University Turbine Systems Research
Project Review Meeting 5 November, 2019

Improving NOx Entitlement with Axial Staging

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Dr. Scott Martin
Eagle Flight Research Center
Embry-Riddle Aeronautical University
Daytona Beach, FL

Tommy Genova, Michelle Otero, Bernie Stiehl, Jonathan Reyes, Dr. Kareem Ahmed and Dr. Subith Vasu
Mechanical & Aerospace Engineering
Propulsion & Energy Research Laboratory
Center of Advanced Turbomachinery & Energy Research
University of Central Florida
Orlando, FL

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

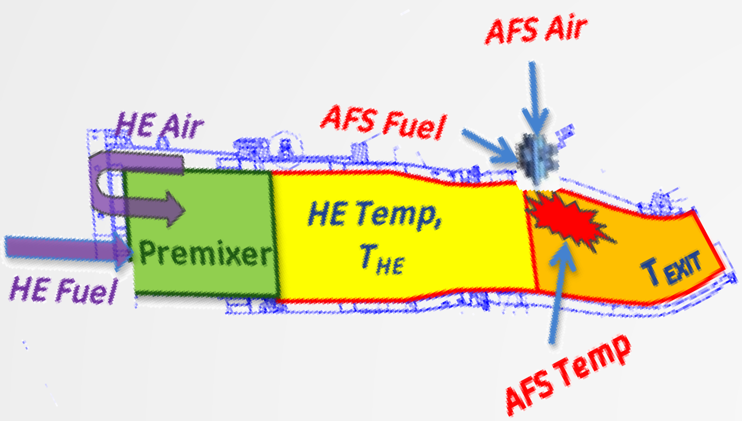
Industry Advisors: Drs. Keith McManus and Carlos Velez, GE Research Center

Outline

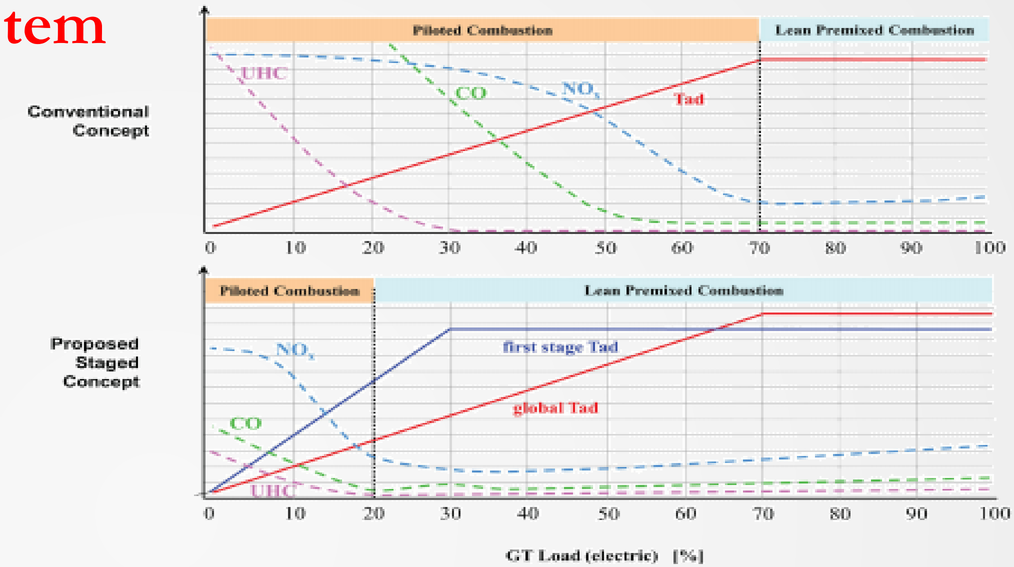
- Introduction
- Objectives
- Experimental Facility
- Fuel Only Jet Preliminary Results
- Premixed Jet Preliminary Results
- PIV and TDLAS Measurements
- Modeling
- Year 3 Work

INTRODUCTION

Axial Stage Combustion System



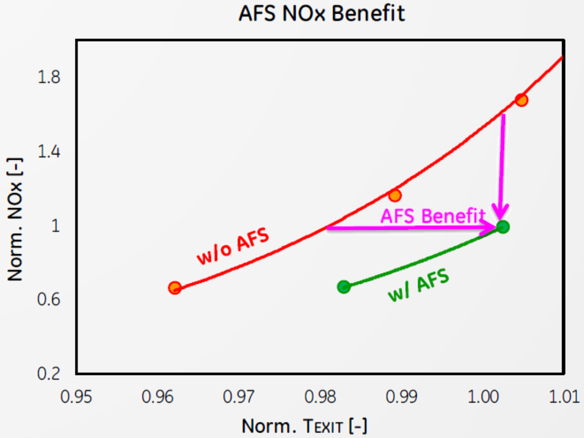
H.Karim *et al.* GE power, TurboExpo 2017



D.Winkler *et al.* GPPS Journal 2017

- 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

Motivation of Study

- 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.

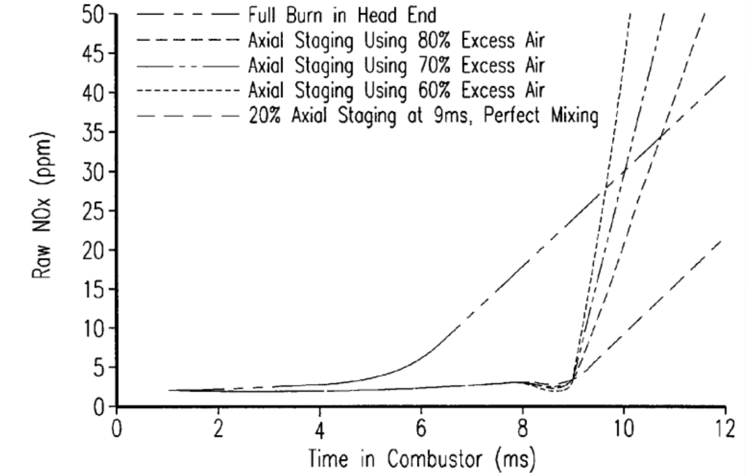
Axial Stage Combustion System Applications

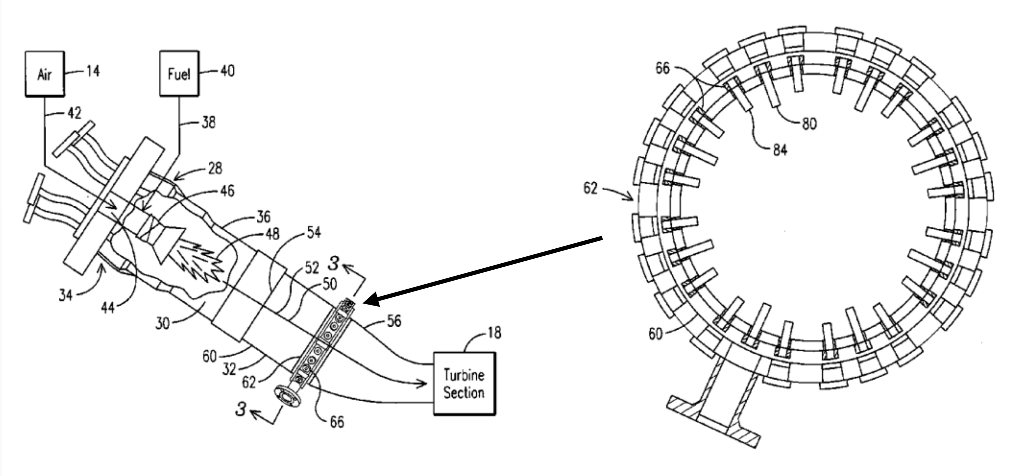
- Power Generation
- Potential for Aircraft Engines

S. Martin et al., Siemens Energy, Orlando, FL

U.S. Patent 8,387,398, 2013

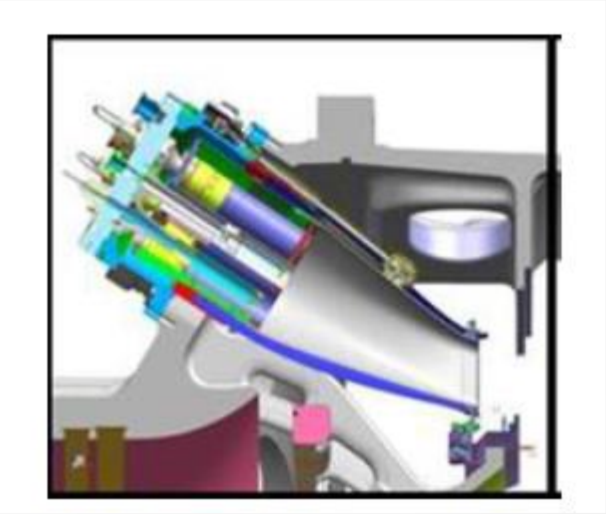
- Apparatus and method for controlling the secondary injection of fuel.
- Adds multiple fuel nozzles in the transition.
- Can be used to improve temperature pattern factor entering the turbine.



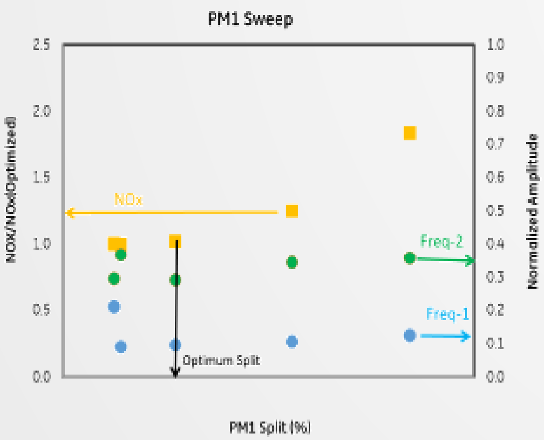


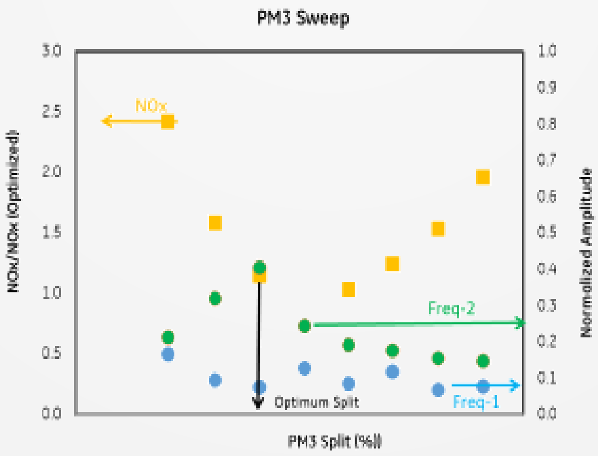
Recent Investigation - 2017

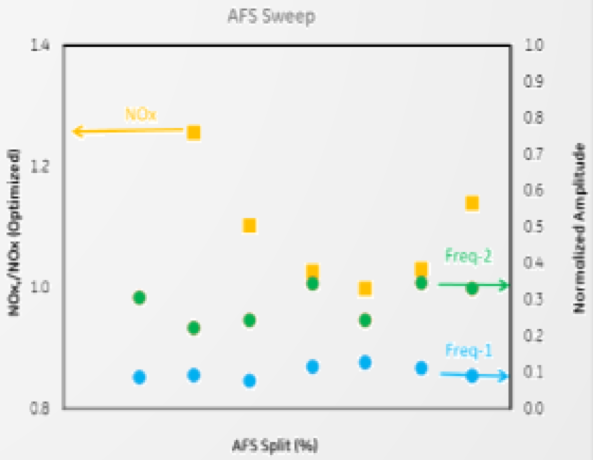
H. Karim et al., GE power, Greenville, SC
ASME Turbo Expo, 2017



