Embry-Riddle Aeronautical University

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Improving NOx Entitlement with Axial Staging

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Dr. Scott Martin
Embry-Riddle Aeronautical University
Daytona Beach, FL

Tommy Genova, Michelle Otero, Bernie Stiehl, Jonathan Reyes, Tyler Worbington,
Dr. Kareem Ahmed and Dr. Subith Vasu
Mechanical & Aerospace Engineering
University of Central Florida
Orlando, FL

DOE University Turbine Systems Research Program PM: Dr. Seth Lawson

Industry Advisor: Dr. Changjin Yoon
GE Research Center

EMBRY-RIDDLE Aeronautical University

Background, Why Axial Staging

- Firing temperature is main parameter to increase efficiency of ground-based gas turbine powerplants.
- NO_x is an exponential function of firing temperature.
- Need to minimize time at peak firing temperature.

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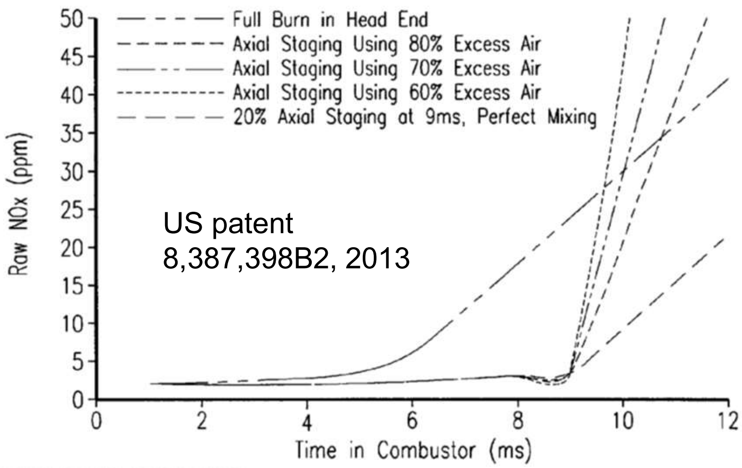


US patent 8,387,398B2, 2013

Axial staging increases the peak firing temperature with a short residence time

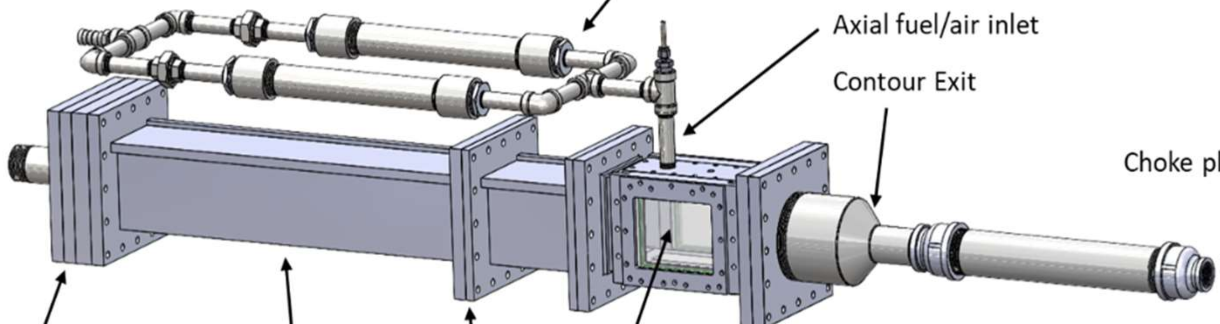
- Obtain axial stage data at industry relevant conditions.
- Develop reacting jet in crossflow correlation and validate CFD for axial stage modeling.

Tasks

- Task 2: Develop moderate pressure axial stage test rig
  - Tune headend to provide similar NO_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

Experimental Facility – Overview

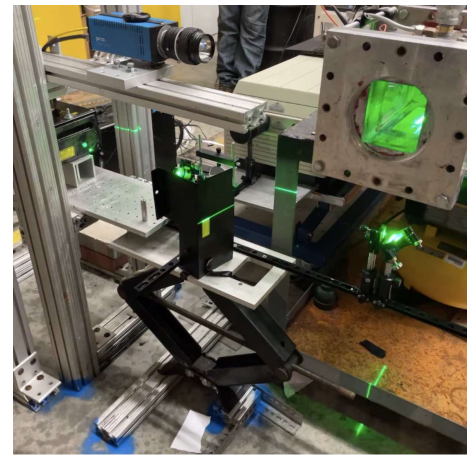


- 5.4 atm combustion facility
- Concentric dump style headend combustor run at lean conditions
- Jet injector diameter = 12.7 mm and 4 mm
- Optically accessible test section for optical diagnostics with variable air heaters
- Contoured nozzle exit that is adjustable in length
- Perforated screen and 6-inch section to improve axial stage boundary conditions
- Increased exit length to improve CO burnout before emissions sampling

Test section
3.5” tall
3.0” wide
4.0” window length
0.5” axial jet diameter
Jet starts 0.5” from window

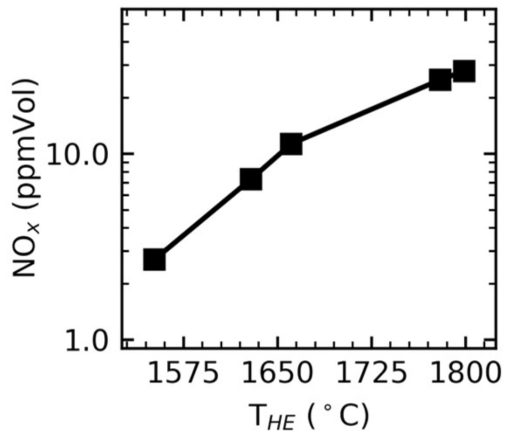
Instrumentation and Diagnostics

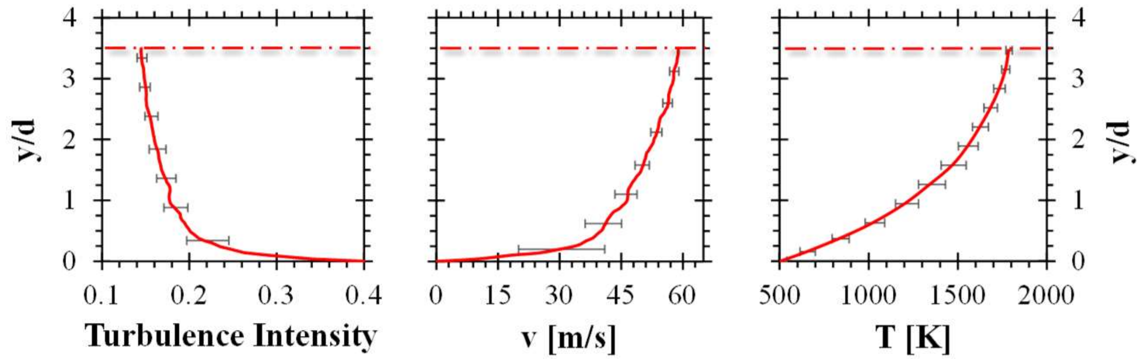
- **Particle Image Velocimetry (PIV)**
  - Double pulse Nd:YAG Evergreen 200, 15 Hz repetition rate
  - Andor Zyla 5.5 sCMOS Camer
  - 530 ± 10 nm filter
  - 3 µm Al_2O_3 particles used for seeding both jet and crossflow
  - Vector resolution: 600 µm/vector, l_f = 1500 micron (3-4 vectors across flame
- **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 Calibration

- Headend conditions to match real-world gas turbines:
  - Headend Φ: 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.





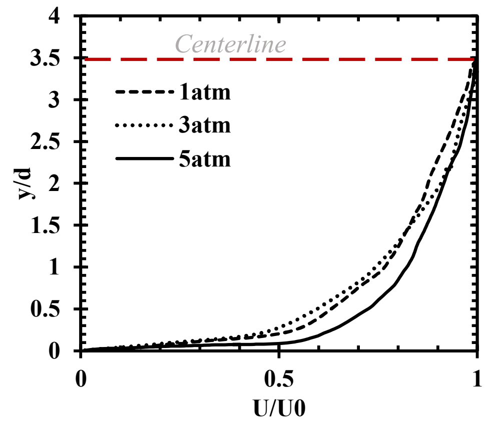
CH4-air axial stage conditions

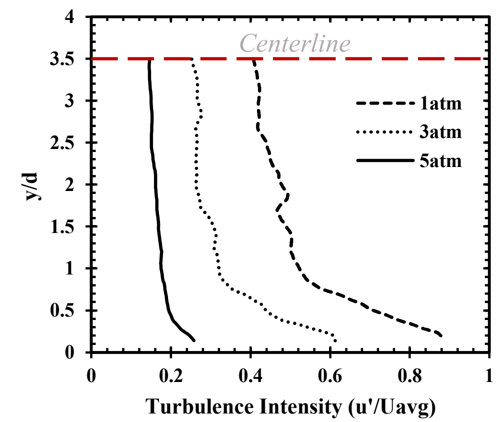
Pressure Effects
Premixing Effects
Preheating Effects
Non-Reacting Jets
Rig Heat Transfer

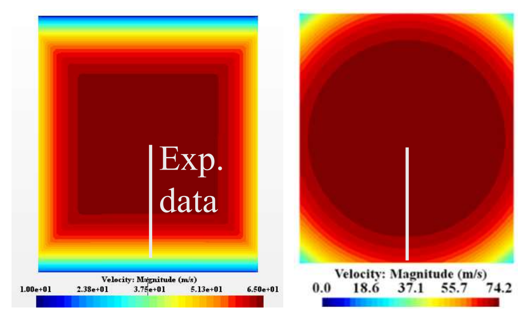
- Stiehl, B., Otero, M., Genova, T., Martin, S., Ahmed, K., “The Effect of Pressure on NO_x Entitlement and Reaction Timescales in a Premixed Axial Jet-in-Crossflow”, Journal of Energy Resources Technology, 2021.
- Otero, M., Genova, T., Stiehl, B., Martin, S., Ahmed, K., “The Influence of Pressure on Flame-Flow Characteristics of a Reacting Jet in Crossflow”. Journal of Energy Resources Technology, 2022.

