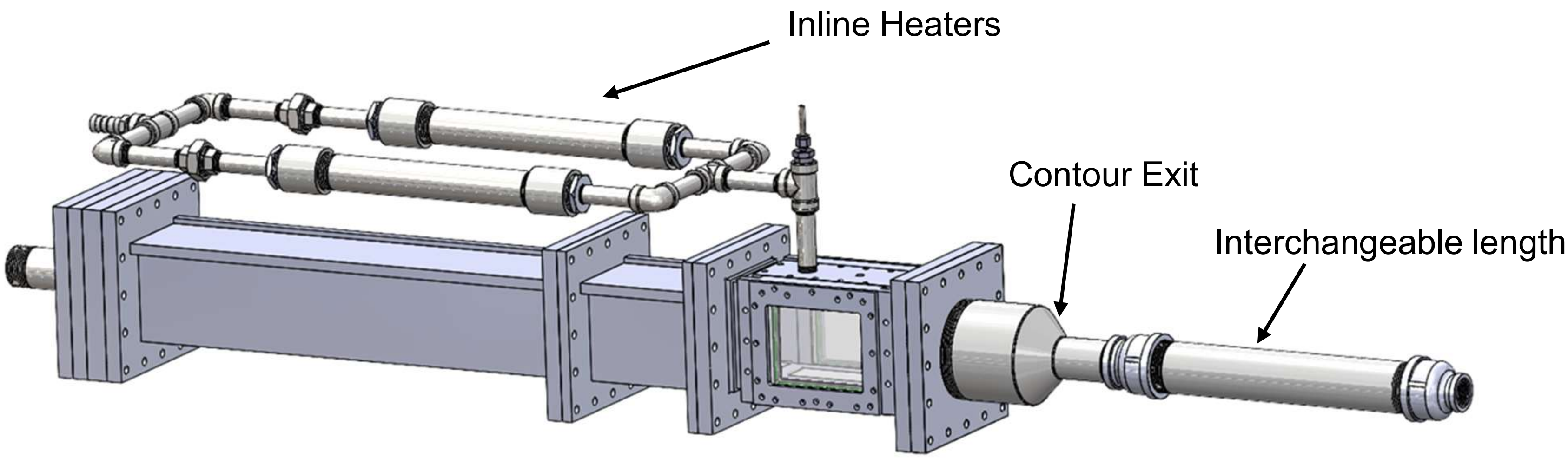




Crossflow Incoming Velocity Profile



Experimental Design - Updates



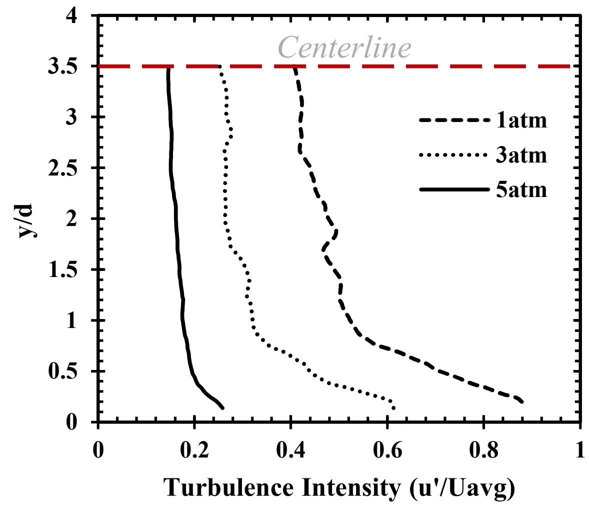
- Addition of air heaters in axial line for preheating
- Contoured exit geometry to assist with acoustic instabilities
- Higher fidelity emission analyzers
- Interchangeable exit length to vary residence time

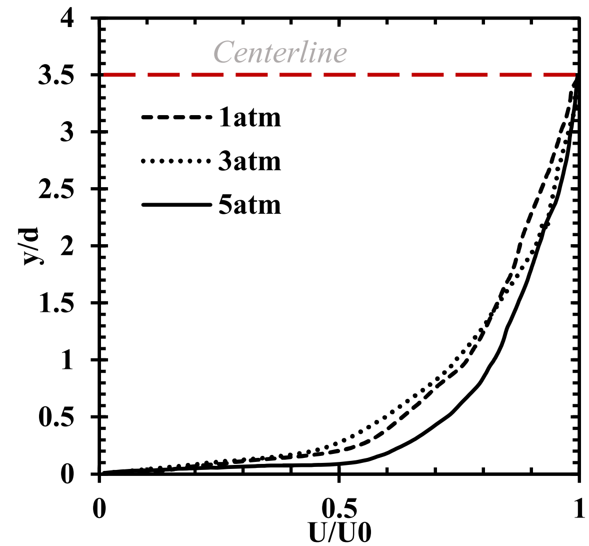
Task 3: Fuel and Air Cases

- Task 3: Fuel and air axial mixtures
  - - Premixed pressure effects
  - - Jet premixedness
  - - Heated premixed jets

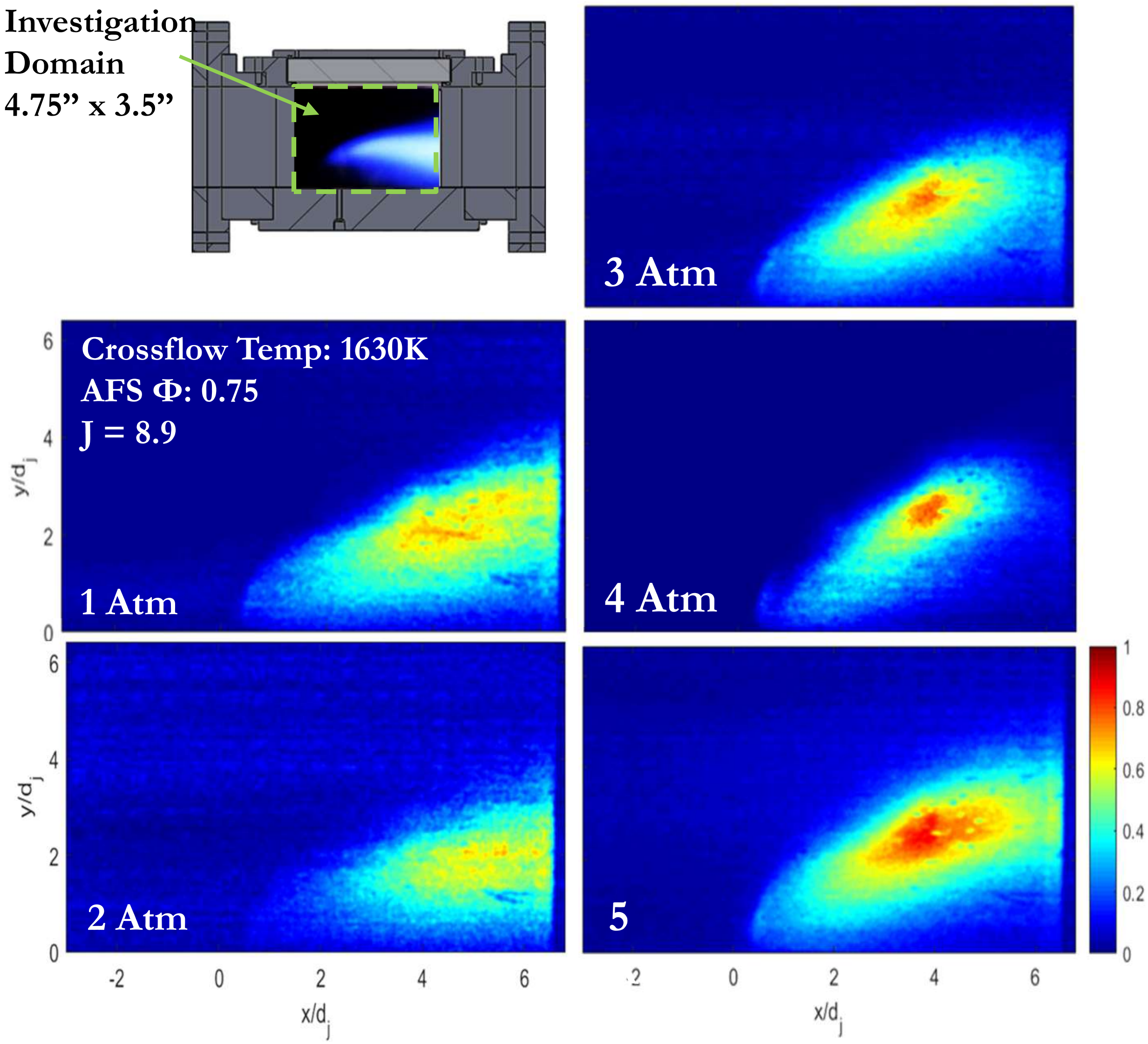
Pressure Effects Results

- **Testing Conditions**
  - Pressure Range: 1- 5 atm
  - Headend Φ: 0.58
  - Axial Jet Φ: 0.75
  - Total Φ: 0.60
  - Momentum Flux Ratio: 15
  - Firing Temperature: 1730 K
  - Fuel: Premixed methane/air for crossflow and axial jet
  - Straight exit geometry
- Uniform normalized incoming velocity profiles with pressure
- Decrease in turbulence intensity at elevated pressure