- 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

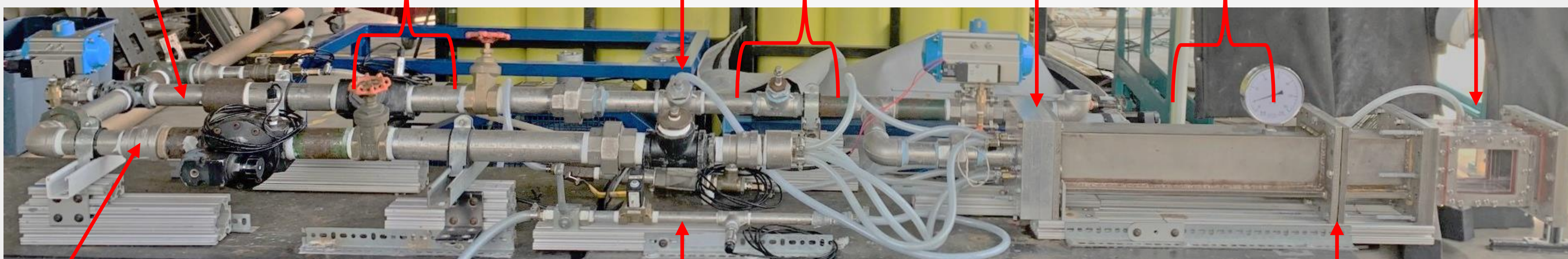
Objectives

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).

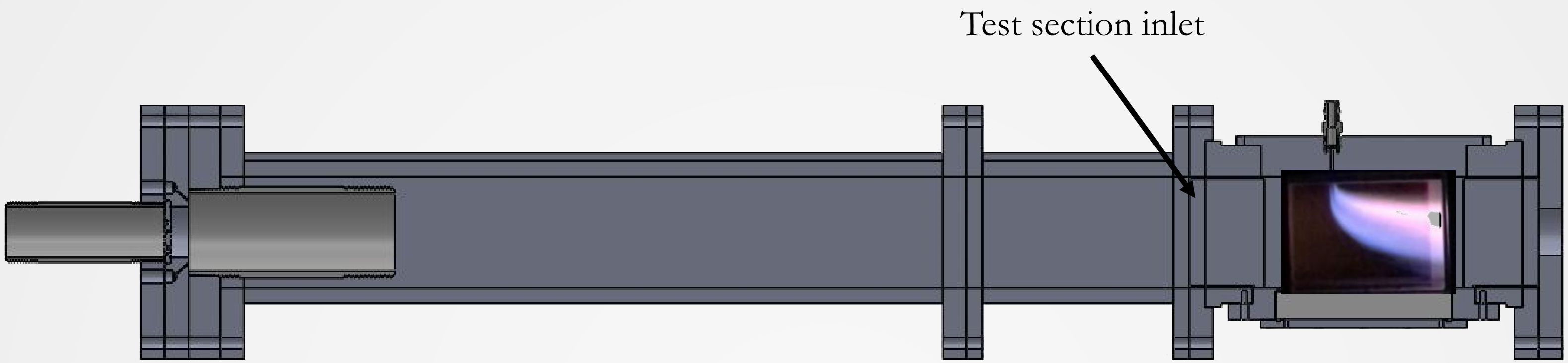
- **Conduct experiments using a high pressure combustion facility.**
- **Tune rig headend to give similar NOx curve as current engines.**
- **Axial stage testing with Fuel/Air and Fuel/Diluent axial mixtures with various levels of premixing.**
- **Obtain detailed measurements of the burning jet to understand the design space and model validation.**
- **Axial Stage Modeling : Develop reacting jet-in-crossflow correlation and validate existing CFD capabilities.**

EXPERIMENTAL FACILITY

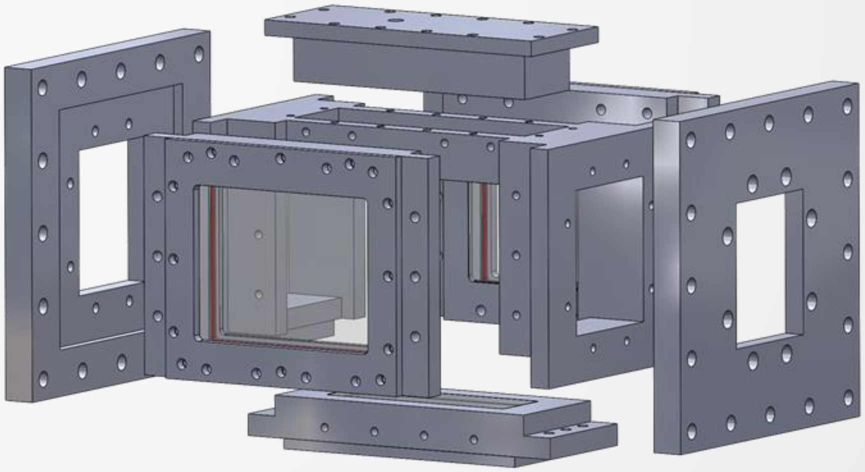
Experimental Approach: Facility Design



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

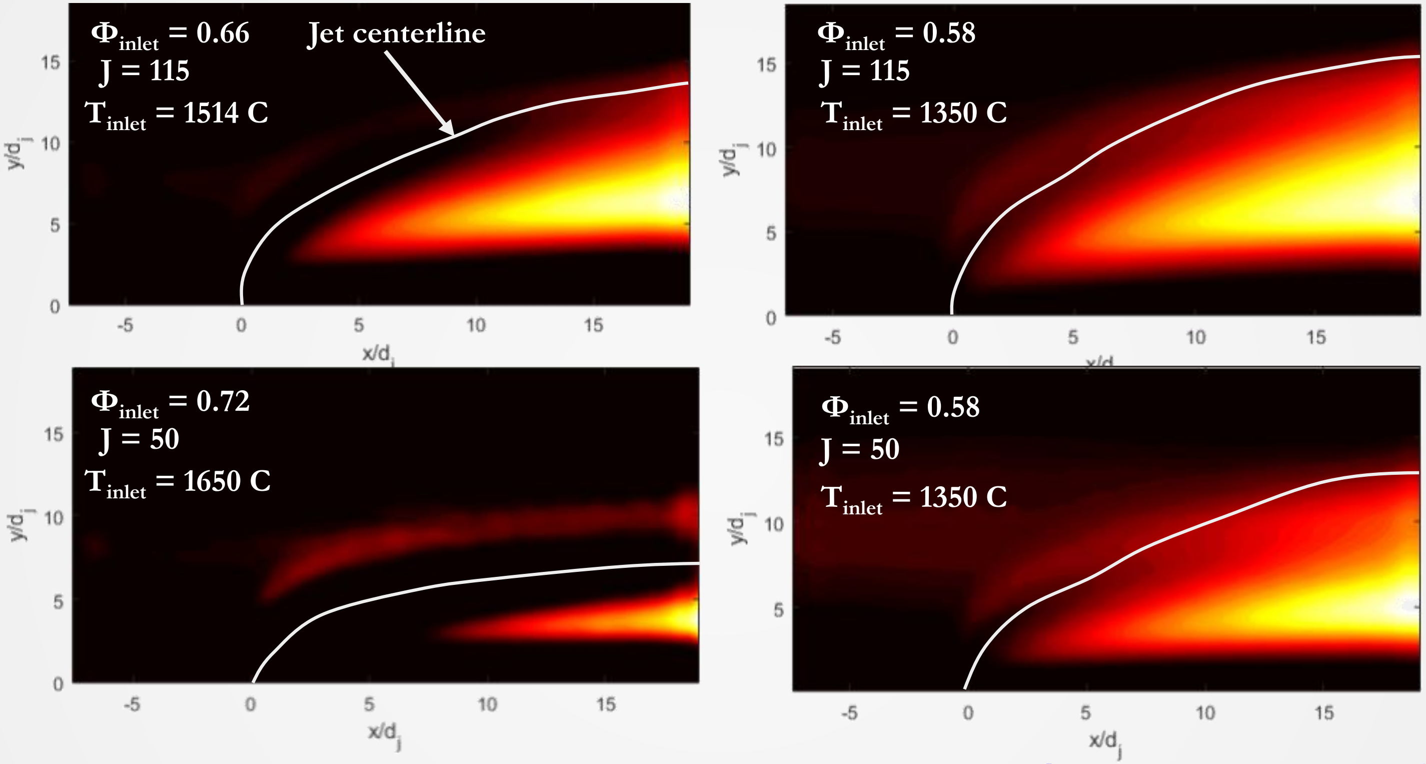
- High-Speed CH* Chemiluminescence
  - 10,000 frames per second
  - FOV = 4.9 x 3.5 in
  - 430 nm filter (used for methane jet)

Axial Stage Conditions

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

- Hydrogen non-premixed jet
  - J = 10-115
  - Φ_{inlet} = 0.58-0.72
  - T_{inlet}: 1350-1650°C

Flame Stabilization – Hydrogen Non-premixed Jet



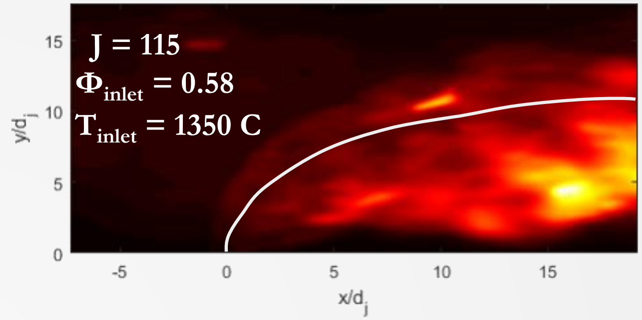
J is momentum flux ratio

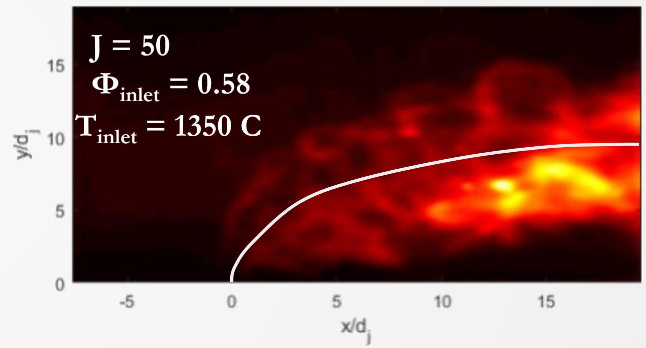
- ❑ Crossflow Equivalence Ratio
  - Lower temperature inlet conditions burn further upstream and wider
  - Leeward and windward flames
- ❑ Leaner crossflow provides more oxygen