Pressure Effects

- **Test Conditions**
  - Pressure Range: 1- 5.4 atm
  - Headend Φ: 0.58
  - Axial Jet Φ: 0.75
  - Total Φ: 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



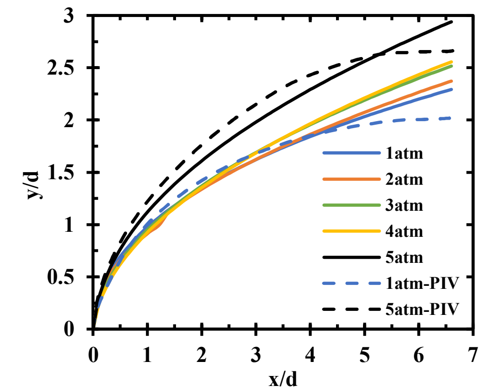




PIV Velocity Profile Extrapolation for CFD

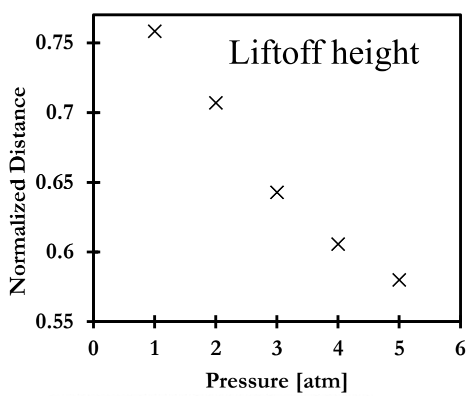
Pressure Effects

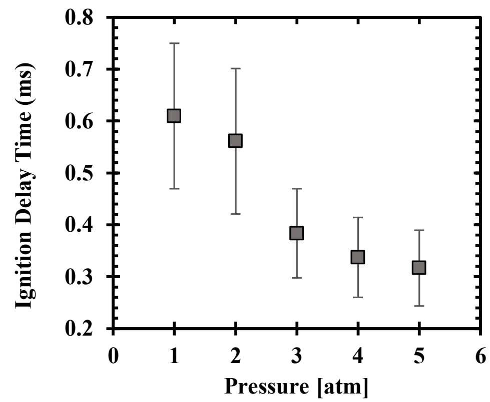
- Decrease in flame lift off height with pressure
- Increase ignition delay time (shorter chemical timescales)
- Increased jet penetration with elevated pressure due to increase in heat release resulting in lower entrainment
- Trajectories underpredicted with literature correlations

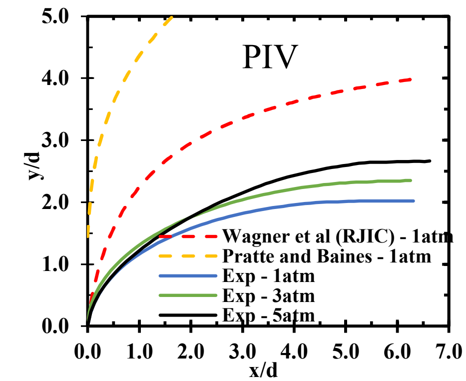


Solid lines CH*
Dashed lines PIV

Noticeable difference between 5 and 1-4 atm.

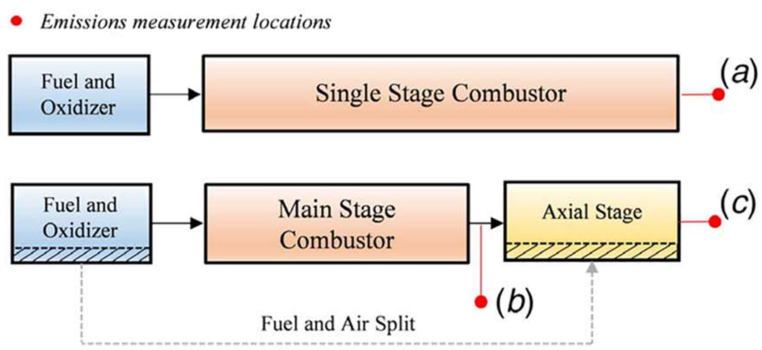


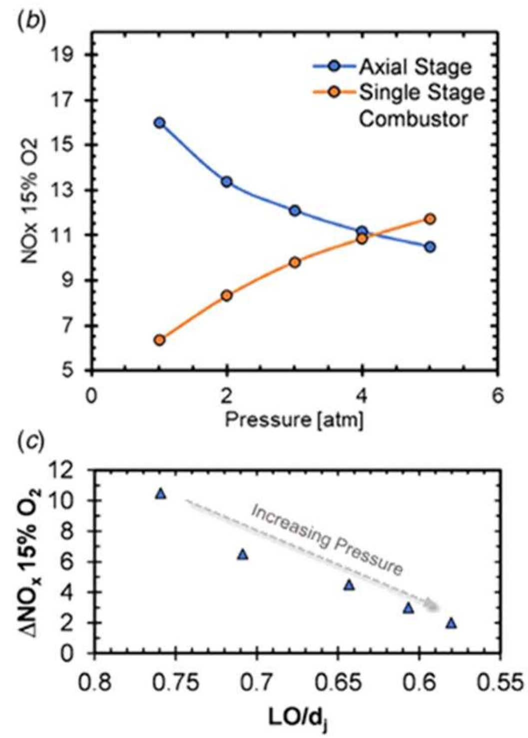




Emissions

- 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





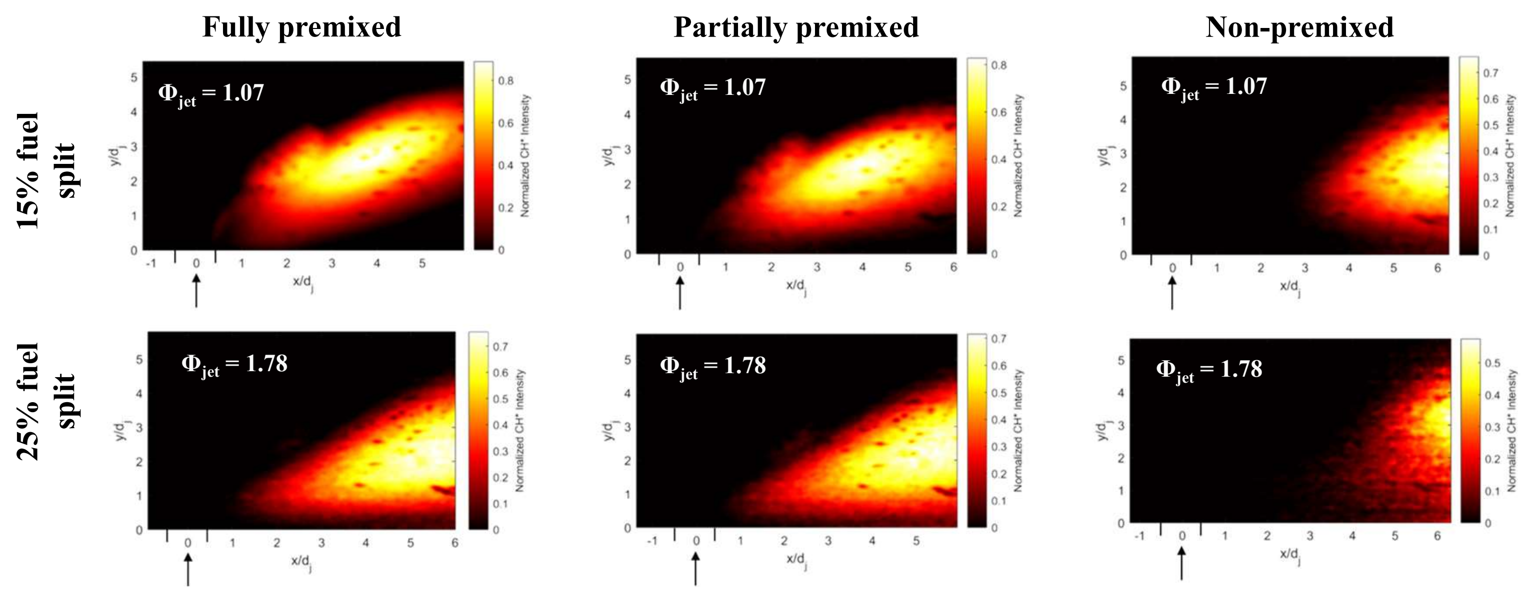
Important to test at a minimum of 5 atm for industry