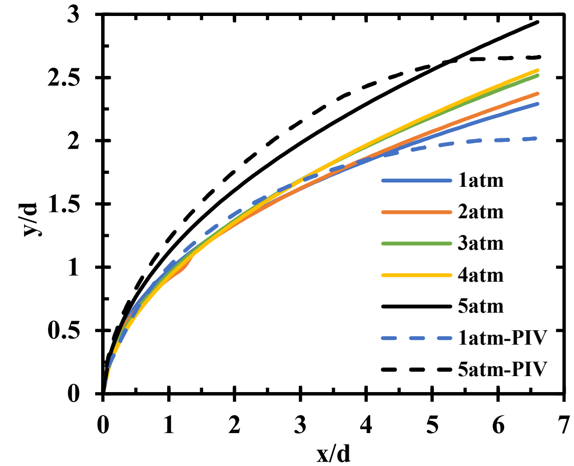
Results: CH* Chemiluminescence

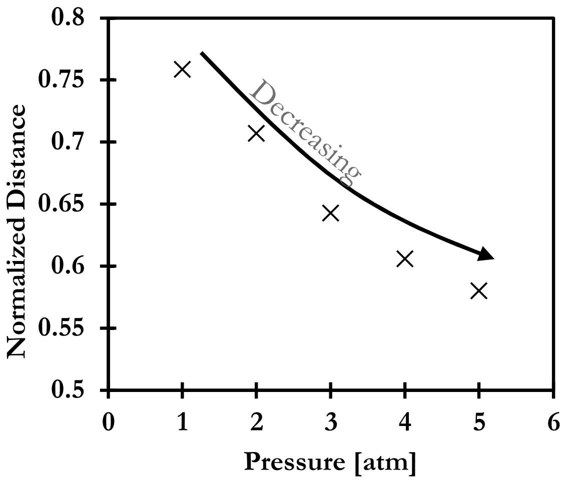


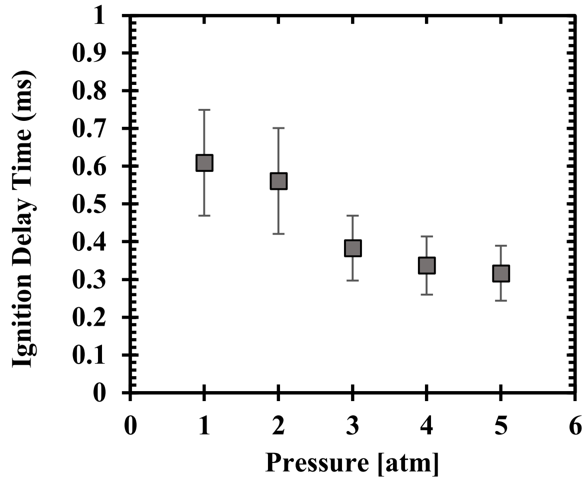
- Time average global heat release area
- Variation in flame spread with pressure
- Lifted flame for all cases
- Leeward stabilized
- Increase in vertical liftoff from combustor wall with pressure
- Reduction in jet flapping was seen with pressure

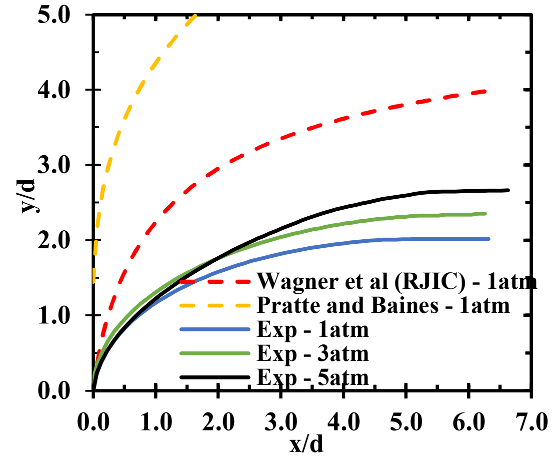
Results: CH* Chemiluminescence

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

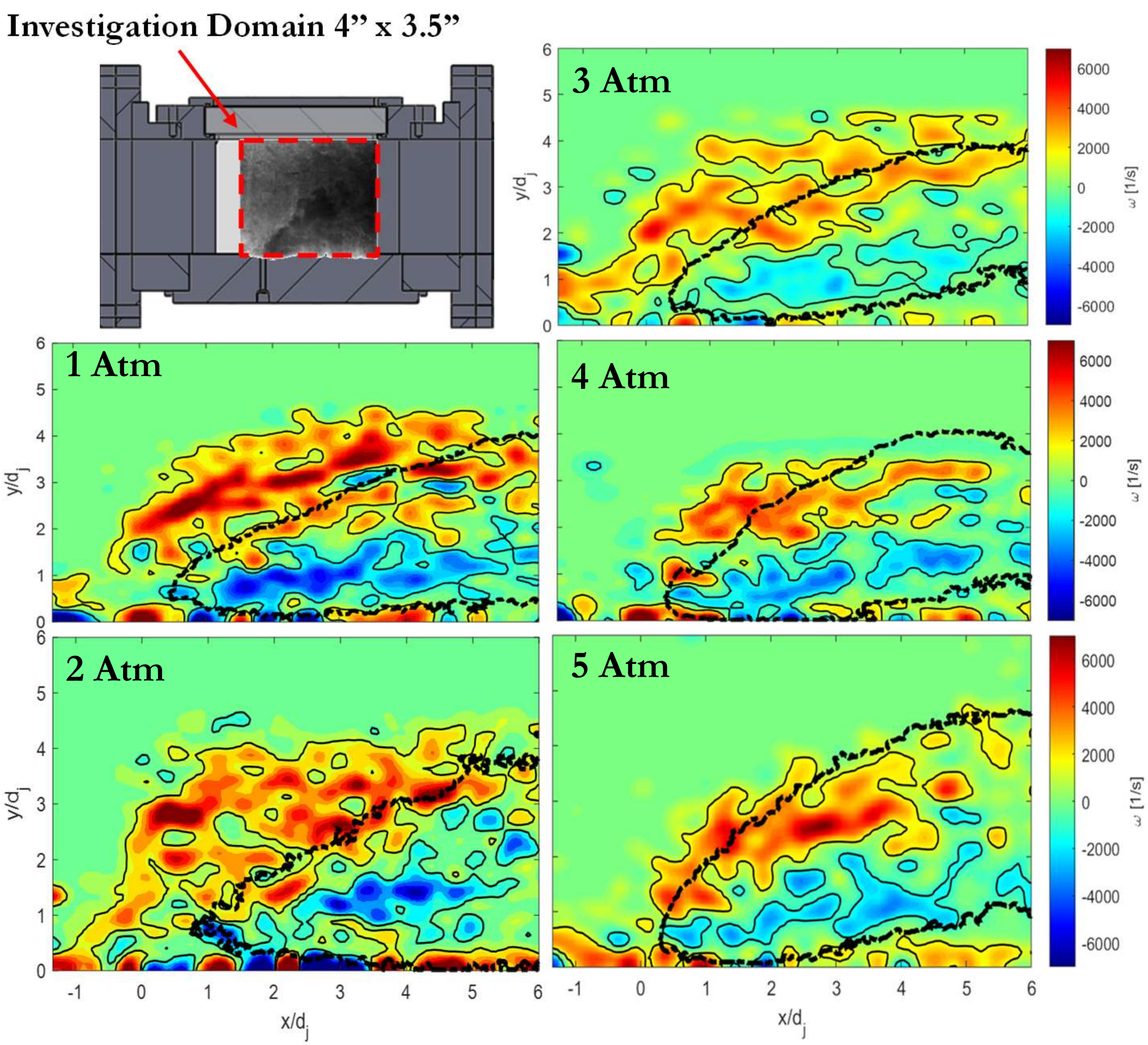




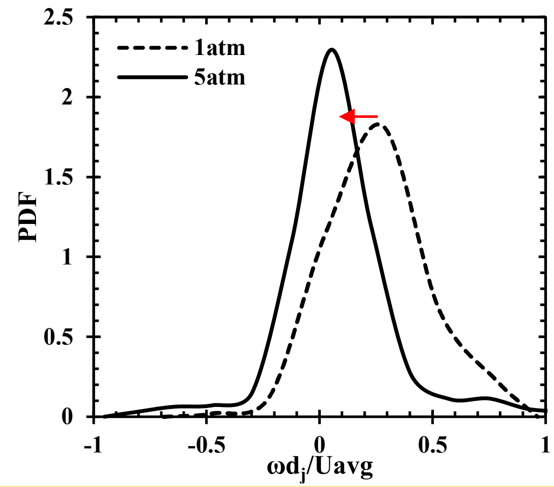




Results: PIV: Average Vorticity

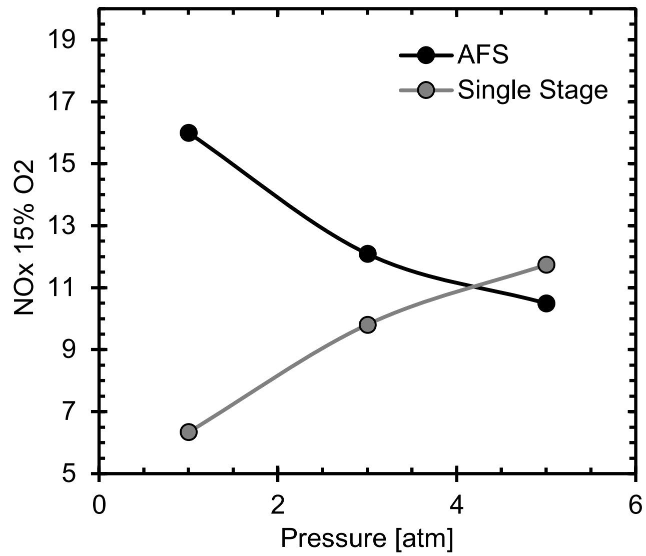


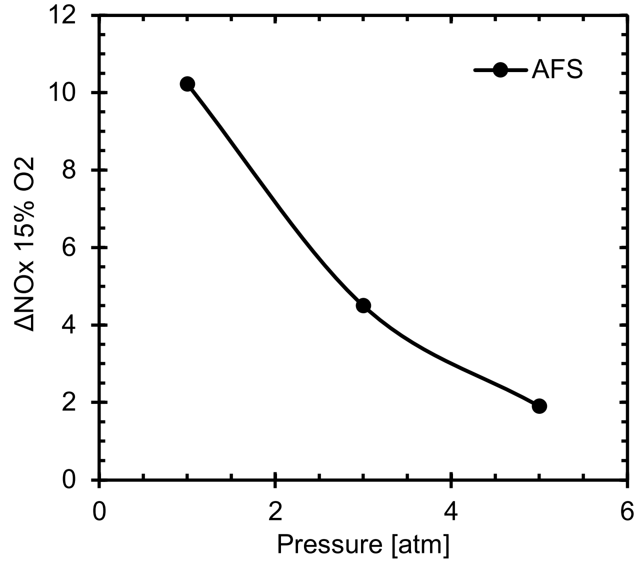
- ❑ Time average vorticity field
- ❑ Ignition on leeward side
- ❑ Higher vorticity along boundary windward edge with pressure
- ❑ Transition from shear burning to core stabilized flame



Results: PIV: Emissions

- ❑ NO_x levels increase with pressure in a single stage combustor
- ❑ Improvement in NO_x level with axial staging for all pressure cases
- ❑ NO_x contribution from AFS decreases with pressure due to variation in kinetics at increasing pressure
- ❑ Shear burning flame (low pressure) demonstrates to contribute to NO_x production greater than core burning flame (high pressure) attributed lower hot zones at higher pressures