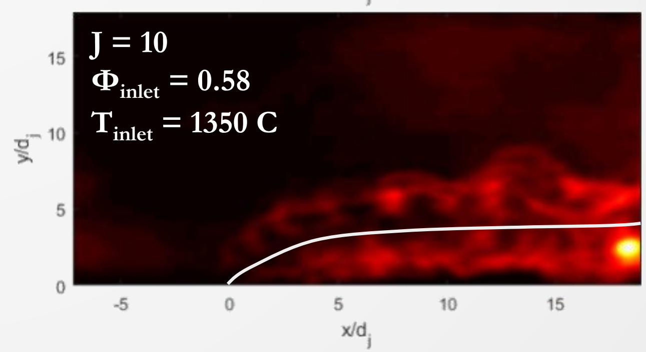
Flame Stabilization – Hydrogen Non-premixed Jet

- **Momentum flux ratio**
  - Crossflow Φ = 0.58
  - All flames lifted
  - Lower momentum flux ignites the same and burns slower

- **Higher momentum flux leads to better oxygen entrainment**

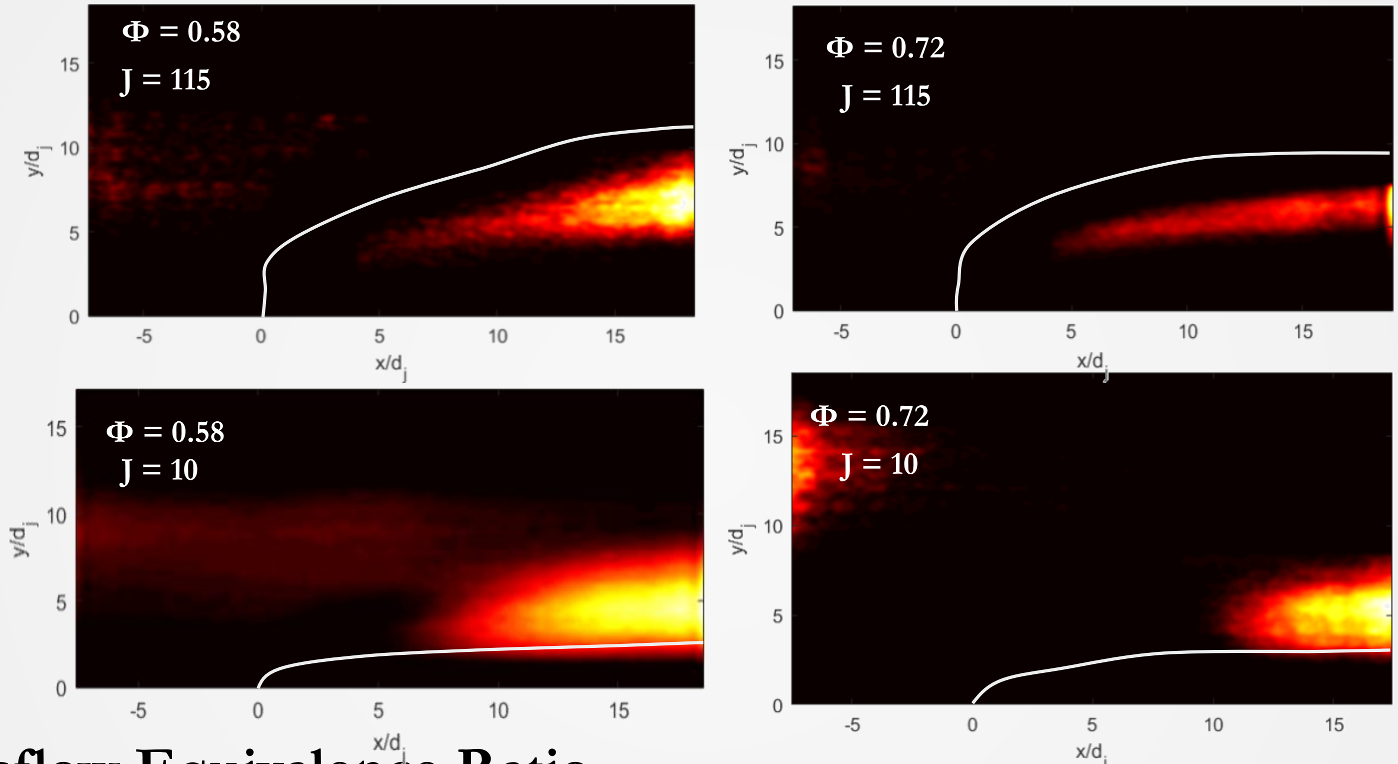






Results

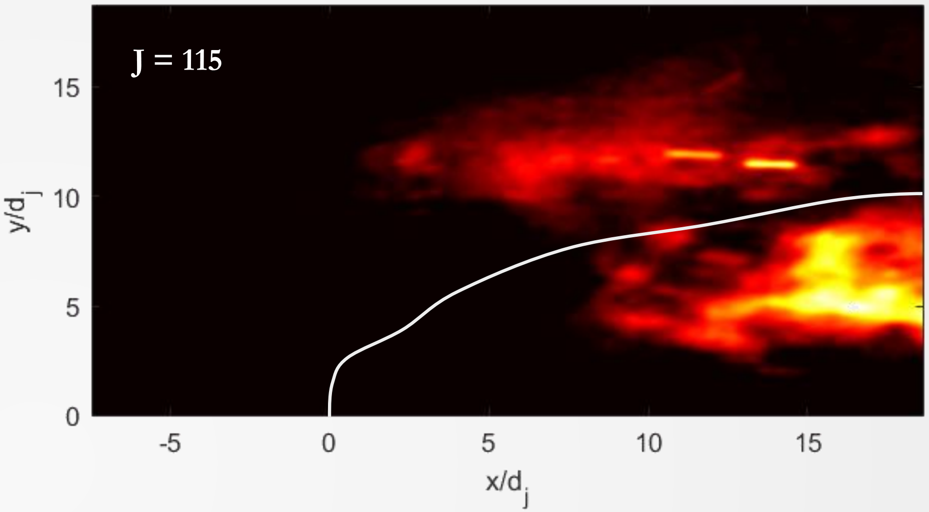
Flame Stabilization – Methane Non-premixed Jet

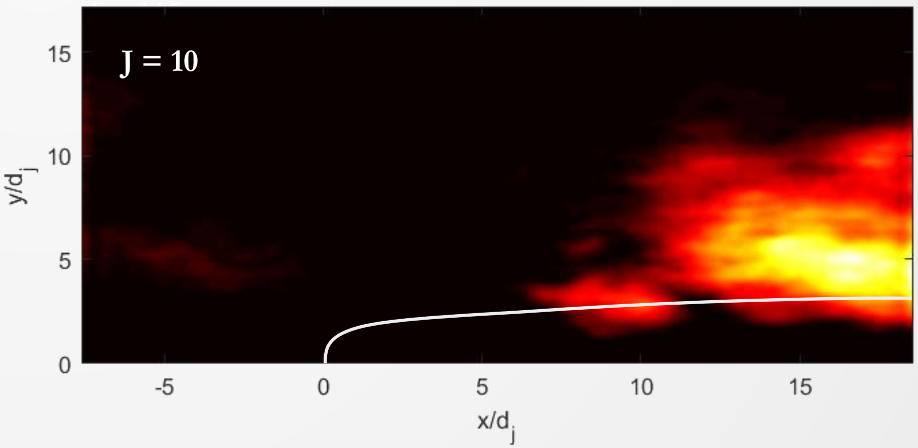


- ❑ Crossflow Equivalence Ratio
  - J = 115 (top) J = 10 (bottom)
  - Leaner flame burns further upstream
  - Leeward shear layer flames
- ❑ Leaner crossflow provides better oxygen entrainment

Flame Stabilization – Methane Non-premixed Jet

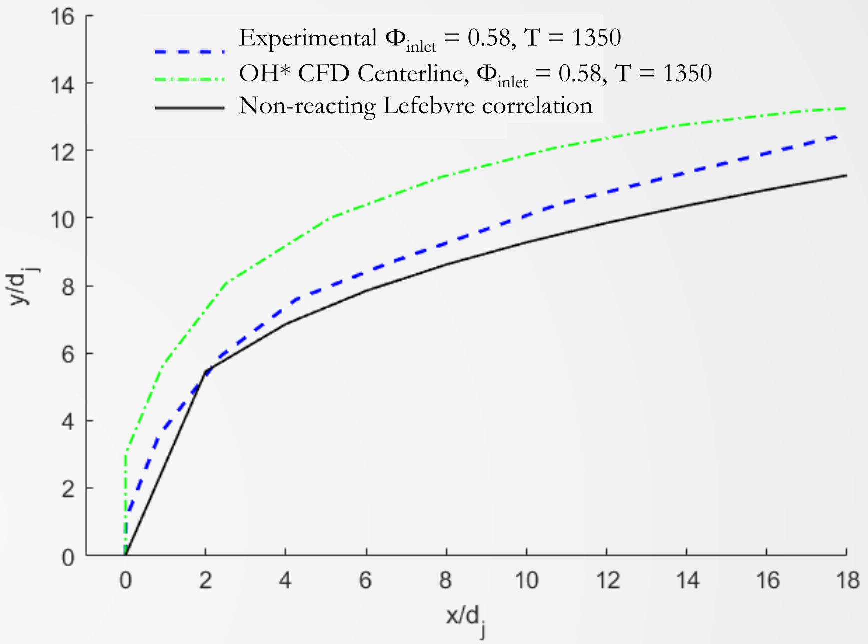
- Momentum flux ratio
  - Crossflow Φ = 0.58
  - Wall jet does not burn in leeward side but on windward side
  - Wall jet not stable experiences blow-off
- Higher momentum flux entrains enough oxygen on both sides to remain lit