CH4-air axial stage conditions

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

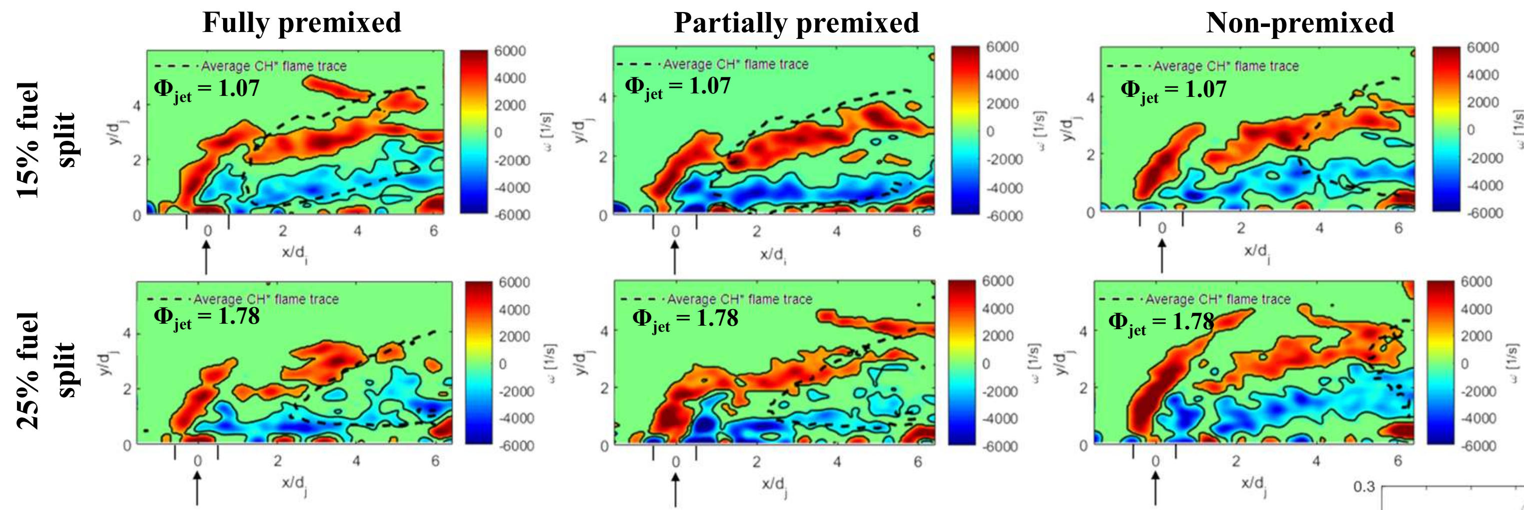
- Genova, T., Otero, M., Reyes, J., Ahmed, K.A., Martin, S., "Partial Premixing Effects on the Reacting Jet of a High Pressure Axially Staged Combustor", Journal of Engineering for Gas Turbines and Power, 2020.
- Stiehl, B., Otero, M., Genova, T., Reyes, J., Ahmed, K., Martin, S., Velez, C., "Simulation of Premixed and Partially Premixed Jet-in-Crossflow Flames at High-Pressure", Journal of Engineering for Gas Turbines and Power, 2020.
- Genova, T., Otero, M., Stiehl, B., Morales, A., Martin, S., Ahmed, K.A., "Preheating and Premixing Effects on NO_x Emissions in a High-Pressure Axially Staged Combustor", Combustion and Flame, 2021.

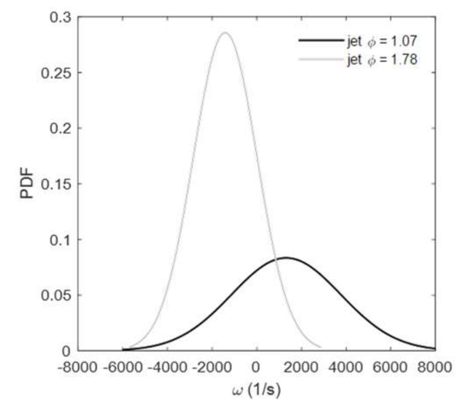
Effect of Premixing at Two Fuel Splits



- 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





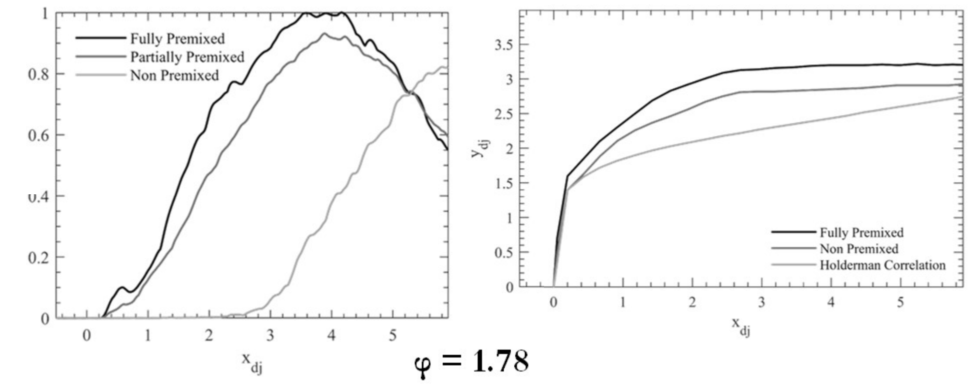
- Contours are vorticity from PIV, dashed line CH*
- Fully and partially premixed flames ignite in leeward shear region
- $\Phi = 1.07$ jet spreads to core while $\Phi = 1.78$ remains mainly in leeward shear layer
- Both non-premixed cases ignite in core
- Flame stabilization function of jet and crossflow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