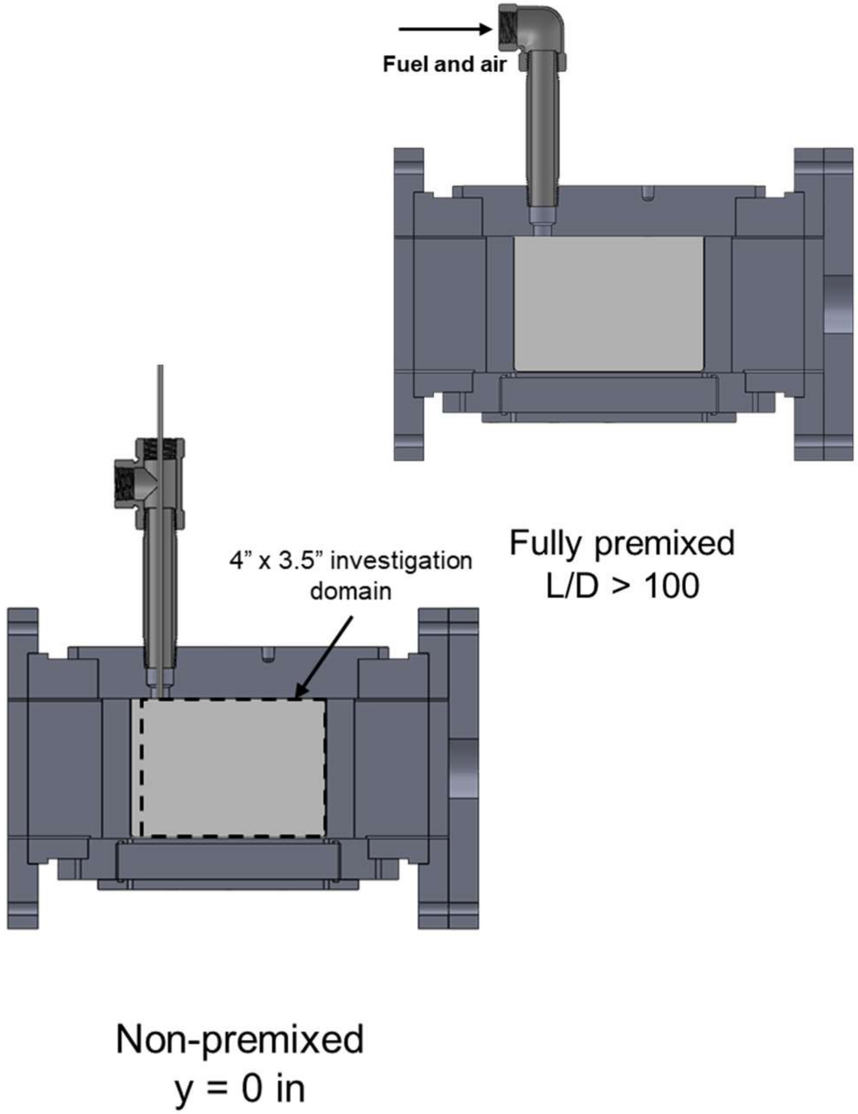
Conclusions: Pressure Effects

- ❑ Further jet penetration with elevated pressure linked to greater heat release (gas expansion increases and entrainment decreases)
- ❑ Flame burns further way from combustor wall with pressure
- ❑ Reduction in overall flame lift off height with pressure
- ❑ Increase ignition delay time (shorter chemical timescales)
- ❑ Flame stabilization transitions from shear layer burning to core burning
- ❑ Greater jet stability with pressure
- ❑ Higher pressure jet result in a reduction of NO_x production
- ❑ Longer fluid time scale coupled with short chemical timescale suggest an increase of Damköhler number with pressure
- ❑ Trajectories are underpredicted by literature correlations

Results: Variation in Jet Premix Levels

- **Testing Conditions**
  - Pressure: 5 atm
  - Global Headend Φ: 0.73
  - Axial Φ: 1.07 to 1.78
  - Momentum Flux Ratio: 5
  - Firing Temperature: 1650 C
  - Fuel: premixed methane/air for crossflow and axial jet
  - Fuel Split: 15% to 25%
  - Straight exit geometry

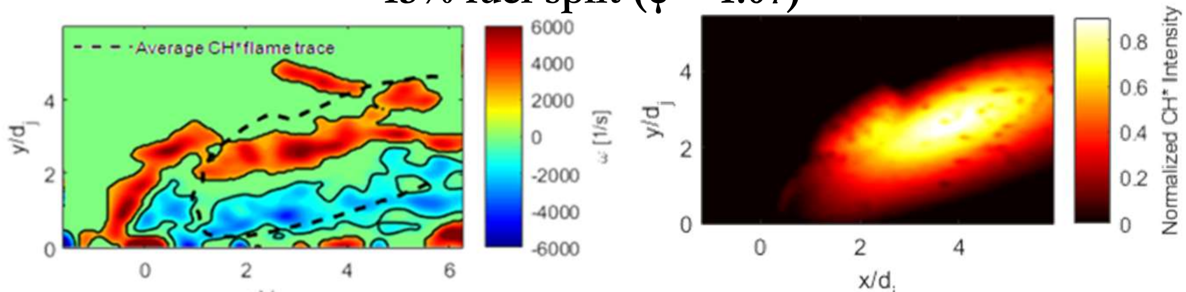
- **Fully premixed vs non-premixed**



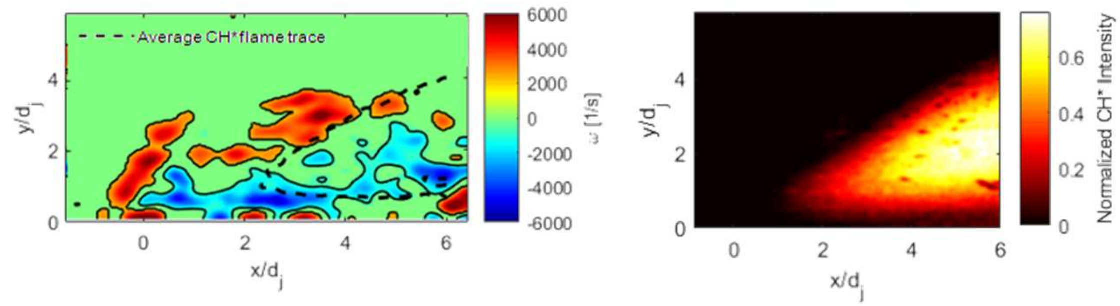
Fully Premixed – Flame/Flow-field Measurements

- Both flames ignite in shear layer
- Leaner jet spreads to jet core quickly
- Richer jet flame resides mainly in shear layer
- Ignition delay dominated by heat transfer timescale and entrainment of crossflow oxygen

15% fuel split (φ = 1.07)



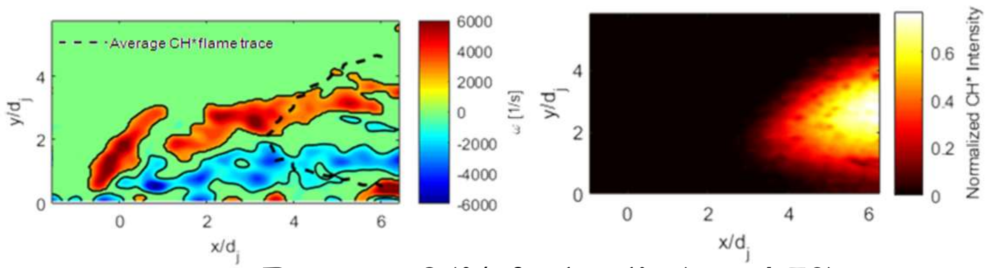
25% fuel split (φ = 1.78)



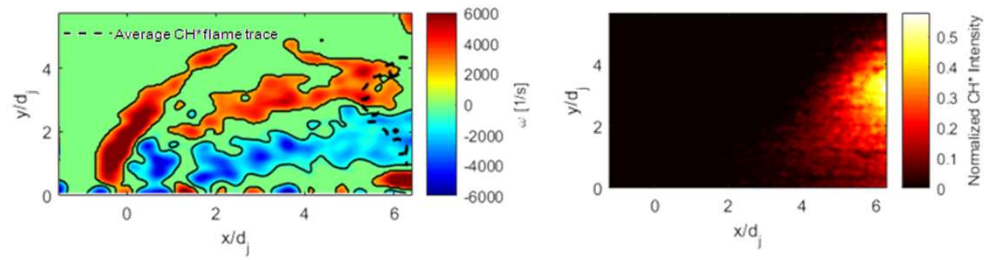
Non-Premixed – Flame/Flow-field Measurements

- Highly lifted flames
- Both leaner and richer jets ignite and burn at their cores
- Both flames burn downstream mainly out of viewing window
- Ignition delay dominated by mixing timescale allowing jet to get to higher temperature and entrain additional crossflow oxygen prior to ignition

Top: 15% fuel split (φ = 1.07)

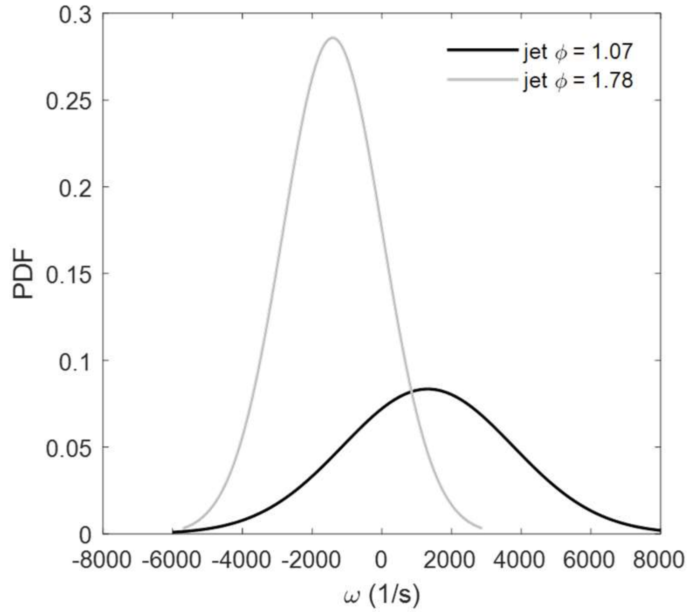


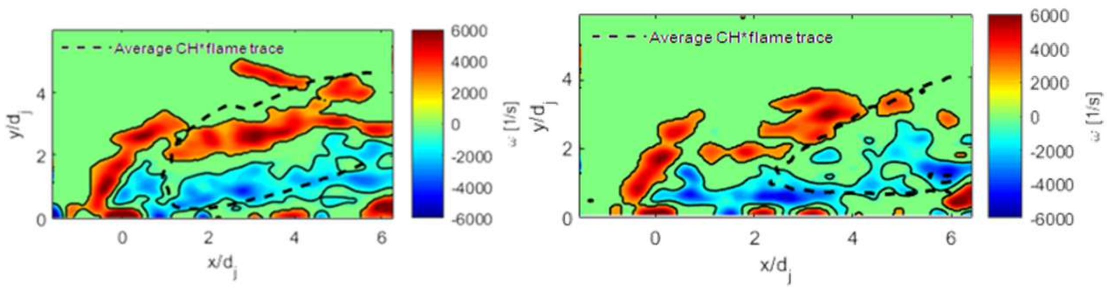
Bottom: 25% fuel split (φ = 1.78)