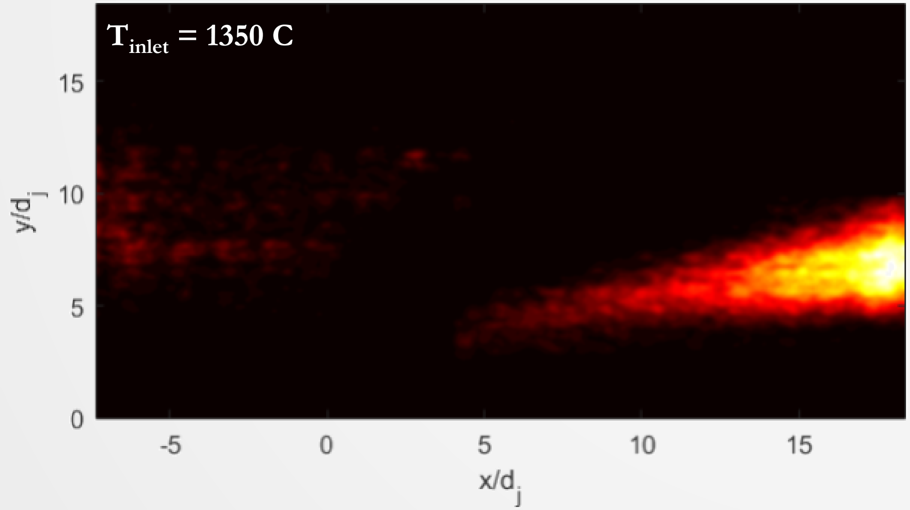




Jet Centerlines

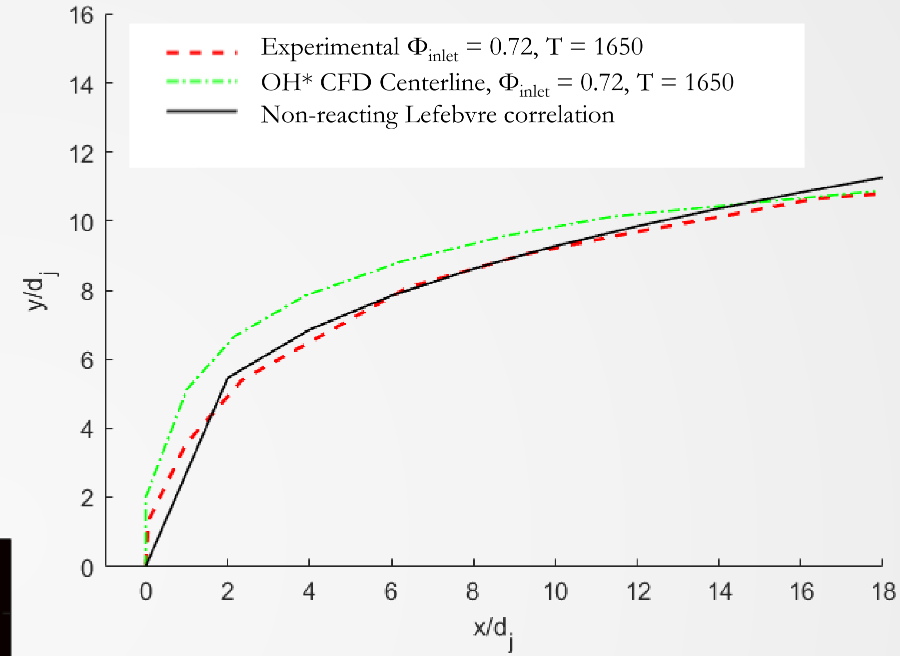
- **Leanest Crossflow - Methane**
  - Leaner crossflow burned in shear layer on leeward side of jet

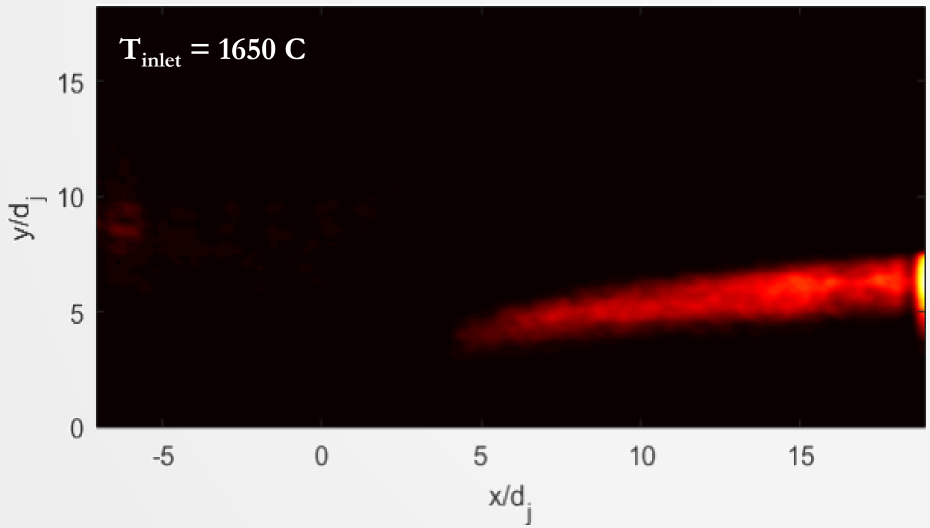




Jet Centerlines

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





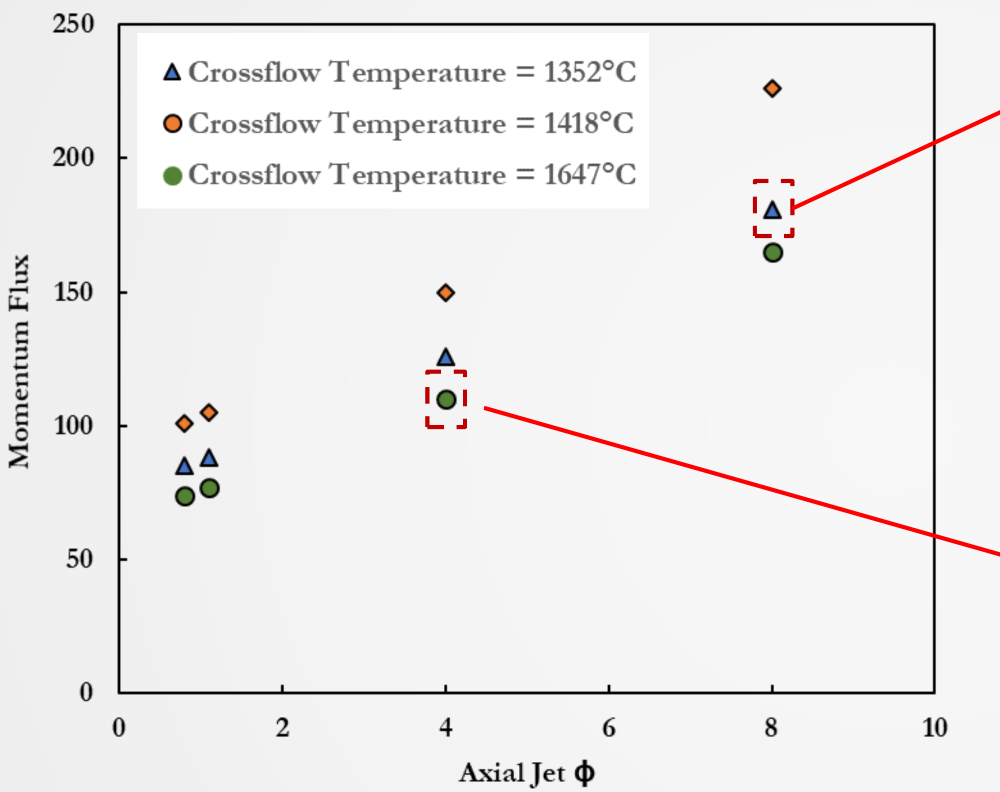
Non-premixed Conclusions

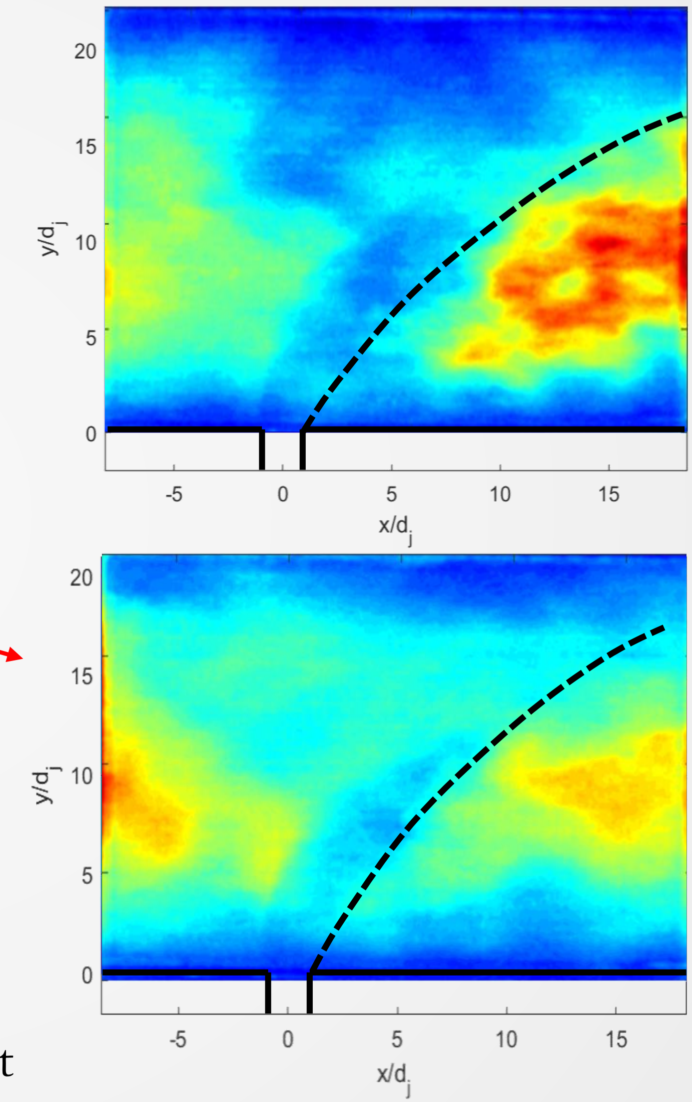
- Leaner crossflow entrains more oxygen
- Higher velocity gradients (large J) entrain oxygen better and burn further upstream
- Two flames observed: stabilized jet with flame kernels constantly forming and flame propagation
- RJIC penetrates further due burning in the wake relative to non-reacting