Premixing Effects

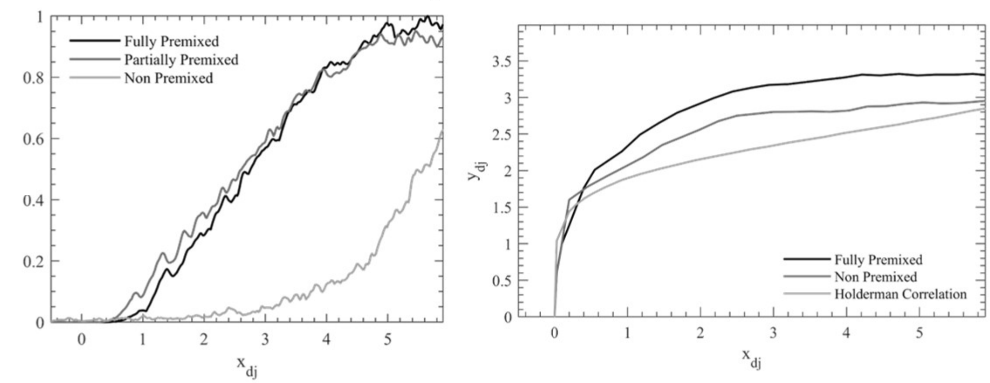
Jet Centerline Trajectories

- 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

φ = 1.07



φ = 1.78

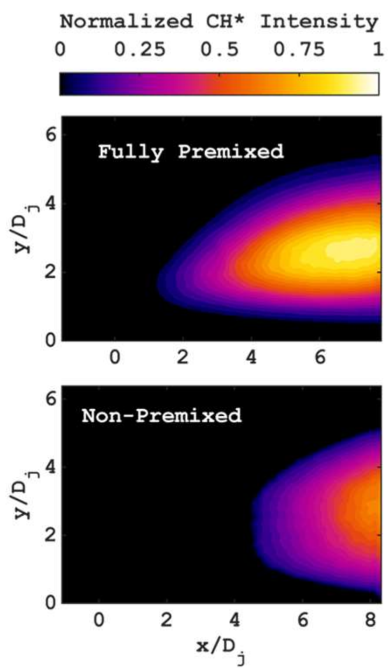


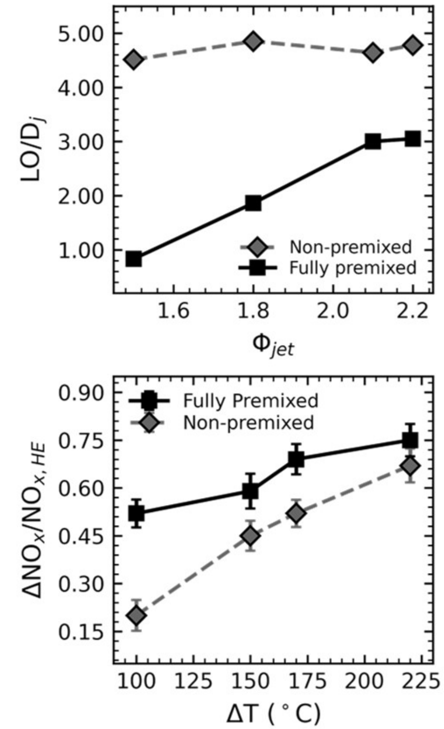
Scaled CH*

PIV

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

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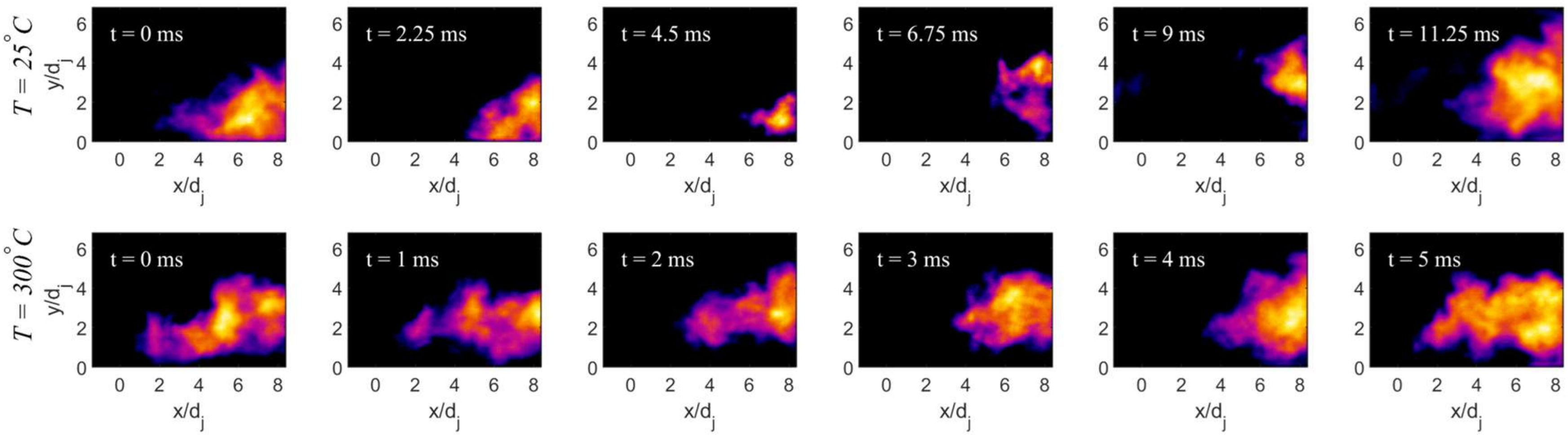
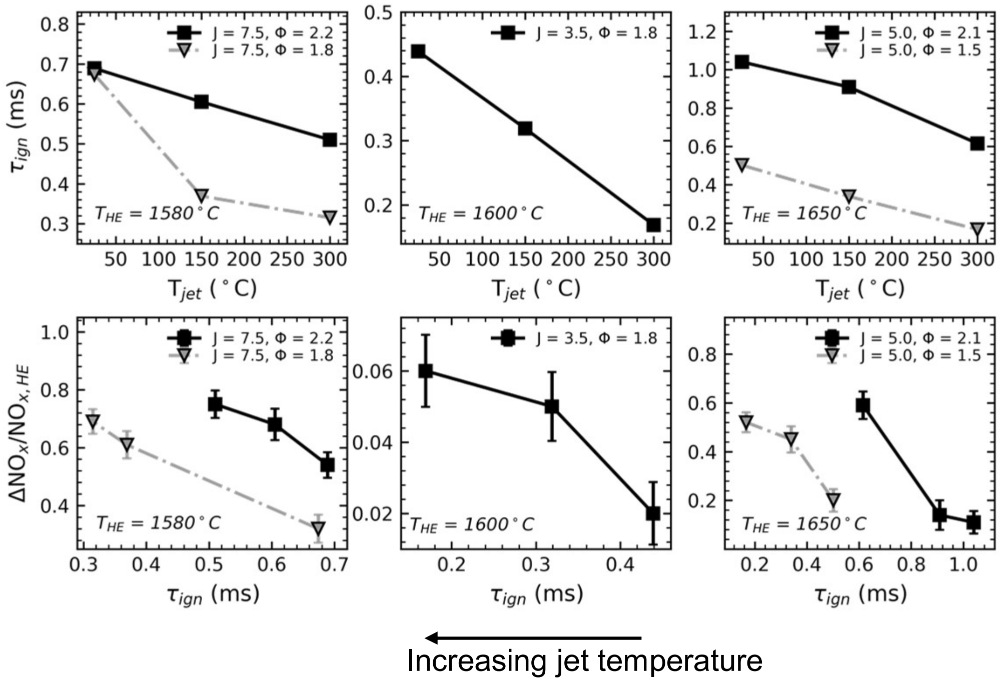
Liftoff Variance



- The 25 C case was noticeably less stable than the 150 C and 300 C caseswith 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 suspectable to these large-scale fluctuations

Emissions

$$\tau_{ign} = \frac{LO}{v_{jet}}$$



- τ_{ign} is used to quantify pre-flame mixing, where LO is liftoff height and v_{jet} is jet injection velocity
- Increasing jet preheat temperature hinders pre-flame mixing
- This leads to increased NO_x compared to non-preheated jets

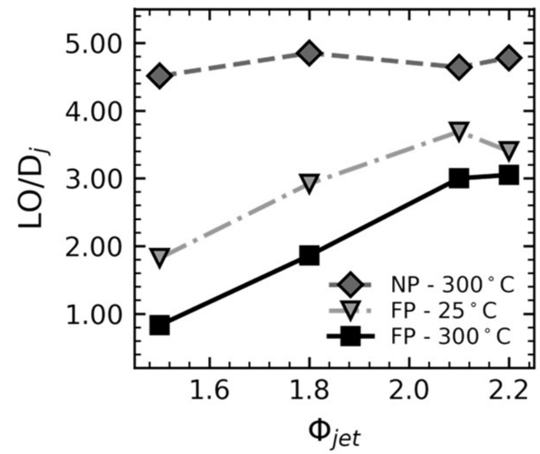
Premixing vs. Preheating

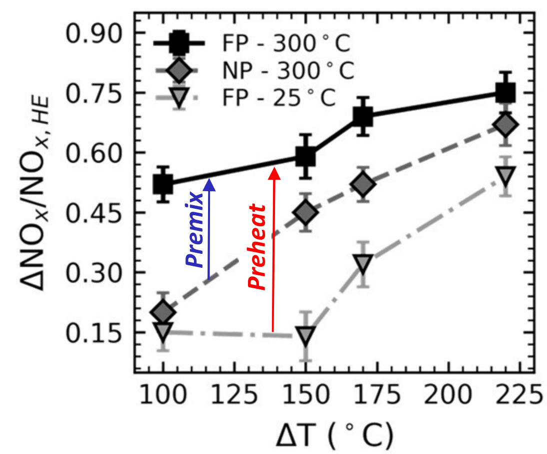
- The non-premixed and non-preheated jets increased ignition delay and showed a NO_x benefit compared to the fully premixed, preheated jet with HE temperature 1,580 C, jet equivalence ratio 1.8 and J=3.5

- 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

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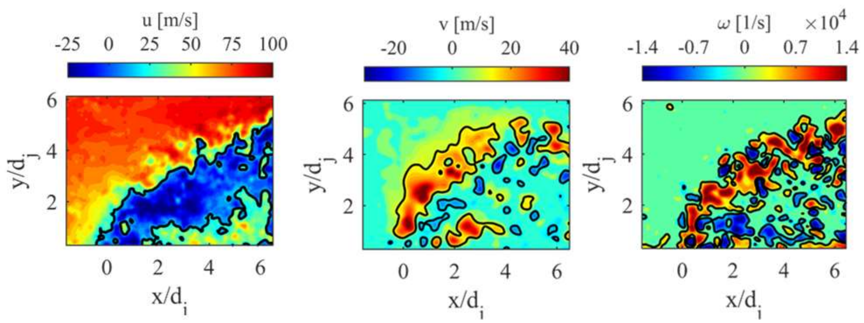
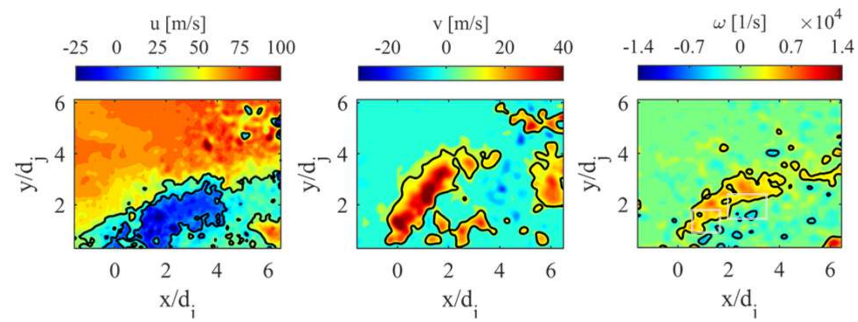
Non-Reacting vs. Reacting

Flow-field Comparisons



Reacting



Non-Reacting

- Non reacting vs reacting for J = 5.5 instantaneous u, v, and ω
- $J = 5.5$, $\Phi_{jet} = 1.62$ (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

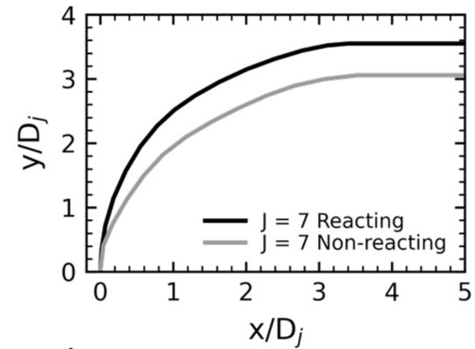
Centerline Jet Trajectories

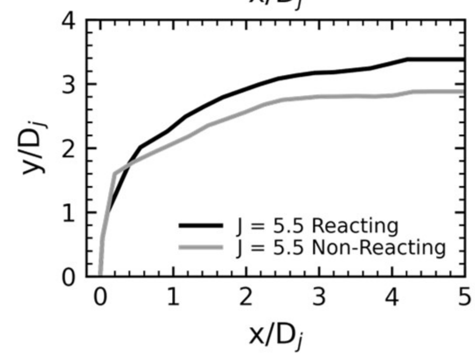
- Non-reacting vs non-reacting for J = 5.5 and J = 7 time-averaged jet centerlines

- For J = 7, Φ_{jet} = 0.95 (for reacting), Φ_{HE} = 0.66, v_{HE} = 69 m/s, v_{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, Φ_{jet} = 1.62 (for reacting), Φ_{HE} = 0.75, v_{HE} = 74 m/s, v_{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 Φ_{jet} = 0.95 compared to Φ_{jet} = 1.62 because the heat release for the leaner jet occurs earlier in the trajectory