Shear Layer vs. Jet Core Flame

- **PDF for leaner jet relatively evenly distributed slightly skewed toward the windward shear layer**
- **PDF for richer jet shows clear skew toward negative vorticity indicating shear layer burning**
- **Flame stabilization function of jet and crossflow equivalence ratio**

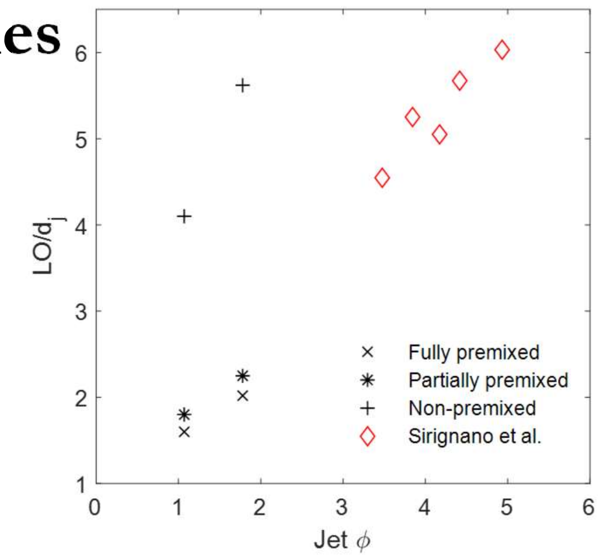




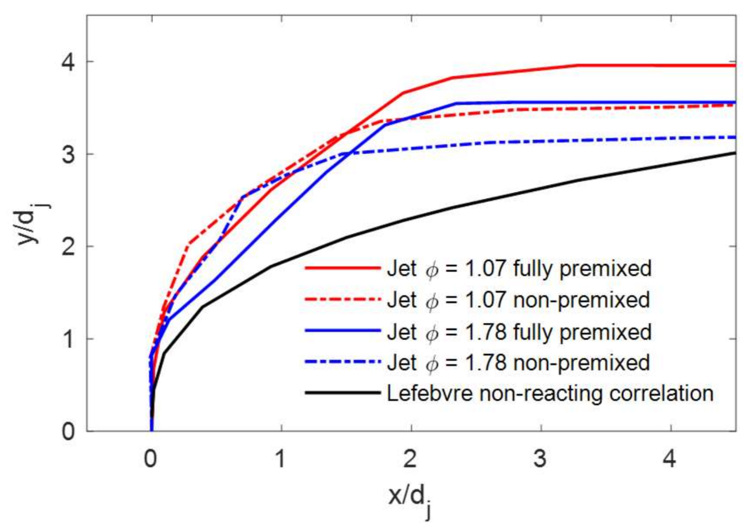
PDF of vorticity within flame for leaner jet (left) and richer jet (right)

Flame Liftoff Height and Jet Trajectories

- More mixing time leads to a flame that is less lifted
- Non-premixed flames show similar liftoff heights to previously studied rich jets
- Where there is sufficient heat release the jets significantly over penetrate the non-reacting correlation



Sirignano *et al., Proceedings of the Combustion Institute*, 2018



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Conclusions: Premixing Effects

- All jets that are partially/fully premixed ignite in shear layer
- Jets that are non-premixed ignite in the core
- Flame for leaner jet ($\Phi = 1.07$) spreads to core while the flame for the richer ($\Phi = 1.78$) resides mostly in leeward shear layer
- As expected, the less time given to premix resulted in a more lifted flame
- The fully premixed leaner jet ($\Phi = 1.07$) over penetrated the maximum penetration correlation

Results: Jet Preheating

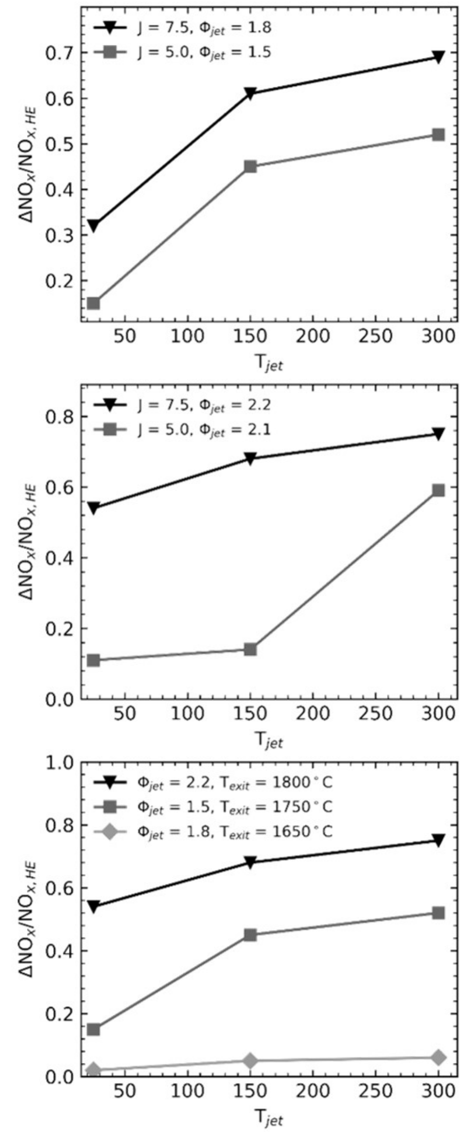
- **Varying Jet Preheat Temperature**
  - Pressure: 5 atm
  - Headend Temperature: 1450-1650 C
  - Axial Jet Φ: 1.5-2.2
  - Firing Temperature: 1650-1800 C
  - J: 3.5-7.5
  - Jet Reactant Temperatures: 25-300 C
  - Contour exit geometry

- For each 300 C case, the non-premixed was also ran
- High speed CH* chemiluminescence for each case was taken at 20 kHz

Results

Varying Jet Preheat Temperature

- Over a range of conditions a clear correlation between jet preheat temperature and NO_x is seen: increasing jet preheat temperature increases NO_x
- Top graph is for an exit temperature of 1750 C at two different momentum flux ratios and equivalence ratios: J = 7.5 & 5.0 and φ = 1.8 & 1.5
- Middle graph is for a firing temperature of 1800 C at two different Js and φs
- Bottom graph compares the three different exit firing temperatures, 1650 C case had only a small amount of NO_x formation
- Across multiple firing temperatures and conditions, NO_x increases with increasing jet temperature



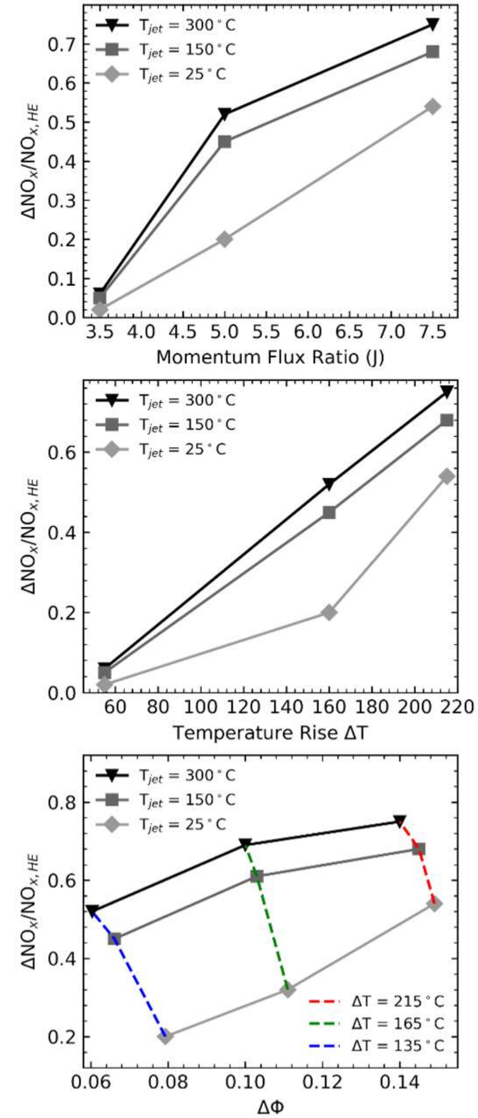
Varying Jet Preheat Temperature

- Looking more into the other varied parameters: as momentum flux ratio is increased, we see an increase in NO_x contribution of the axial stage. This makes sense as we increase J, we increase the flowrate to the jet hence increasing NO_x

- Similar trends are seen for ΔT and $\Delta \varphi$. For increasing J, ΔT, and $\Delta \varphi$, a monotonic increase in NO_x is observed.

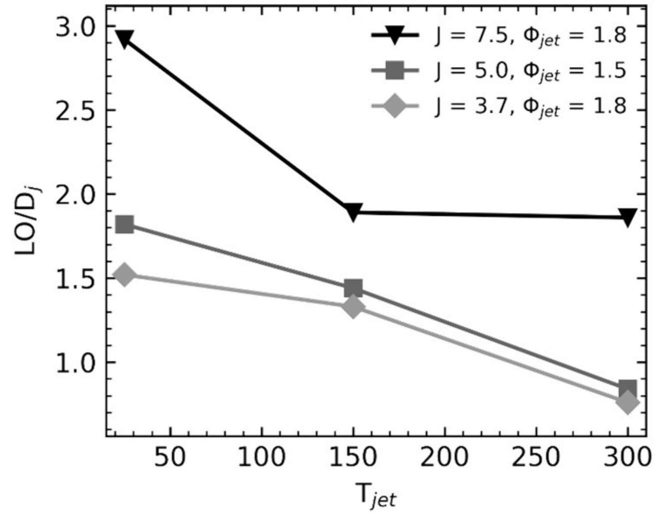
- For increasing J and ΔT, the rate at which NO_x increases with preheated jet temp

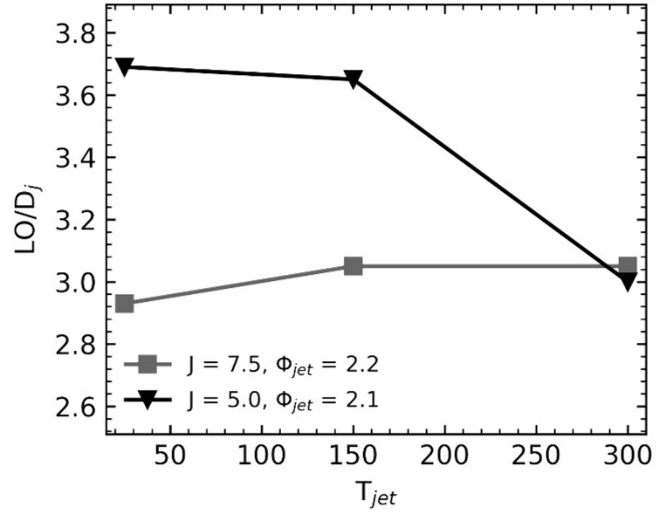
- For increasing $\Delta \varphi$ however, the rate at which NO_x increases is about the same for each jet preheat temperature



Varying Jet Preheat Temperature

- Liftoff height obtained from CH* chemiluminescence decreases with increasing jet temperature
- The liftoff seemed to be more sensitive of the jet equivalence ratio and momentum flux ratio rather than the headend firing temperature
- Suggests a coupling between liftoff and NO_x emissions. As the flame is lifted further downstream, the jet can entrain more oxygen and burn at a leaner equivalence ratio
- We will look to further decouple liftoff and NO_x in the next slide by running the non-premixed configuration for the 300 C cases.