Premixed Jet Preliminary Results

Experimental Approach: Target Conditions

Testing Conditions

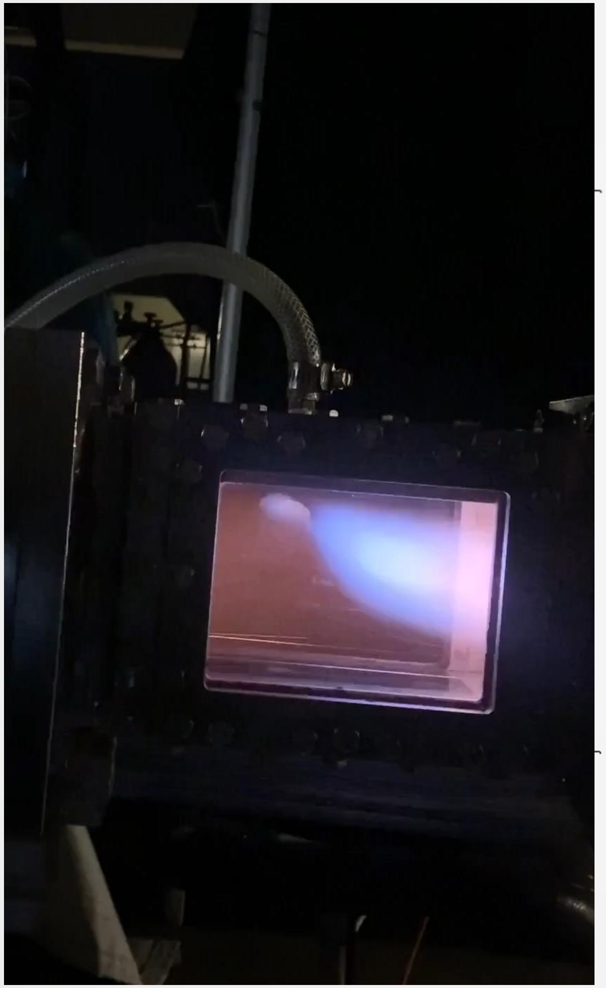




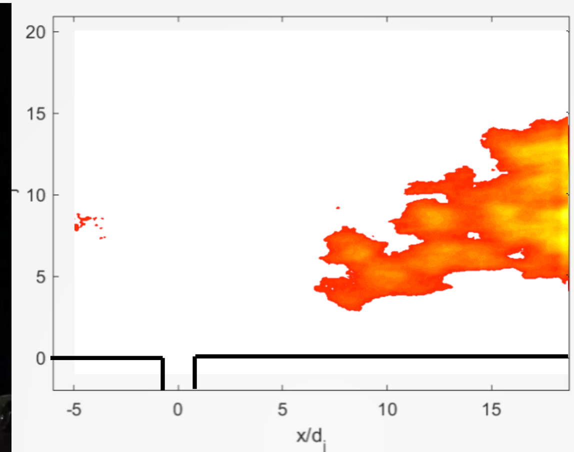
- ❑ Mass Flow Rate: 0.5kg/s
- ❑ Pressure: 5atm
- ❑ Premixed Methane/Air Crossflow and Axial Jet

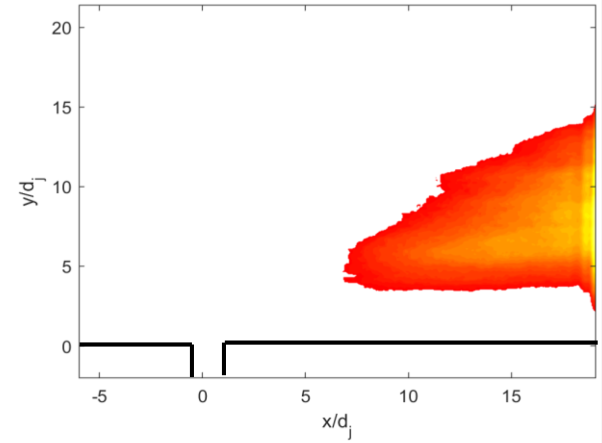
Results: Flame Shape Constant Crossflow

- ❑ Crossflow Temperature: 1352° C

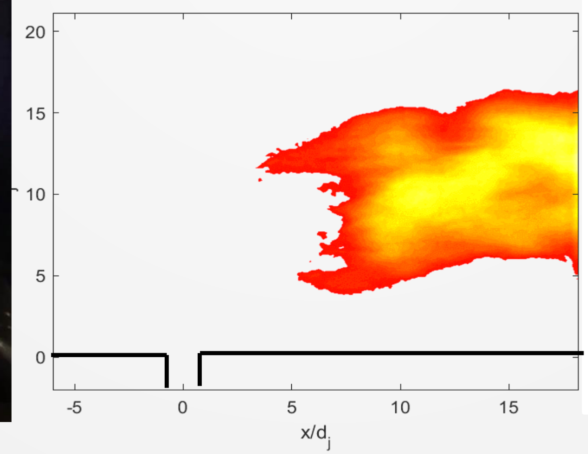


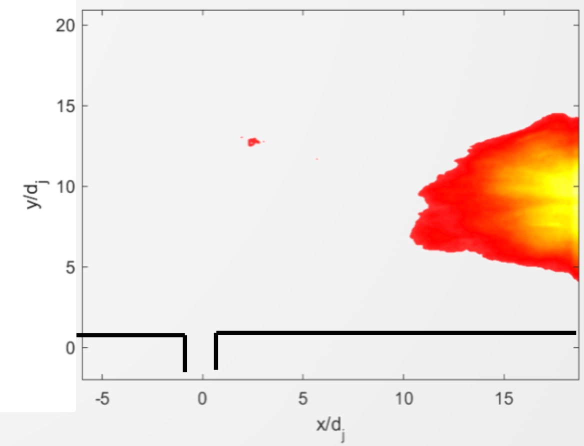
Jet ϕ = 4

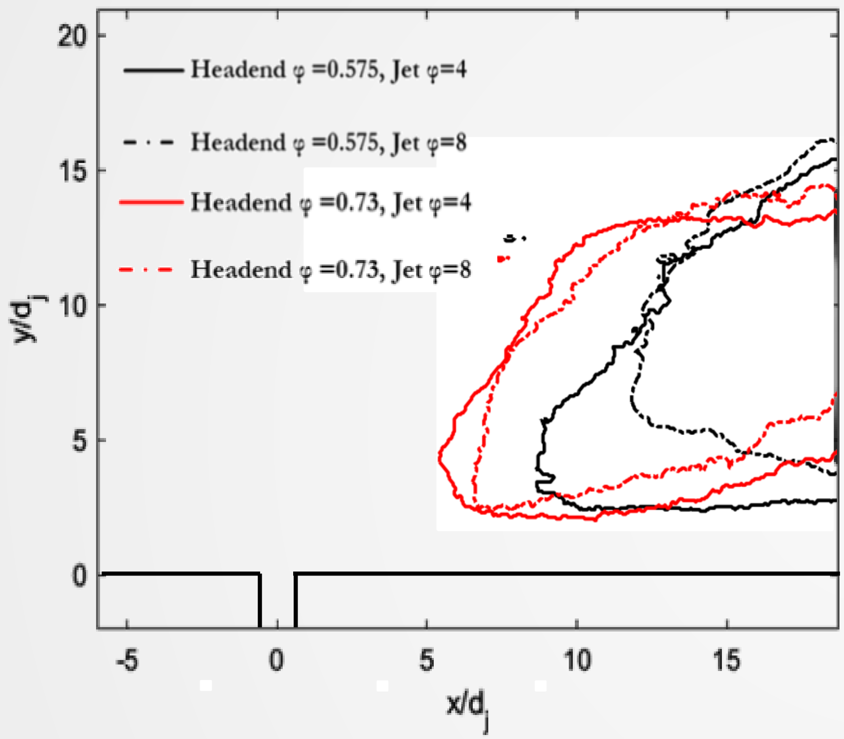


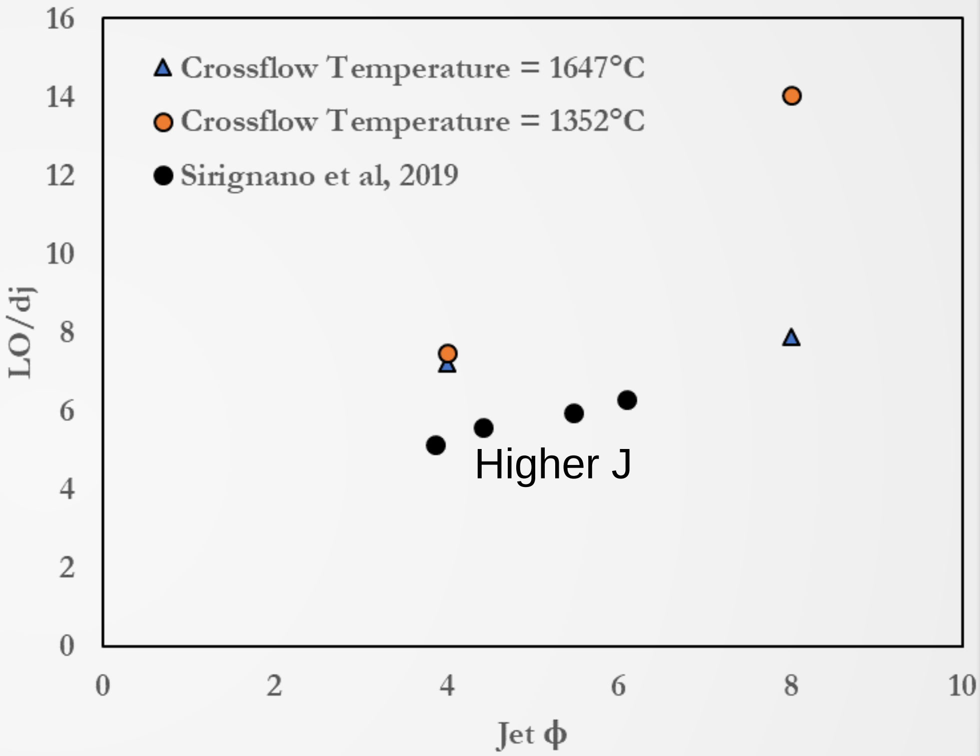


Jet ϕ = 8





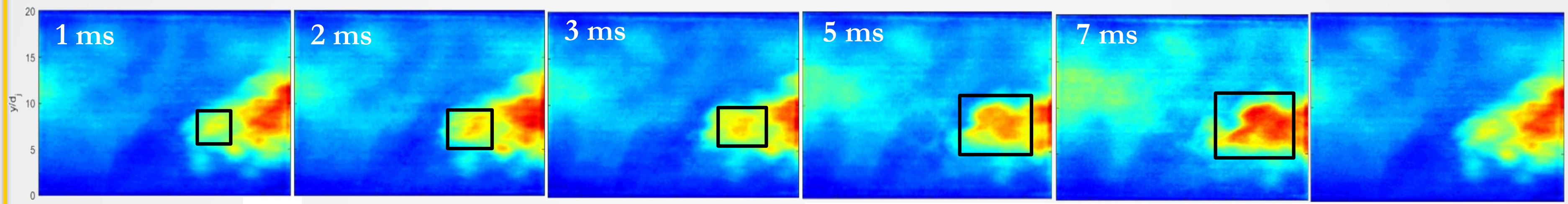




- Rich jet approaches non-premixed jet behavior.