CH4-air axial stage conditions

Pressure Effects
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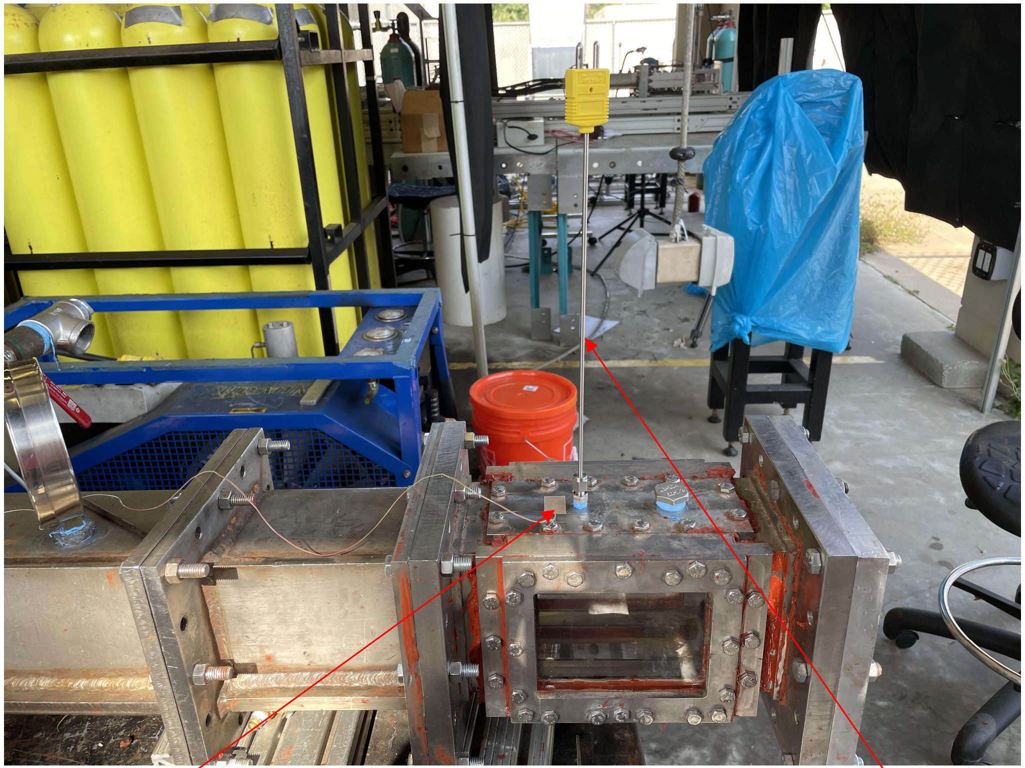
Rig Heat Transfer

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

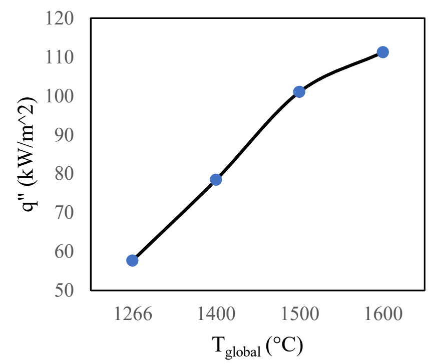


Surface mounted k-type thermocouple

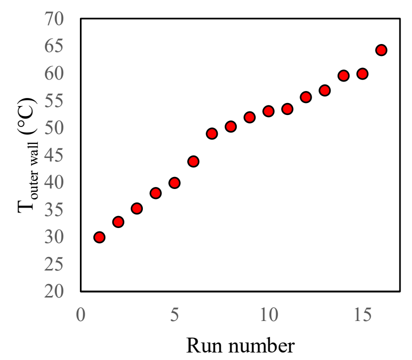
Wall flush exposed bead k-type thermocouple

Heat Transfer Results

P (atm)	φ_{global}	T_{global}(°C)	T_{inner} (°C)	T_{outer} (°C)	ΔT (°C)	q" (kW/m^2)
1	0.684	1564	44	226	182	91
5	0.517	1266	52	168	116	58
5	0.597	1400	55	212	158	78
5	0.649	1500	58	261	203	101
5	0.706	1600	62	286	224	111

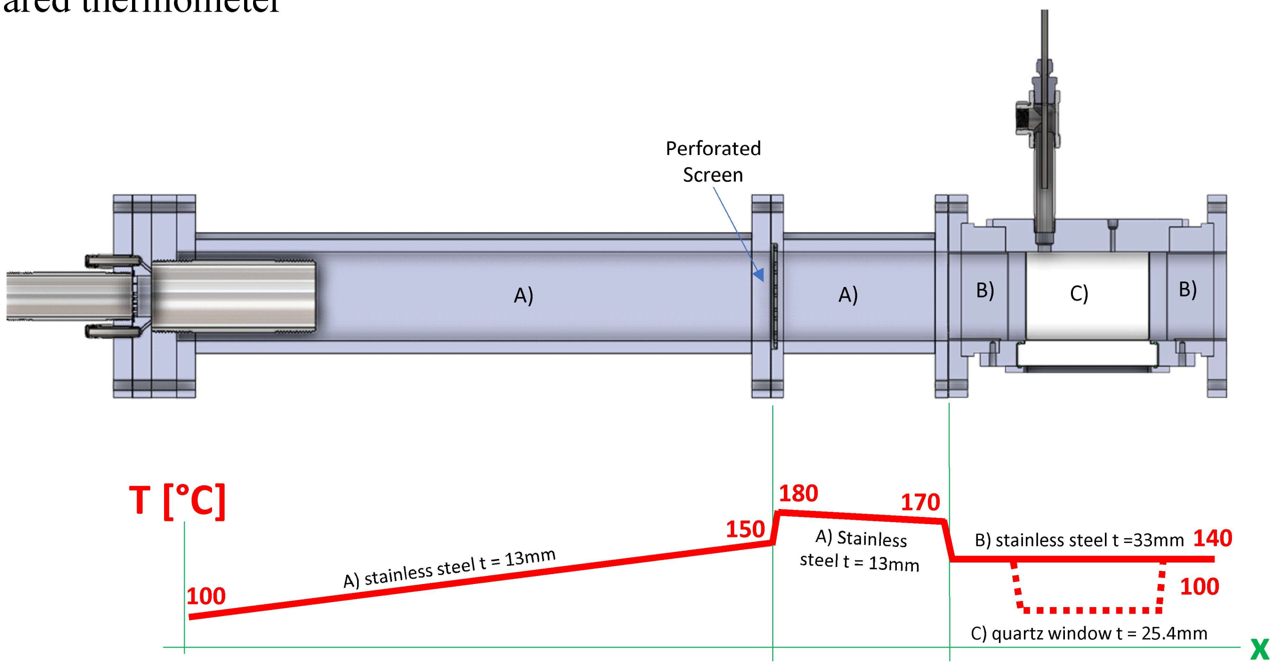


- Temperature results for each case
  - Headend was varied between 1266-1600°C
- The outer wall temperature increased throughout the campaign, but did not vary much during each individual run



Outer Wall Temperature

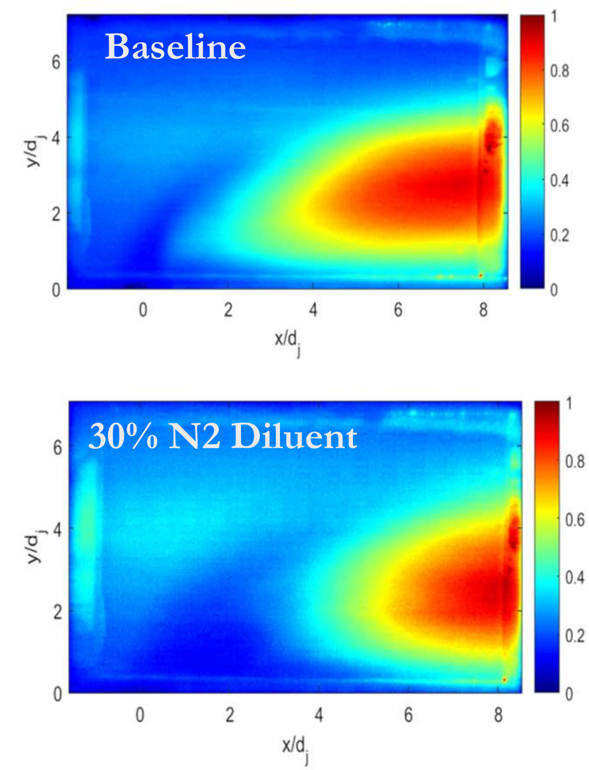
- Recorded after 40 back-to-back runs
- Quasi steady-state
- Taken with infrared thermometer



CH_4-air/diluent axial stage conditions

Testing Conditions

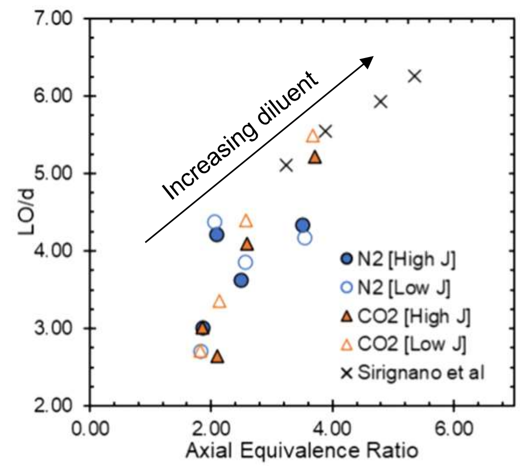
- Mass Flow Rate: 0.5kg/s
- Pressure: 5atm
- HE equivalence ratio : 0.70
- Diluent gas: CO_2 and N_2
- Diluent %: 0 to 50 (replace air in axial stage)
- axial equivalence ratio: 1.75 to 3.5
- Fuel mass remain constant
- Momentum flux ratio: 5 and 8 without diluent
- Premixed Methane/Air Crossflow and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