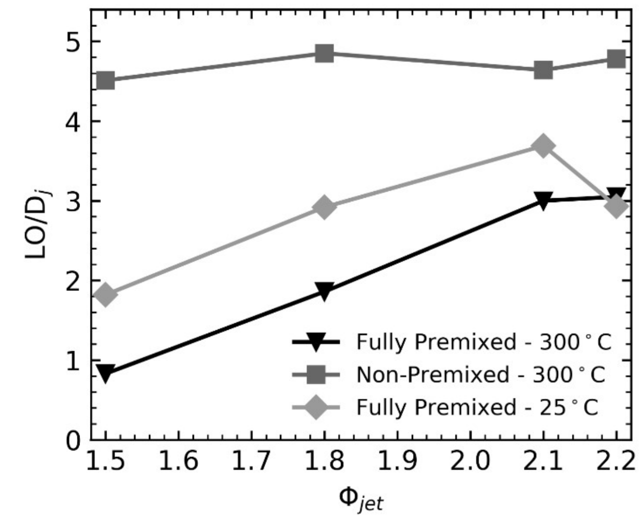
Non-Premixed Condition

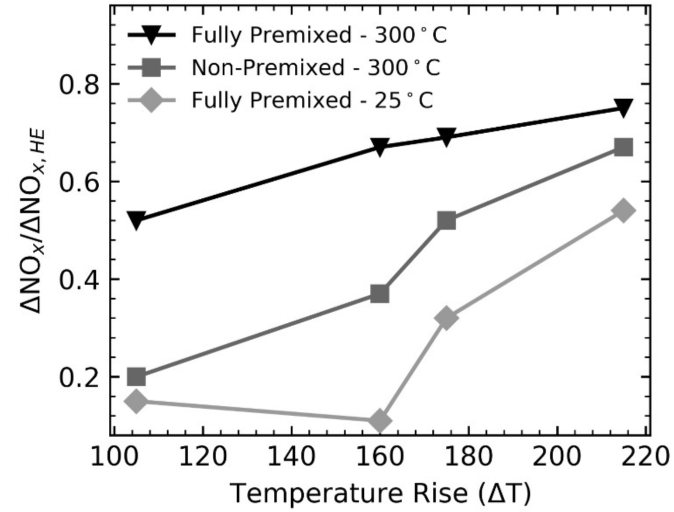
- For each 300 C cases the non-premixed configuration was run to increase the ignition delay by forcing the fuel and air to mix in the facility

- For the non-premixed configuration, there was a small variation liftoff with varying jet equivalence ratio, while for the fully premixed condition the liftoff increased with increasing jet equivalence ratio

- The non-premixed conditions presents a clear benefit in terms of NO_x. As the temperature rise increases, the fully premixed and non-premixed begin to converge.

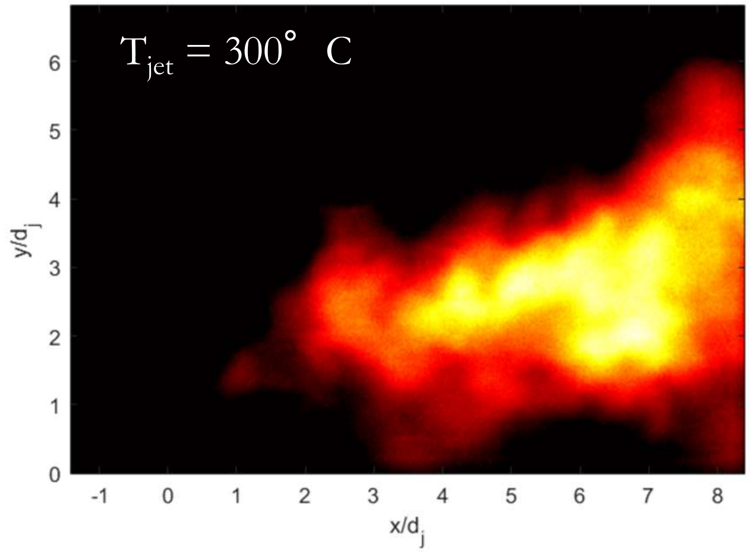
- This is also true for the liftoff; as temperature rise increases the difference in liftoff decreases which could explain why NO_x begins to merge

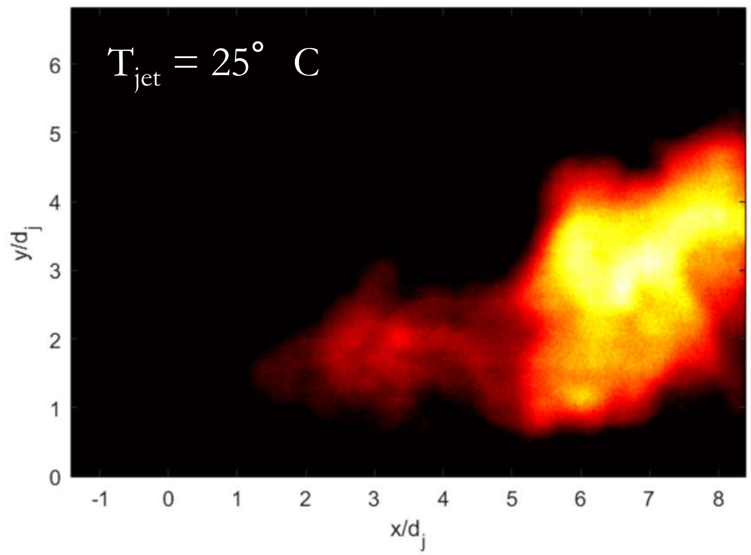




Flame liftoff variance

- Both cases are same conditions:
  - $\Phi_{cf} = 0.65$
  - $\Phi_{jet} = 1.8$
  - $\Delta T = 169$ C
  - J = 5
- Both unsteady but the preheated jet remains lit near jet exit while non-preheated stabilizes then moves downstream and comes back
- Preheating assists in stabilizing the flame although there is still a variance in flame stabilization location
- The standard deviations for the liftoff for each preheat temperature are:
  - 300 C: 0.59 D_j
  - 150 C: 1.05 D_j
  - 25 C: 1.24 D_j





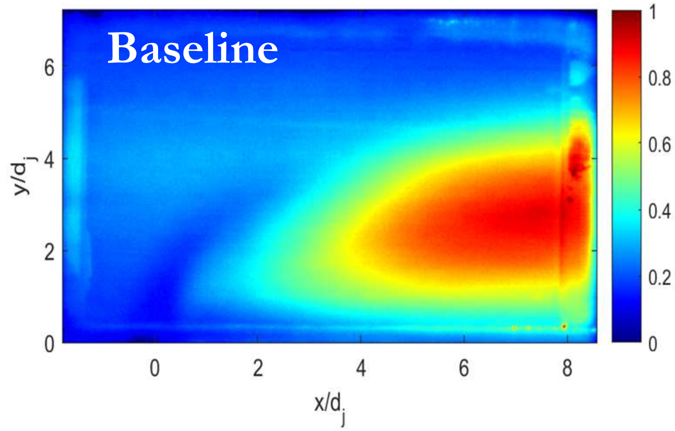
- Task 4: Fuel and diluent axial mixtures

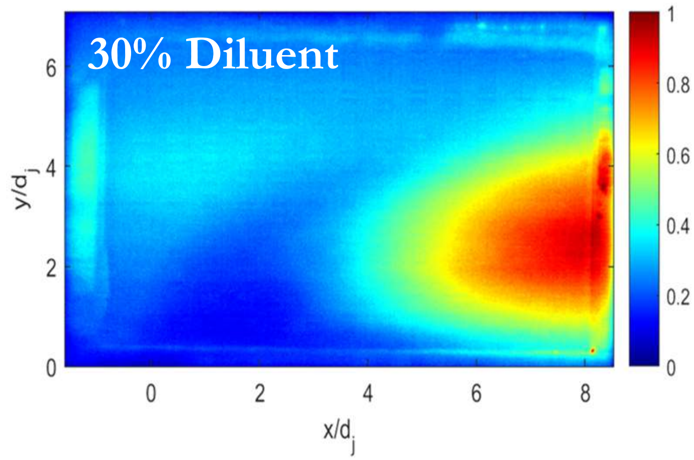
  - Heated Premixed

Diluent Influence – Test Conditions

Testing Conditions

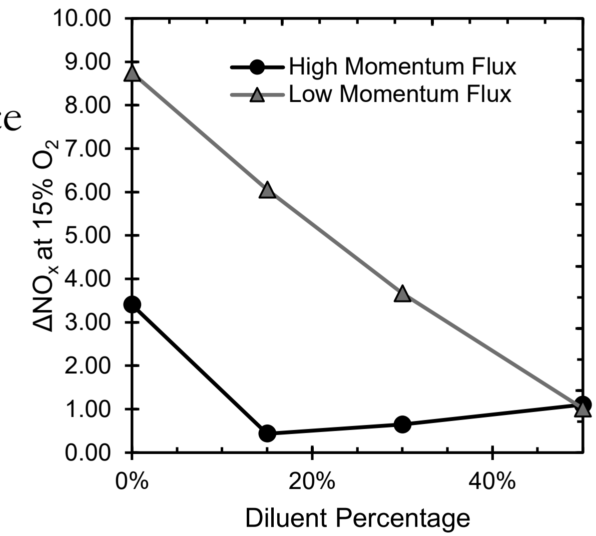
- ❑ Mass Flow Rate: 0.5kg/s
- ❑ Pressure: 5atm
- ❑ HE equivalence ratio : 0.70
- ❑ Diluent gas: CO_2 and N_2
- ❑ Diluent %: 0 to 50 (replace air in AFS)
- ❑ AFS equivalence ratio: 1.75 to 3.5
- ❑ Fuel mass remain constant
- ❑ Momentum flux ratio: 5 and 8 without diluent
- ❑ Premixed Methane/Air Crossflow and Axial Jet
- ❑ Contour exit geometry