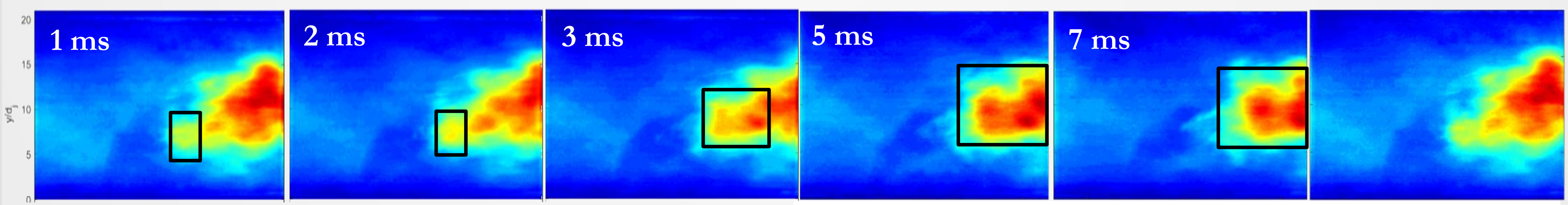
- Crossflow Temperature: 1352° C

Jet ϕ = 4

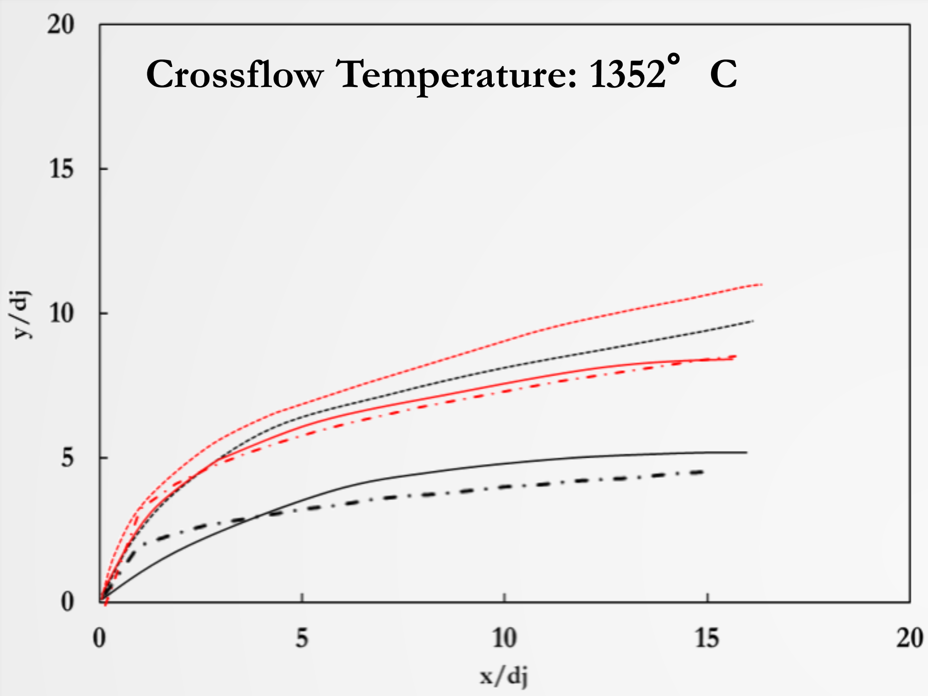


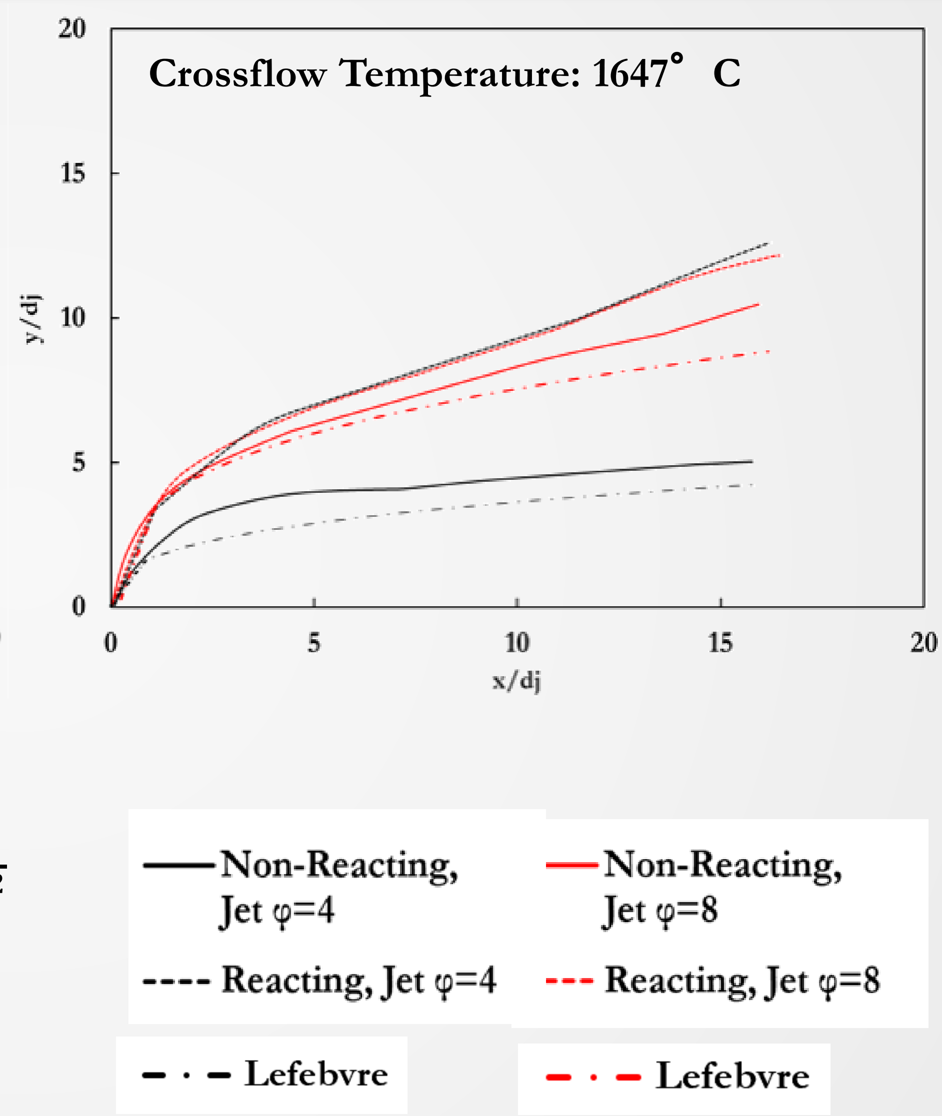
Increasing Time

Jet ϕ = 8



Increasing Time

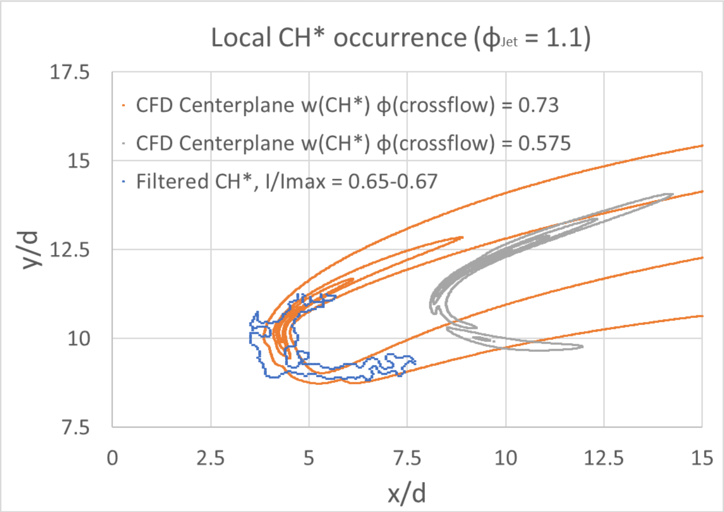


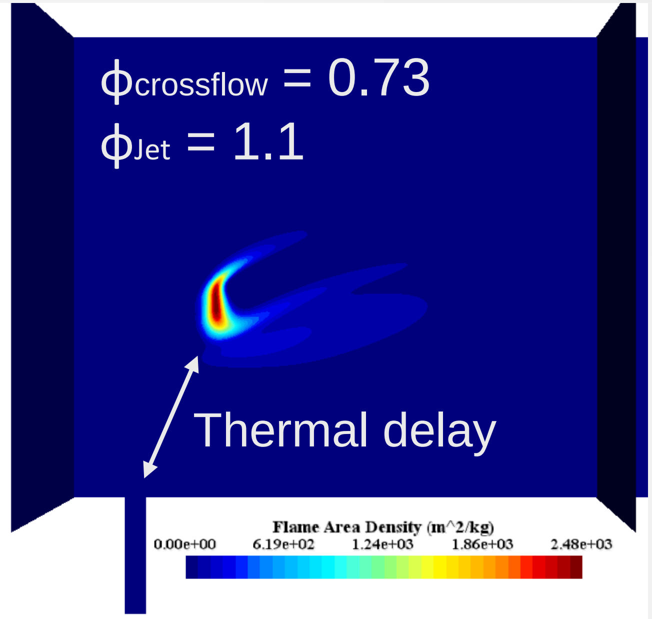


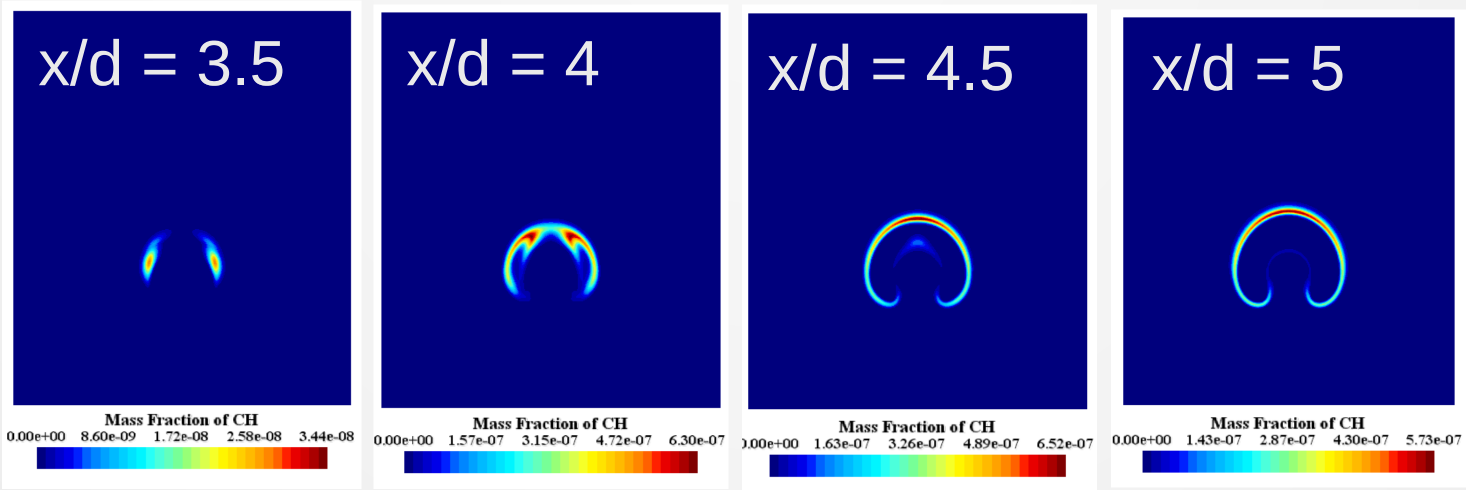
- Lefebvre jet trajectory correlations:

$$\frac{y}{d_j} = 0.82J^{0.5}\left(\frac{x}{d_j}\right)^{0.33} \quad \text{Where } J = \frac{\rho_j U_j^{2}}{\rho_m U_m^{2}}$$

CFD of Premixed CH_4 Flames, 4mm Jet







Premixed Conclusion

- 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.