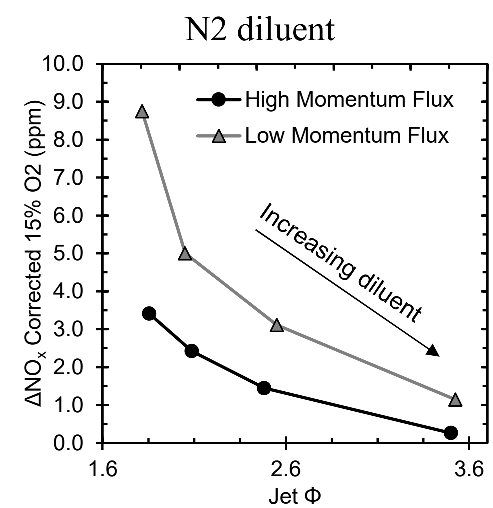


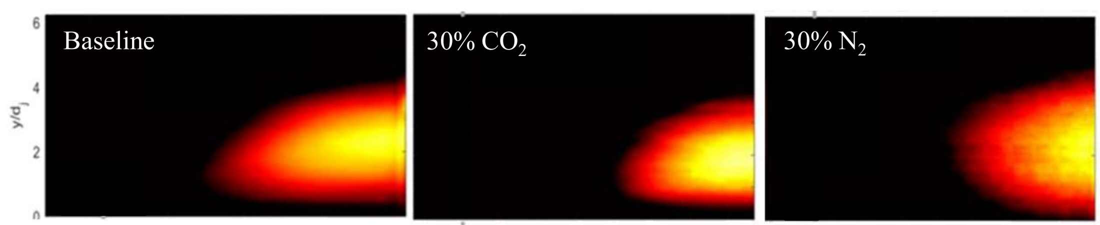
Diluent

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



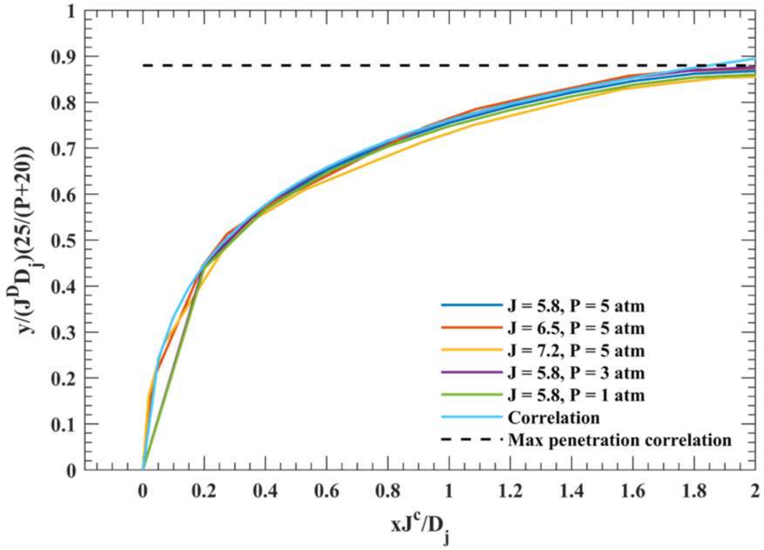




Reacting Jet-in-Crossflow Correlation

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

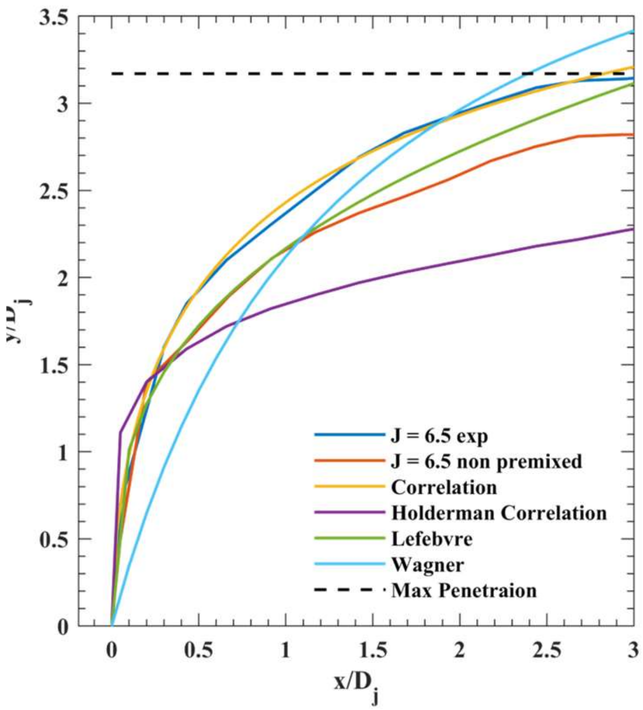


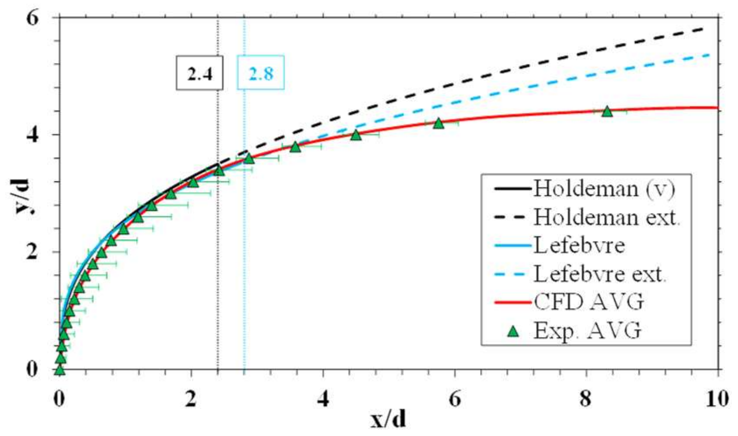
$$\frac{y_c}{d_j} = 1.13J^{0.68}\left(\frac{\left(\frac{x}{d_j}J^{-0.23}\right)^{0.59}}{\left(\frac{x}{d_j}J^{-0.23}\right)^{0.59}+0.8}\right)P^{0.12}$$

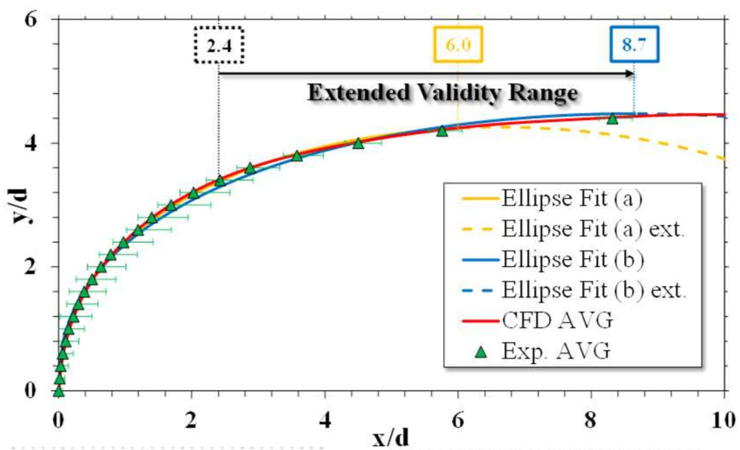
$$\frac{y_{max}}{d_j} = 0.73J^{0.68}P^{0.12}$$

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

$$\frac{y}{d} = a * J^b * \left(\frac{x}{d}\right)^c$$

sqrt-type	a	b	c
Lefebvre [33]	0.82	0.5	0.33
Holdeman [34]	0.89	0.47	0.36
Demuren [32]	0.7-1.3	0.36-0.52	0.28-0.40

Approximate 12.7mm jet data with quarter-Ellipse

$$\frac{y}{d} = \sqrt{\frac{2\alpha J * \left(\frac{x}{d}\right)^{\beta} - \left(\frac{x}{d}\right)^{2}}{\sqrt{J}^{\gamma}}}$$

Ellipse	α	β	γ
(a)	1.0	0.88	1.0
(b)	1.65	0.82	1.76

CFD Validation

Operating Conditions

Headend conditions				Axial jet conditions		
Main air flow	0.290	kg/s		Air flow	0.03618	kg/s
Main CH4 flow	0.010	kg/s		CH4 flow	0.002104	kg/s
By-pass air flow, total	0.071	kg/s		Inlet temperature	573	K
Hydrogen pilot flow, total	0.00048	kg/s		Inlet density	3.364	kg/m^3
Products velocity	49	m/s		CH4 mass fraction	0.05517	-
Products density	1.125	kg/m^3		O2 mass fraction	0.2202	-
Products temperature	1545	K		N2 mass fraction	0.72463	-
Pressure	5.4	atm.		Turbulence intensity	17	%
CO_2 mass fraction, exit	0.0761	-		Turbulence length	0.0012	m
H_20 mass fraction, exit	0.07378	-		Axial jet diameter	12.7	mm
N_2 mass fraction, exit	0.74468	-		J	10.0	
O_2 mass fraction, exit	0.10544	-		T increase	100	K
Turbulence intensity	5	%				
Turbulence length scale	0.004	m				