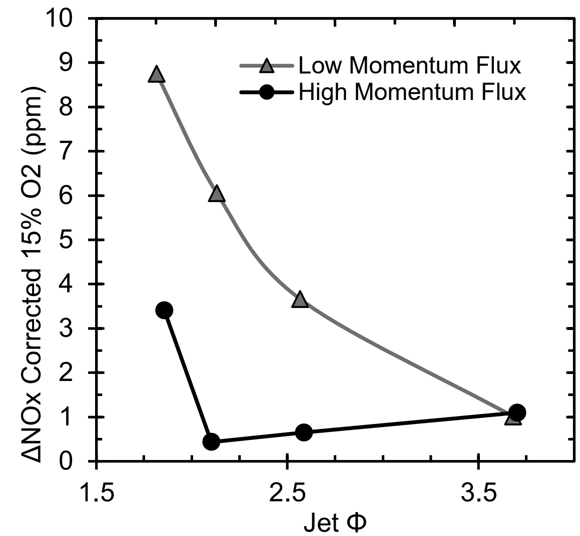


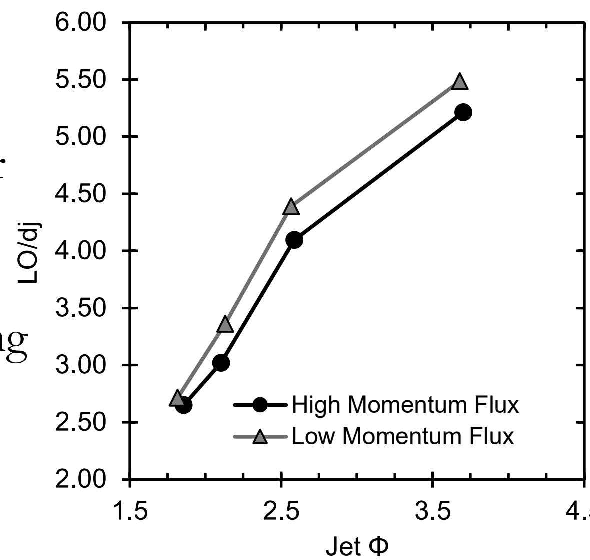


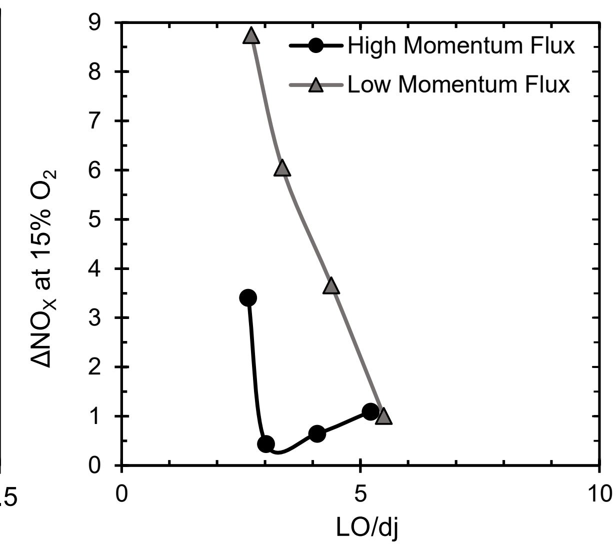
Diluent Results [CO_2]

- Higher percentage of CO_2 diluent addition show to reduce NO_x levels compared to a fuel/air axial jet only.
- Greater flame liftoff with diluent mixture, richer jets require more oxygen entrainment from crossflow
- Same axial equivalence – lower momentum flux cases have higher liftoff heights suggesting NOx production is mixing driven



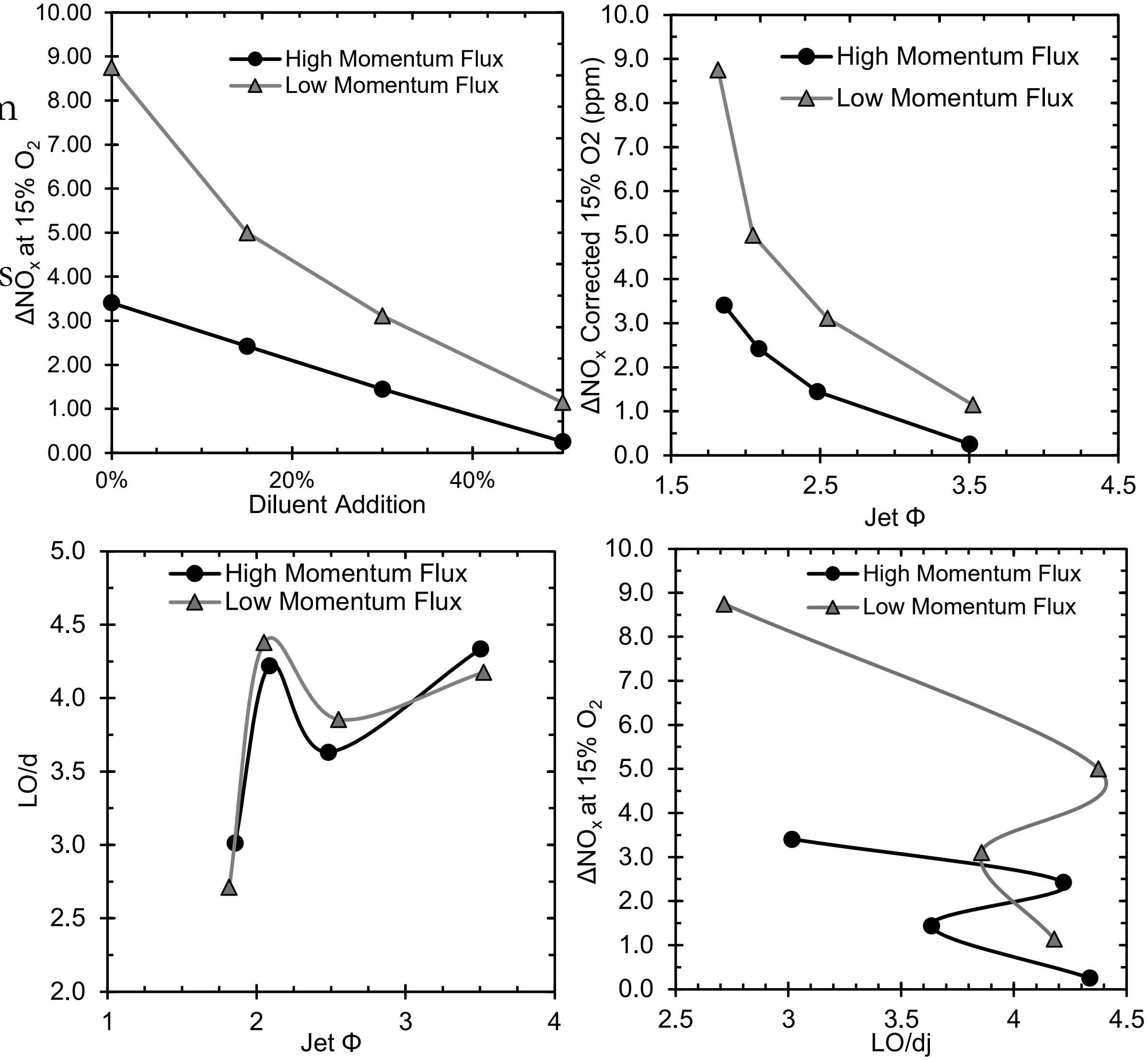






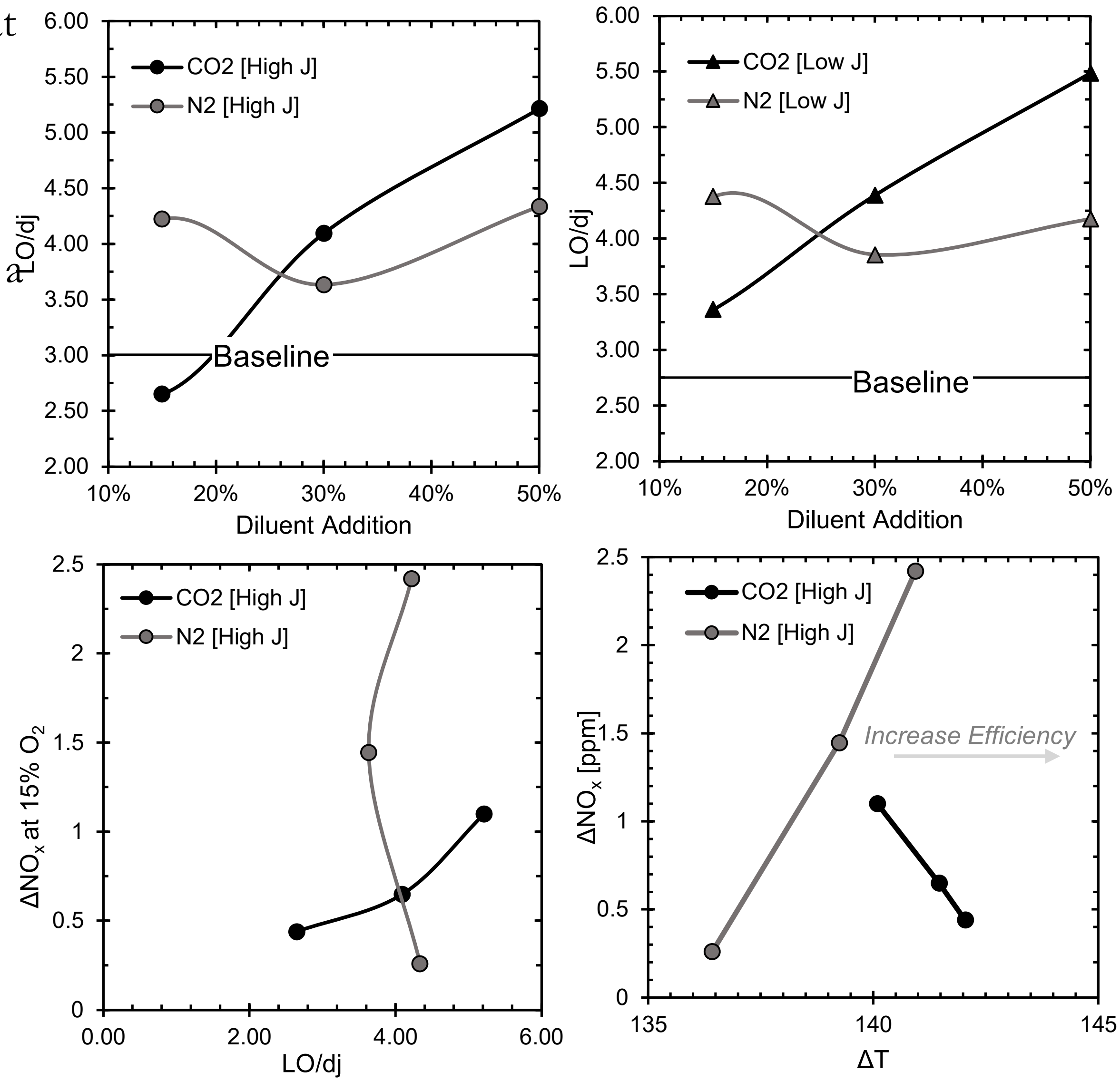
Diluent Results [N_2]