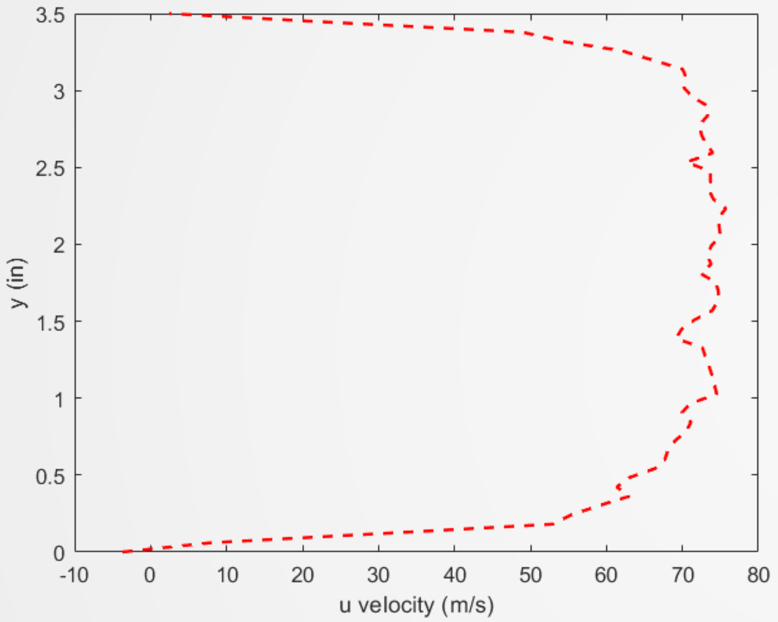
PIV AND TDLAS MEASUREMENTS

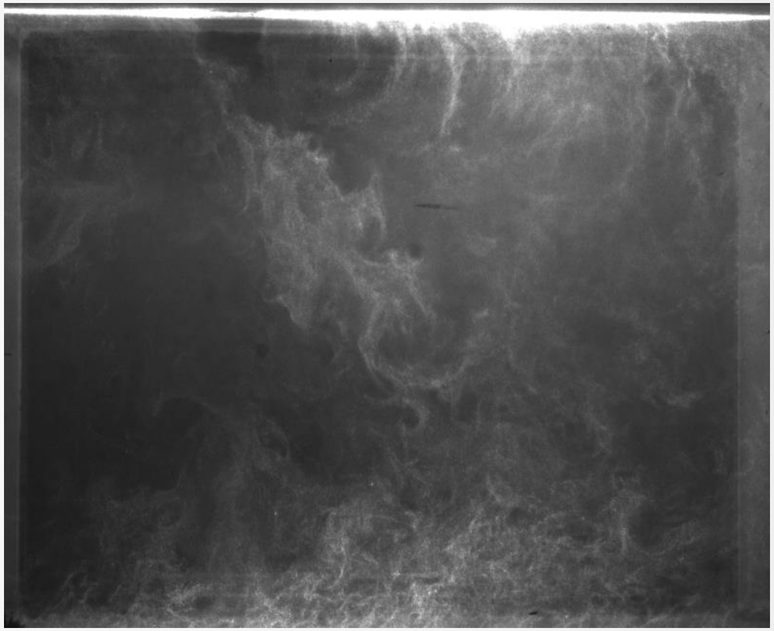
Diagnostic Setup

- 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

Inlet Velocity Profile





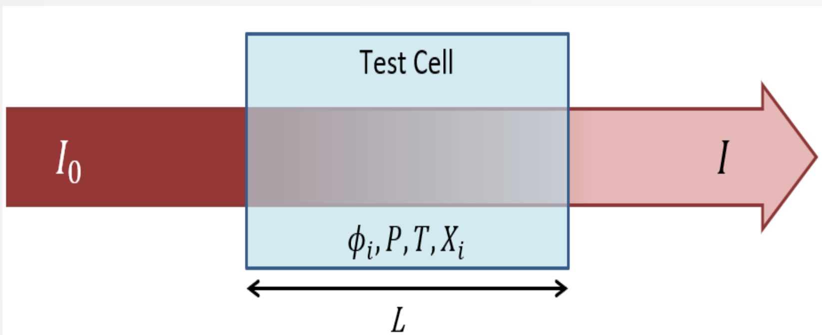
- Crossflow φ = 0.575
- Velocity profile at inlet of test section

Thermocouple	Baseline	Total Mass	Total Main Air	Total Fuel	Total Air	Global Phi	Local Phi
1316	1400	0.548	0.406	0.0176	0.531	0.575	0.750

Pressure (PSIG)	Split %	Axial Air	Main Air	Seeder Air	Bypass Air	Axial Air ROU	Main Air ROU	Bypass Air ROU	Seeder ROU	Axial PSIG	Seeder PSIG	Bypass PSI	J	Y(in)
60	20%	0.065	0.341	**0.025**	0.100	0.22	0.5625	0.24	0.089	151	350	154	15	2.1
60	22%	0.065	0.341	**0.028**	0.098	0.22	0.5625	0.24	0.1	151	320	163	15	2.1
60	25%	0.065	0.341	**0.031**	0.094	0.22	0.5625	0.24	0.1	151	367	156	15	2.1
60	27%	0.065	0.341	**0.034**	0.091	0.22	0.5625	0.24	0.1	151	398	151	15	2.1

Beer-Lambert Law for Species Detection

$$\alpha = -\ln\left(\frac{I}{I_0}\right) = \sum_i \sum_j S_{ij}(T) X_j P L \phi_{ij}\left(\nu - \nu_{0_{ij}}\right)$$



Red	Raw Sensor Data
Blue	HITRAN/HITEMP/PNNL Databases, UCF Lab
Green	PCB/CTAP –or- TDLAS
Black	Hardware Constraint/Constant
Yellow	Processed Sensor Data

$I = Transmitted\ Intensity\ \left(\frac{W}{cm^2 srHz}\right)$

$I_0 = Incident\ Intensity\ \left(\frac{W}{cm^2 srHz}\right)$

$S_{ij} = Linestrength\ \left(\frac{cm^{-2}}{atm}\right)$

$T = Static\ Temperature\ (\mathrm{K})$

$X_j = Mole\ Fraction$

$P = Static\ Pressure\ (atm)$

$L = Path\ Length\ (cm)$

$\phi_{ij} = Lineshape\ Function\ (cm)$

$\nu = Optical\ Frequency\ (Hz)$

$\nu_{0_{ij}} = Line\ Center\ Optical\ Frequency\ (Hz)$

Subscripts

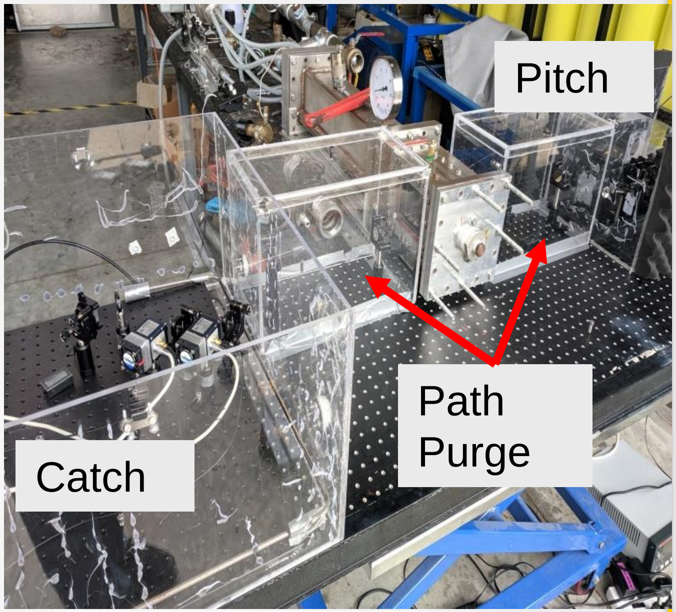
$i = Quantum\ Transition$

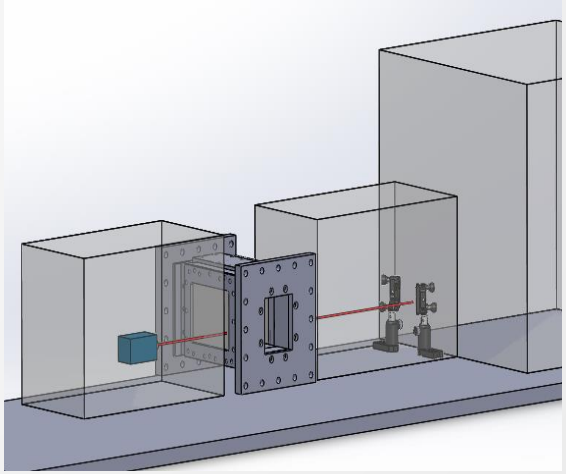
$j = Atomic/Molecular\ Species$

Temperature Measurements

- 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

CFD with Star CCM+

- Symmetric jet-in-crossflow axial stage geometry
- Structured, locally refined mesh with (1–50) E6 cells
- Computational Cost: 1000-5000 datacenter hours

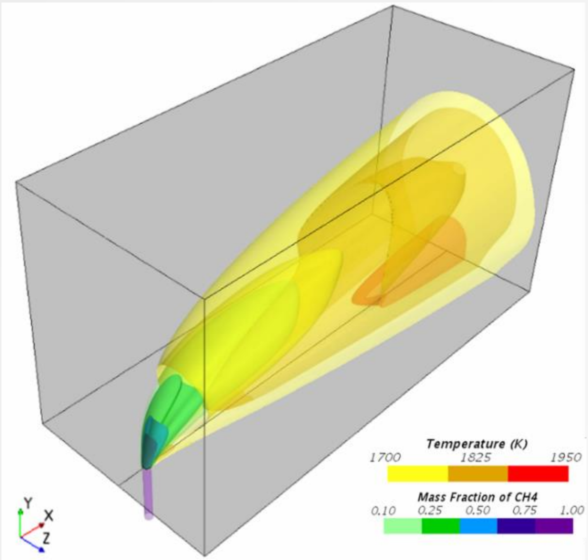
- Reactive Domain:

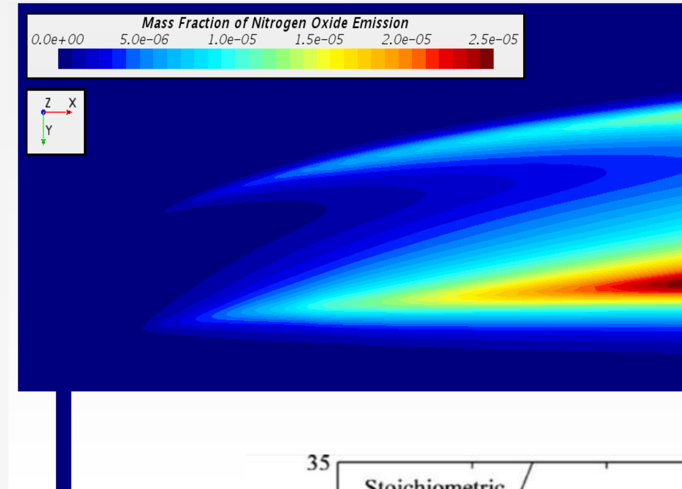
  A) Detailed Chemistry

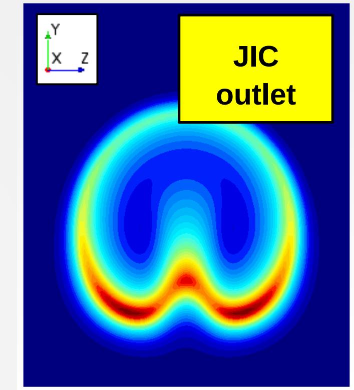
  B) Flamelet Approach

  - Non-premixed: Steady Laminar Flamelet
  - Partially Premixed: FGM with Turbulent Flame Closure
  - Premixed: FGM with Coherent Flame Model

CFD of Non-Premixed CH_4 Flames, 4mm Axial Jet

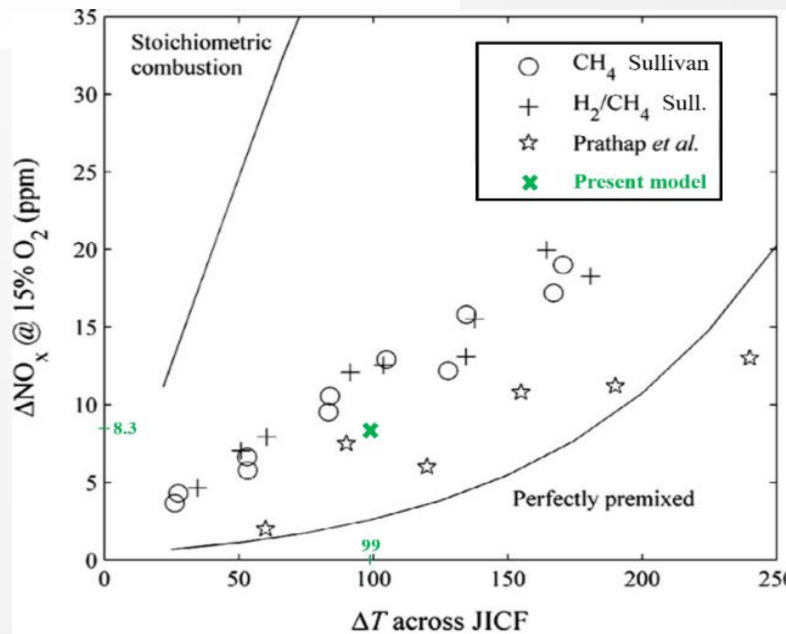






Axial Stage: NO_x Emission

CFD prediction and comparison with literature data



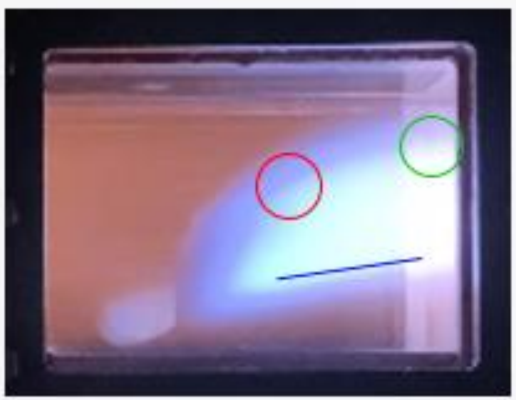
Preferred: Detailed Chemistry Model

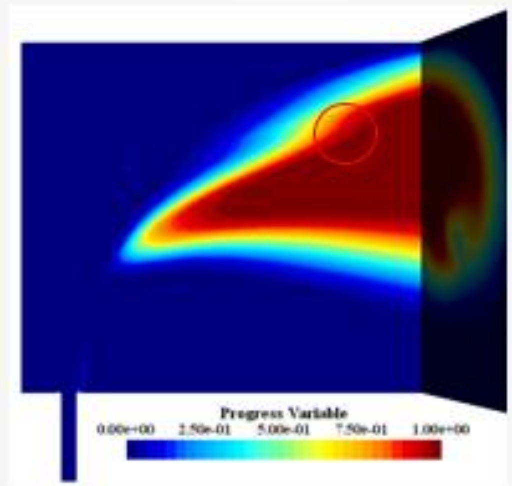
Poor: Flamelet + Thermal NO_x Model

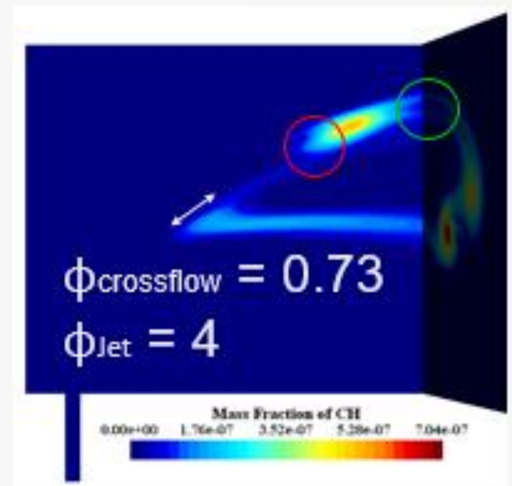
CFD of Partially Premixed CH_4 Flames, 4mm Jet

Unheated 4mm jet, control parameters to *accelerate* local flame ignition:

Windward branch	Lee-side branch
$\dot{m}_{CH4}^{crossflow} \downarrow$	$T^{crossflow} \uparrow$
$w_{O2}^{crossflow} \uparrow$	$w_{O2}^{crossflow} \uparrow$



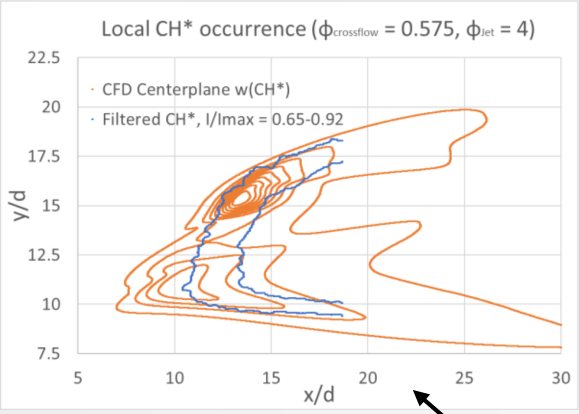


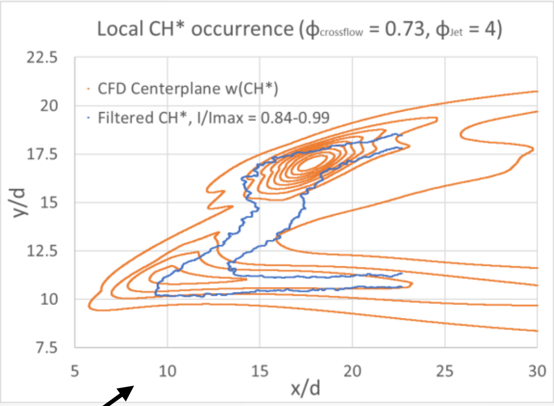


Combustion instabilities visible in the windward flame branch

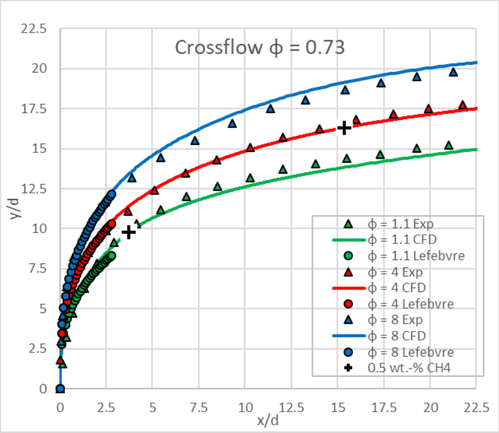
CFD of Partially Premixed CH_4 Flames, 4mm Jet

w_{CH^*} @ z=0 [CFD] and CH* Chemi [Exp.]



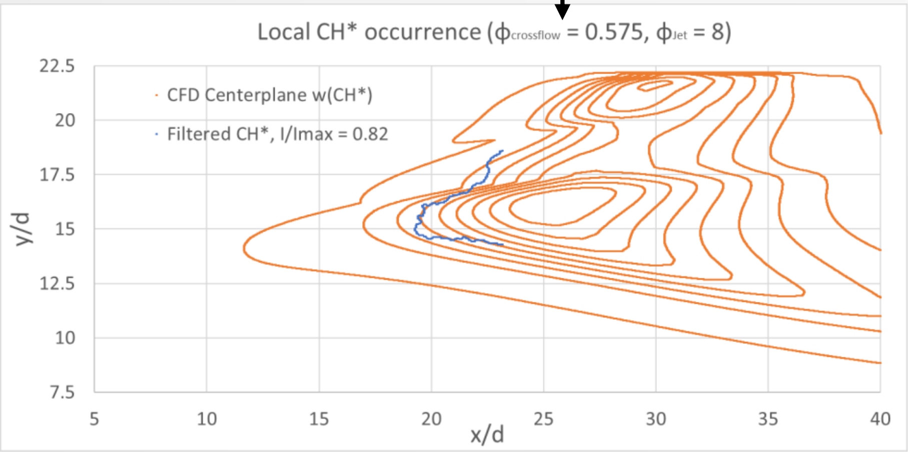


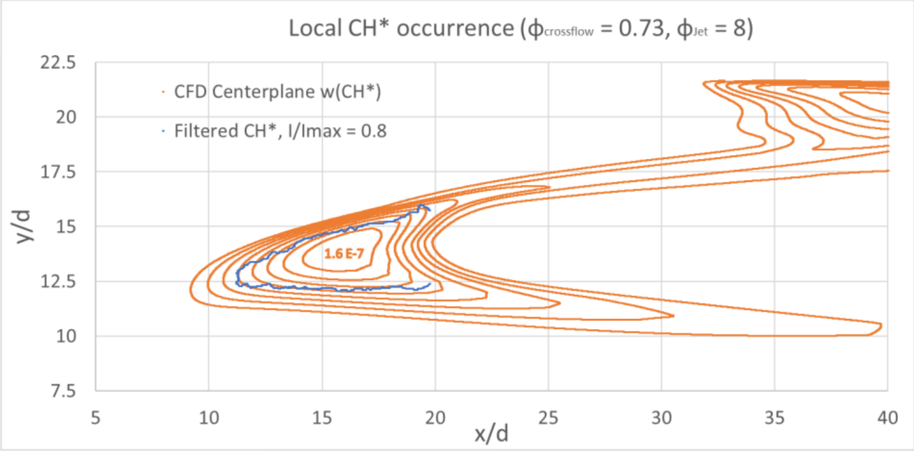
Jet Penetration



Closed flames

Divided flame





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