CFD Methodology

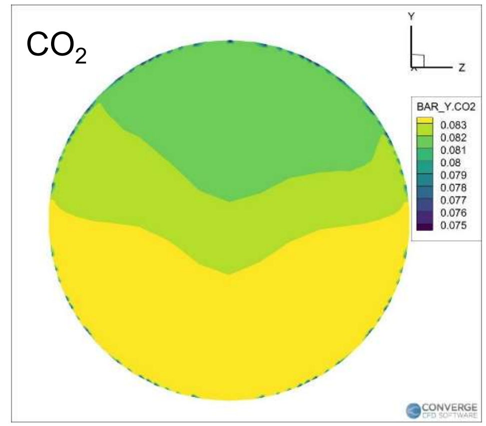
CONVERGE 3.0 URANS & LES
Sage laminar combustion model with full GRI 3.0 kinetic mechanism
Adiabatic wall BC's
Modeled full width of rig from test section entrance to choke plate exit

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

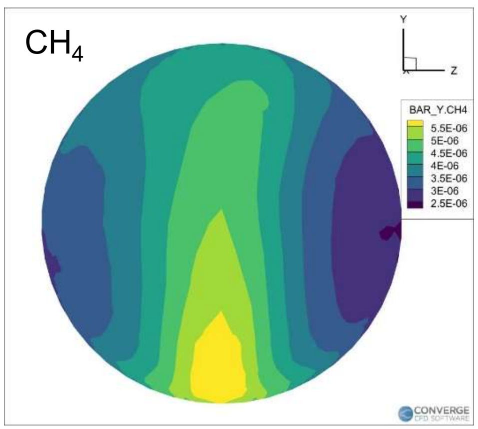
LES
Dynamic Smagorinsky SGS turbulence
11.2 M cell mesh
2.5 mm base mesh with embedding, no AMR
0.03025 s of statistics
170 hrs on 360 cores

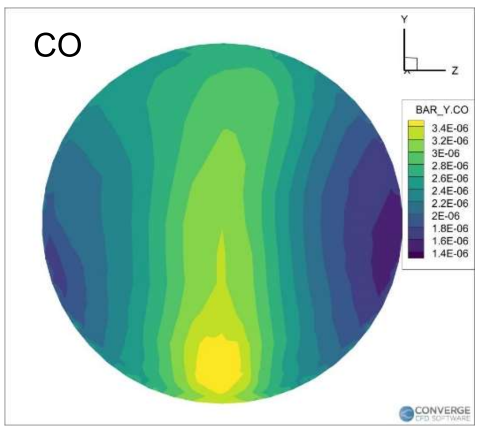
Exit emissions data and CFD

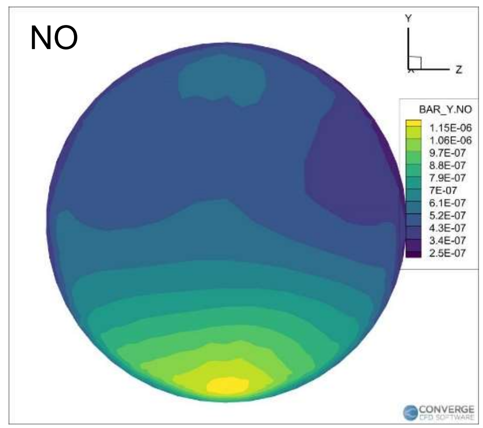
Emissions	Data	LES probe	LES area average	
CO_2	6.5	6.1	6.1	% Vol dry
CO	4.1	1.9	1.6	ppm dry 15% O_2
NO_x	5.9	0.8	0.9	ppm dry 15% O_2

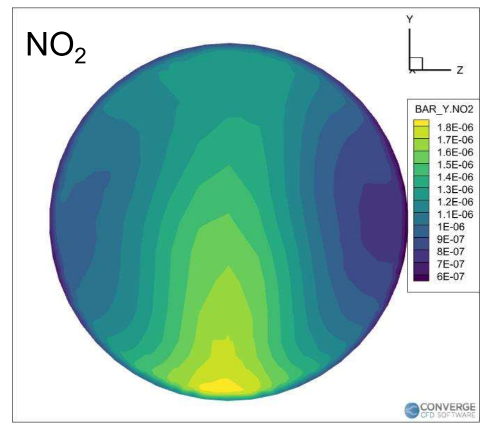


Note: CFD O_2 and H_2O from equilibrium calculation

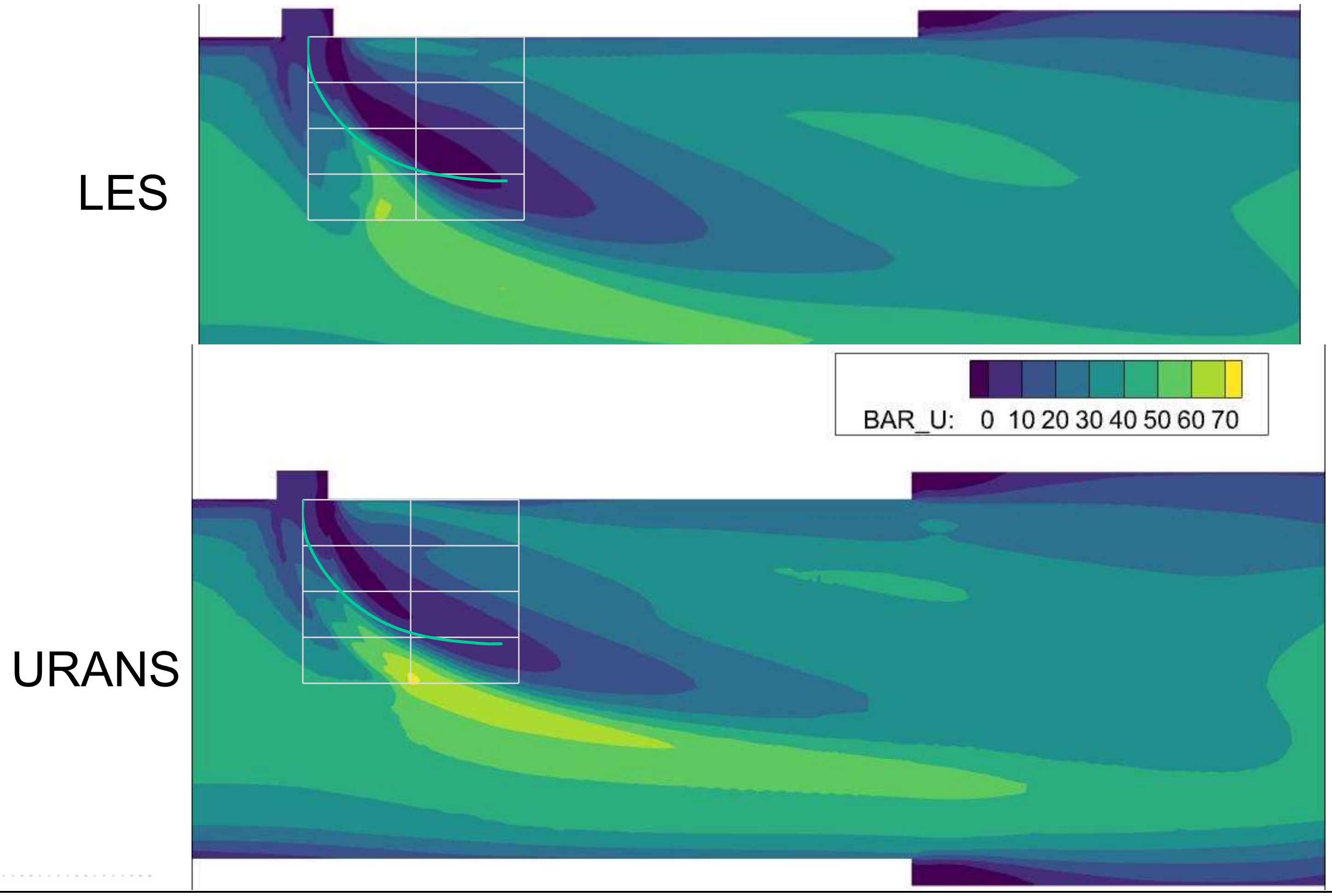








Averaged axial velocity and PIV centerline trajectory



URANS Axial Stage Results

Simulation cases

	PIV EXP	1. Sim Inlet, Adiabatic	2. Sim Inlet, Adiabatic, Default turb	3. Sim Inlet, Heat Loss	4. Exp Inlet	5. DI Inlet
Turbulence model	-	k-epsilon	RNG	k-epsilon	k-epsilon	k-epsilon
Inlet velocity	-	Case a	Case a	Case b	Experiment	Uniform
Inlet temperature	-	Case a	Case a	Case b	Case a	Uniform
Inlet turbulence	-	Case a	Case a	Case b	Experiment	Uniform

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

Emissions

NO_X (ppmvd) 15% O2	**5.9**	**6.3**	**14.1**	**3.5**	**5.9**	**6.1**
CO (ppmvd) 15% O2	4.1	1.1	1.5	1.3	1.2	1.3
CO_2 (vol frac dry)	0.065	0.060	0.060	0.060	0.060	0.060