- Overall reduction of NO_x with N2 for the different momentum flux cases
- The low momentum flux shows to greater reduce NO_x compared to their baseline condition due to longer mixing timescale



Diluent Results [CO_2 vs N_2]

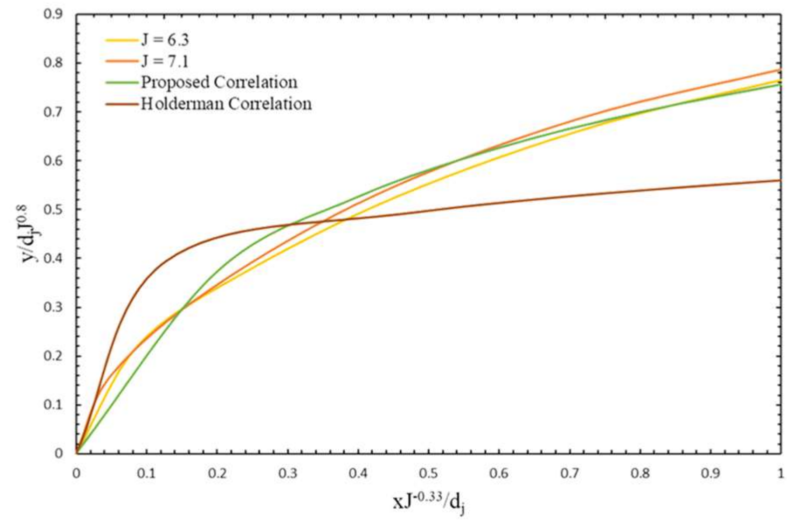
- CO_2 and N_2 cases are compared at constant ΔT
- For all momentum flux ratios, increase of CO_2 diluent results in a higher flame liftoff compared to N_2.
- Ignition timescales increase with CO_2 greater than N_2 due to its chemical properties
- CO_2 demonstrates to provide greater reduction in NO_x compared to N_2, suggesting chemical kinetics is driven NO_x



Conclusions: Diluents

- Diluent addition results in a decrease of flame lift off and lower NO_x production compared to the baseline
- Increase in axial jet equivalence ratio results in an increase of flame lift off but only at lower momentum flux ratio does it seem to influence NO_x production
- CO_2 shows to have stronger effects on flame behavior and NO_x production compared to N_2
- Ignition process occur through autoignition on the leeward side and propagates towards the windward side of flame

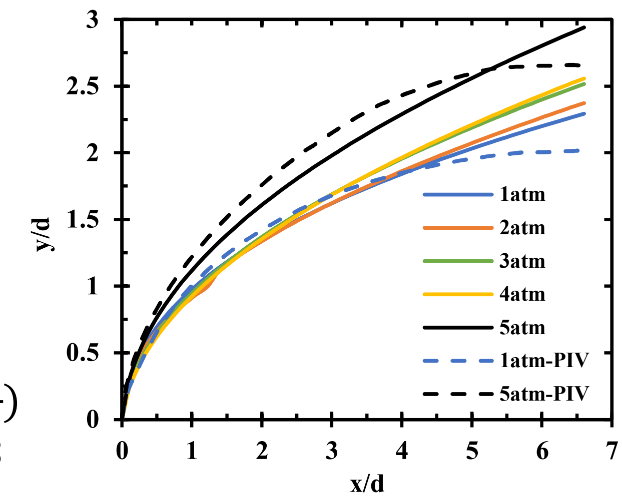
- Dependency on J to collapse each condition onto each other:
  - $Y = \left(\frac{y}{d_j J^{0.8}}\right), X = \left(\frac{x J^{-1/3}}{d_j}\right)$



- Equation holds for cases where heat release occurs prior to jet being deflected into crossflow.
  - Non-premixed configuration underpenetrates correlation because heat release (dilatation) is delay further downstream compared to the fully premixed

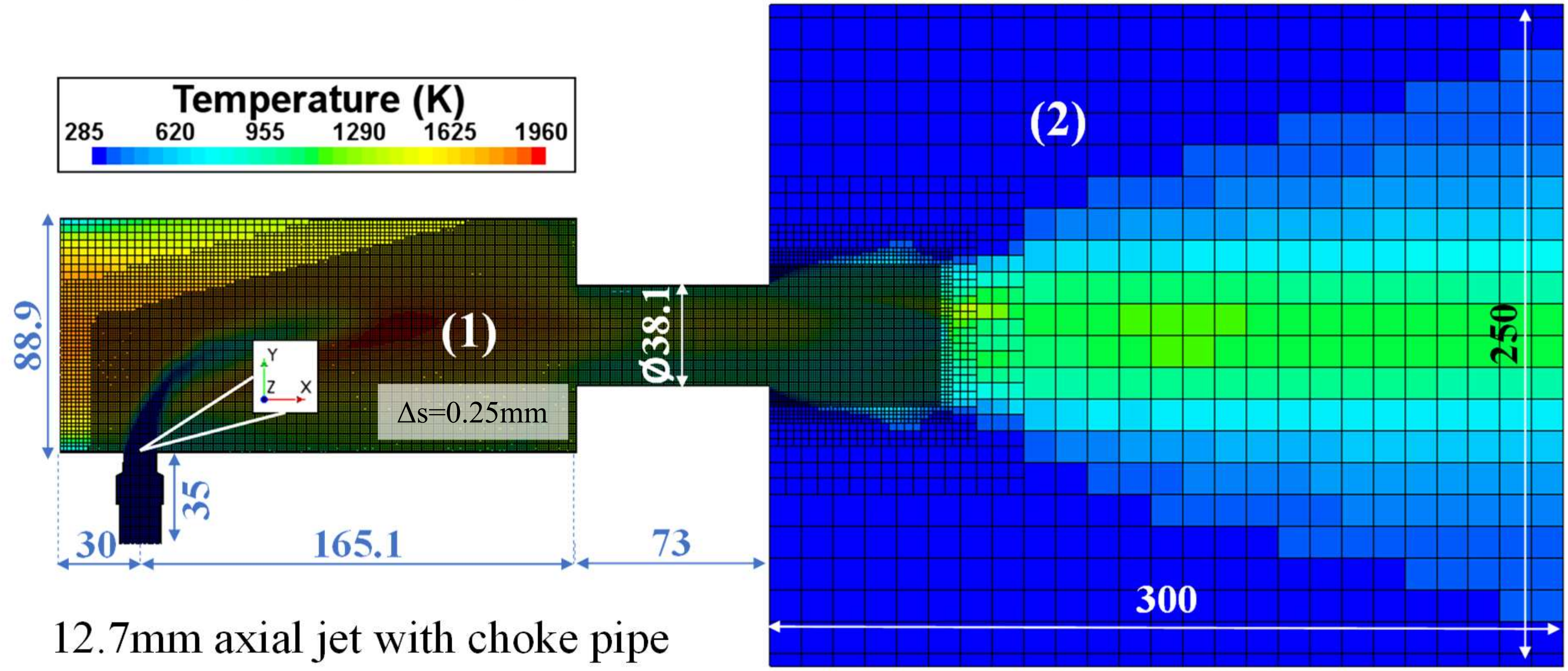
- Currently working on additional dependency on pressure and density ratio

$$\frac{y}{d_j} = 0.9J^{0.8}\left(\frac{\frac{x}{d_j}^{2/3} J^{-0.218}}{\frac{x}{d_j}^{2/3} J^{-0.218} + 0.58}\right)$$