Cases 1, 4 & 5 give best NO_x match

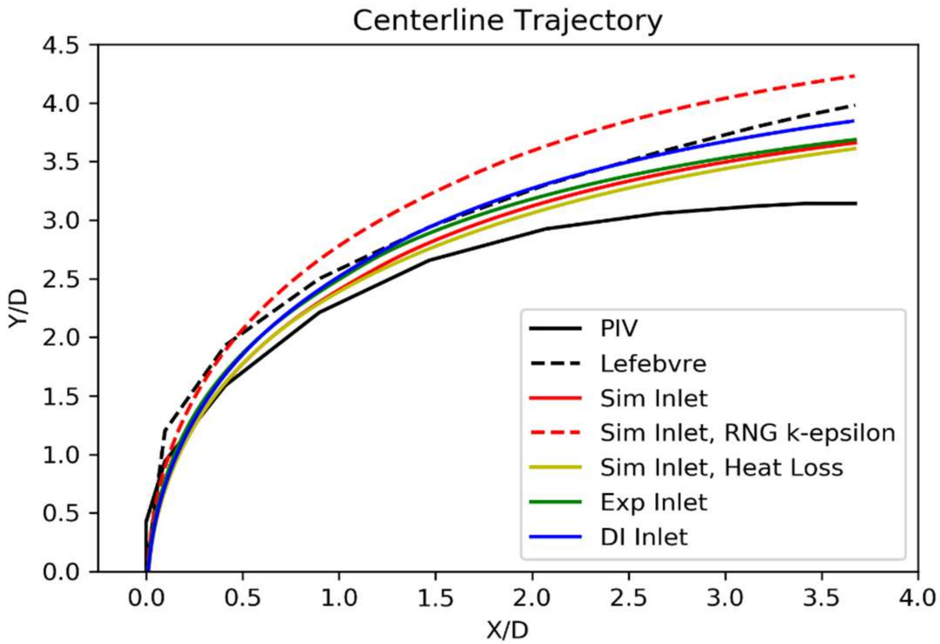
URANS Axial Stage Results

Lefebvre jet penetration correlation

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

Momentum flux ratio

$$J = \frac{(\rho V^2)_{jet}}{(\rho V^2)_{crossflow}} = 10$$

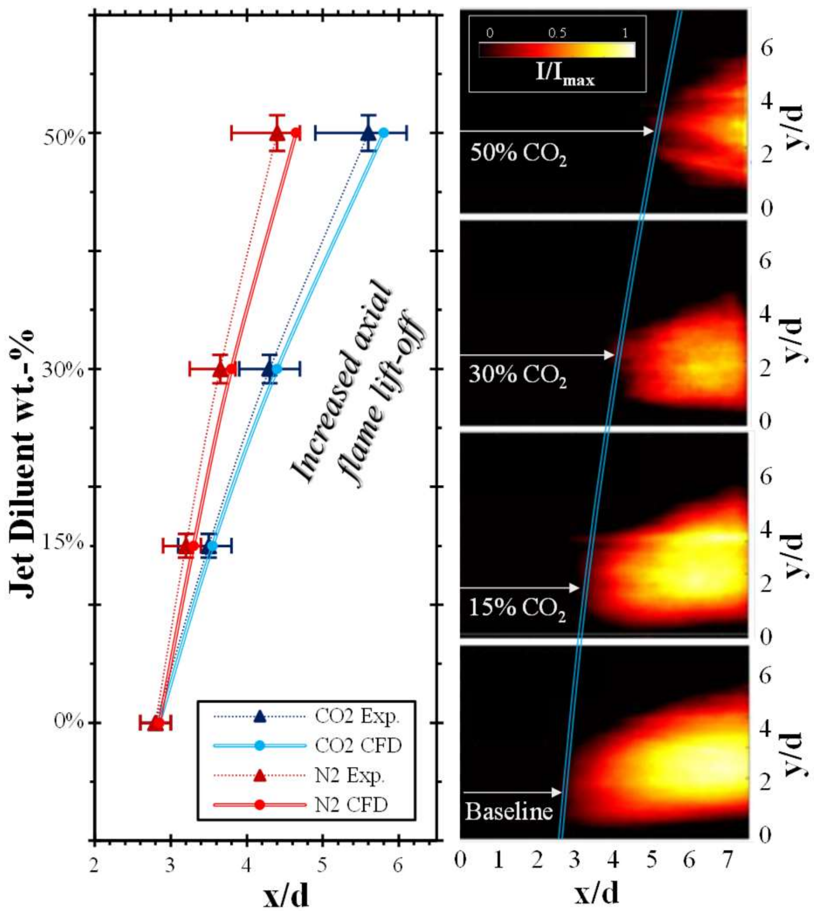


Cases 1, 3 & 4 give best penetration match

CFD with Star CCM+

EMBRY-RIDDLE Aeronautical University

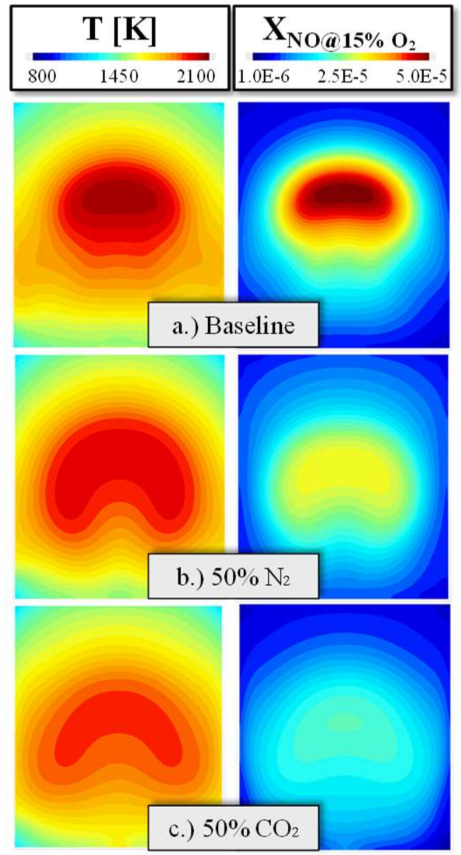
- Substitute between 0 and 50% of axial jet air with either CO_2, or N_2 diluent
- CO_2 dilution reacts slower than with N_2
- Higher Lift-off for CO_2 relative to N_2
- Chemiluminescence vs. CFD simulation
- Detailed chemistry with GRI 3.0 RANS CFD with half-width symmetric model 5M cells validated with experimental flame position (axial flame lift-off captured within 8% deviations)



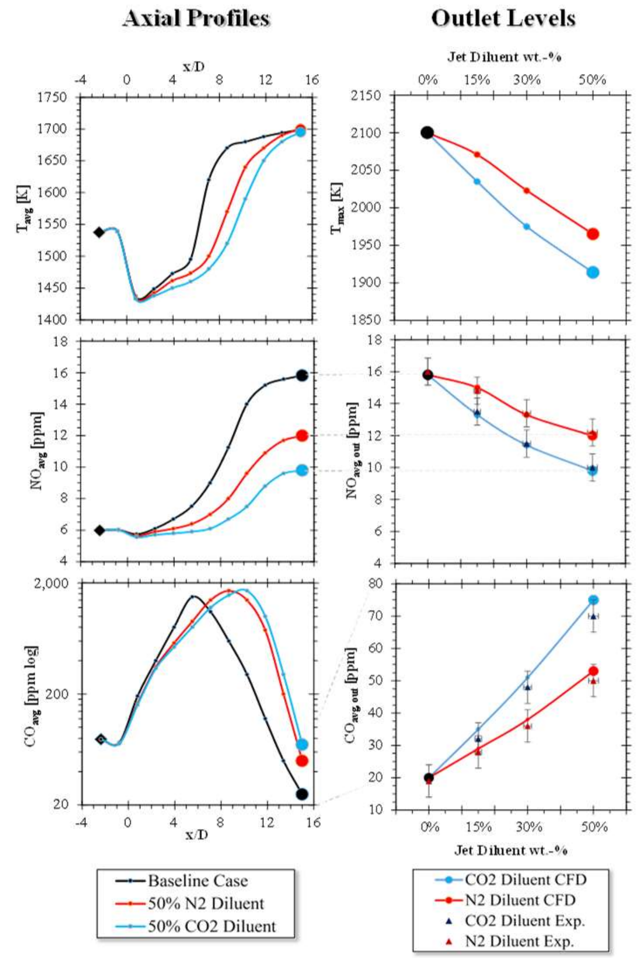
CFD with Star CCM+

Embry-Riddle Aeronautical University

- 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



CATER

UCF

Journal Publications

Genova, T., Otero, M., Reyes, J., Ahmed, K.A., Martin, S., "Partial Premixing Effects on the Reacting Jet of a High Pressure Axially Staged Combustor", Journal of Engineering for Gas Turbines and Power, 2020

Stiehl, B., Otero, M., Genova, T., Reyes, J., Ahmed, K., Martin, S., Velez, C., "Simulation of Premixed and Partially Premixed Jet-in-Crossflow Flames at High-Pressure", Journal of Engineering for Gas Turbines and Power, 2020

Stiehl, B., Genova, T., Otero, M., Reyes, J., Martin, S., Ahmed, K., "Fuel Stratification Influence on NO_x Emissions in a Premixed Axial Reacting Jet-in-Crossflow at High Pressure", Journal of Energy Resources Technology, 2021

Stiehl, B., Otero, M., Genova, T., Martin, S., Ahmed, K., "The Effect of Pressure on NO_x Entitlement and Reaction Timescales in a Premixed Axial Jet-in-Crossflow", Journal of Energy Resources Technology, 2021

Otero, M., Genova, T., Stiehl, B., Martin, S., Ahmed, K., "The Influence of Pressure on Flame-Flow Characteristics of a Reacting Jet in Crossflow". Journal of Energy Resources Technology, 2022

Genova, T., Otero, M., Stiehl, B., Morales, A., Martin, S., Ahmed, K.A., "Preheating and Premixing Effects on NO_x Emissions in a High-Pressure Axially Staged Combustor", Combustion and Flame, 2021

Stiehl, B., Genova, T., Otero, M., Martin, S., Ahmed, K., "Controlling Pollutant Emissions in a High-Pressure Combustor with Fuel-Diluent Blending", Fuel, 2022 *(in preparation)*

Thank you!

Questions?