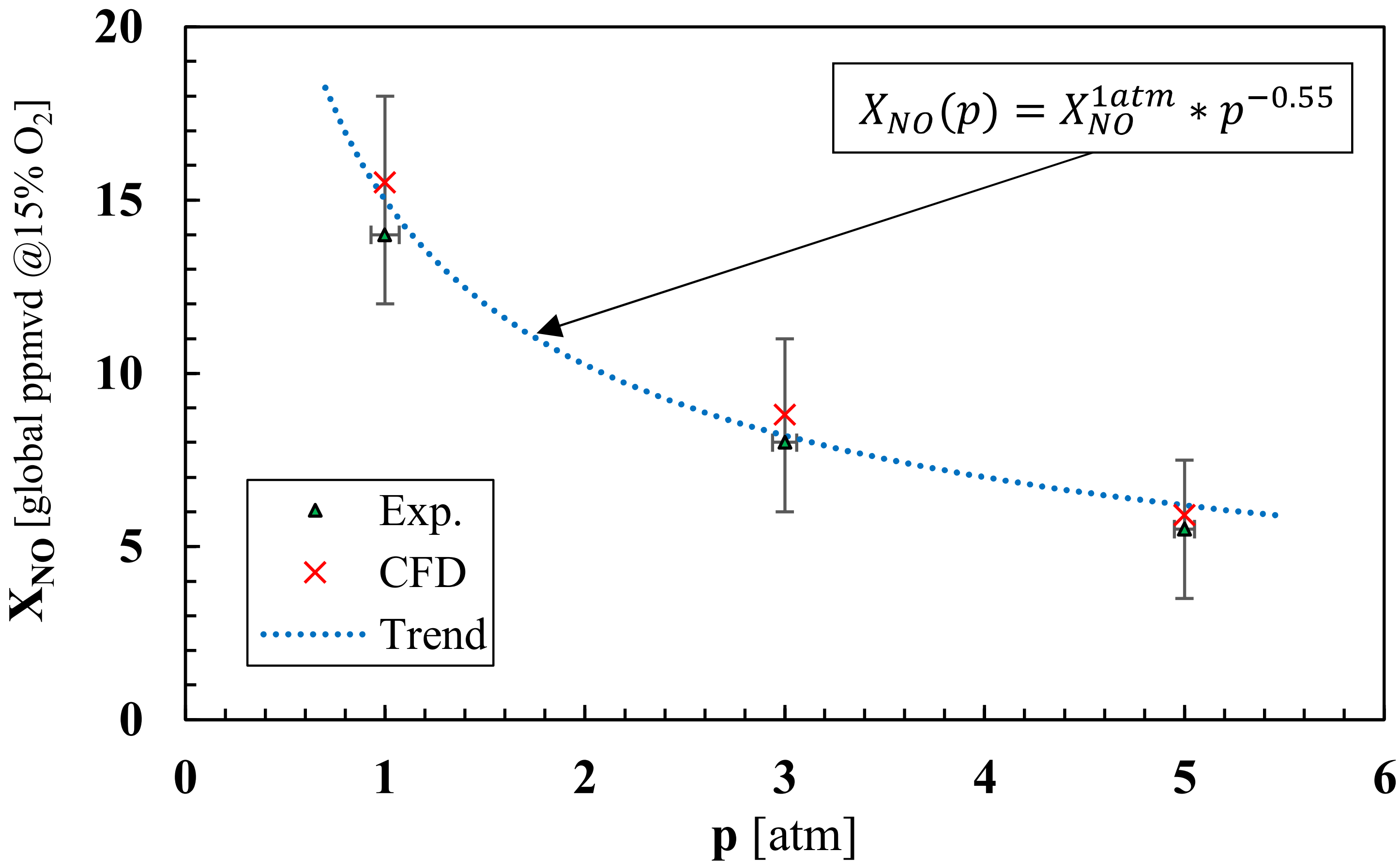
Task 4: CFD with Star CCM+

- Full GRI 3.0 Mechanism with Laminar Chemistry
- Hexahedral Mesh grid 2-50M cells for half domain
- Very fine mesh required to improve flame prediction
- Headend BC: equilibrium species, profiles for V and T
- Premixed jet with wall $y^+ = 1–3$



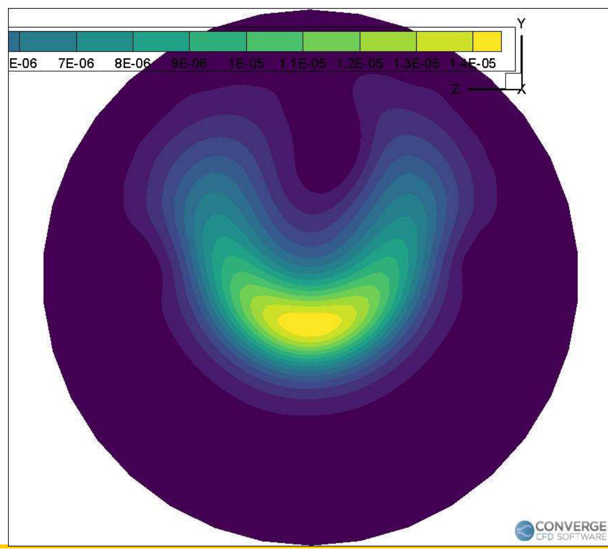
12.7mm axial jet with choke pipe

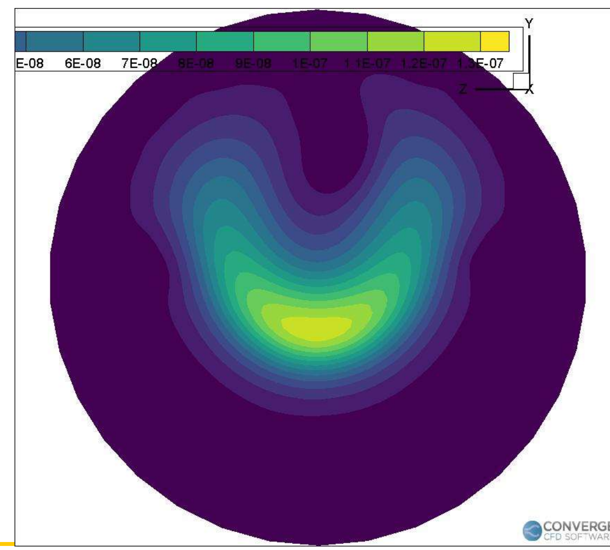
- Pressure dependency of global NO Emission with 12.7 mm premixed jet



Task 4: CFD with Converge

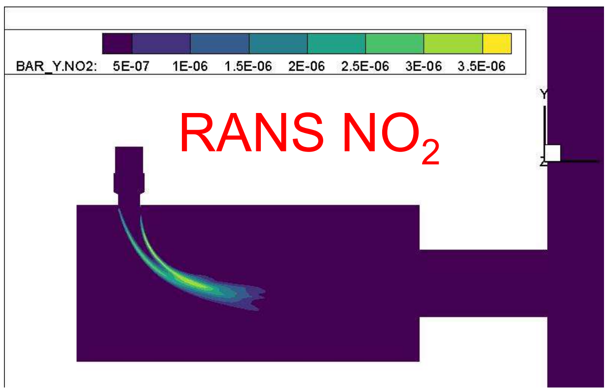
- RANS with RNG turbulence model using 2.85M cell mesh for full domain.
- Adaptive mesh refinement was used to resolve the flame and minimize mesh size
- 12.7 mm premixed CH_4-air jet, 5 atm.
- Laminar chemistry with full GRI3.0 mechanism.
- Exit NO and NO_2 assuming no inlet NO or NO_2.
- Measurement is 4 ppm over HE value.
- Average here is about 3 ppm.

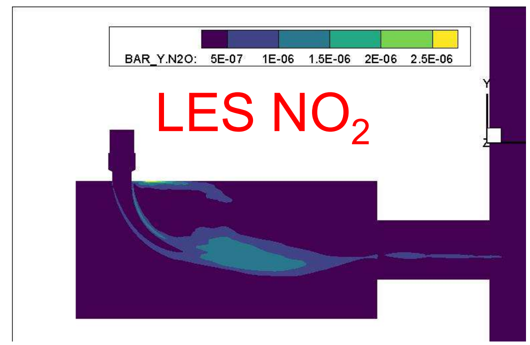


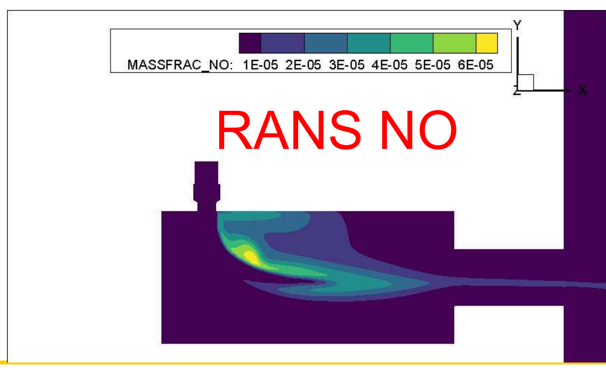


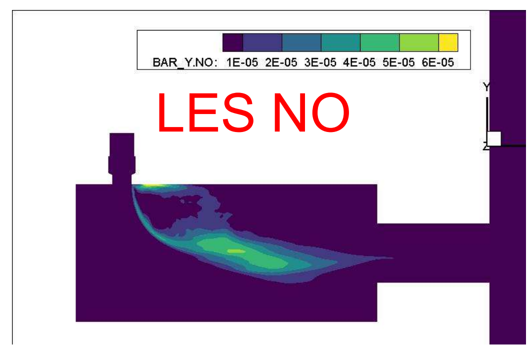
Task 4: CFD with Converge

- A 25.9 million mesh with LES and GRI 3.0 with laminar chemistry.
- LES requires 120 hrs to run 1.5 flow through times using 360 cores.
- The full test section was modeled using measured inlet conditions with a large section downstream of the choke plate to give a clean subsonic exit boundary condition.









Task 3: Expanded Scope

An additional year of funding was added to obtain additional BC's for CFD

- ❑ Measure heat transfer between the inner and outer wall for higher fidelity temperature modeling
- ❑ Measure mixture fraction across the axial jet to quantify unmixedness
- ❑ Measure non reacting jets at elevated pressures

Publications

Journals

-Partial Premixing Effects on the Reacting Jet of a High Pressure Axially Staged Combustor, T. Genova, M. Otero, B. Stiehl, K. Ahmed, ASME Journal of Engineering for Gas Turbines and Power, 2020

-Simulation of Premixed and Partially Premixed Jet-in-Crossflow Flames at High-Pressure, B. Stiehl, M. Otero, T. Genova, K. Ahmed, ASME Journal of Engineering for Gas Turbines and Power, 2020

-The Influence of Pressure on Flame-Flow Characteristics for a Reacting Jet in Crossflow, M.Otero, T.Genova Jr. B.Stiehl (in progress)

Conferences

- Otero, M., Genova, T., Reyes, J., Stiehl, B., Ahmed, K.A., Martin, S., "Characteristics of a Premixed Reacting Jet-in-Crossflow at Elevated Pressures", Propulsion and Energy, Indianapolis, IN, 2019

- Genova, T., Otero, M., Reyes, J., Ahmed, K.A., Martin, S., Velez, C., " High-Pressure Reacting Characteristics of Axial Stage Combustion", 58th AIAA Aerospace Sciences Meeting and Exhibit, Orlando, 2020

-Stiehl, B., Worbington, T., Miegel, A., Martin, S., Velez, C., Ahmed, K., "Characteristics of a Lean Axial-Stage Combustor", Turbomachinery Technical Conference & Exposition, Phoenix, AZ, 2019

- Genova, T., Otero, M., Stiehl, B., Reyes, J., Ahmed, K.A., Martin, S., " Exploration of Reacting Jet-in-Crossflow in a High-Pressure Axial Stage Combustor", 56th AIAA Aerospace Sciences Meeting and Exhibit, Indianapolis, IN, 2019

- Otero, M., Genova, T., Reyes, J., Stiehl, B., Ahmed, K.A., Martin, S., "Characteristics of a Premixed Reacting Jet-in-Crossflow at Elevated Pressures", Propulsion and Energy, Indianapolis, IN, 2019