University Turbine Systems Research Project Review Meeting 30 October, 2018

Improving NOx Entitlement with Axial Staging

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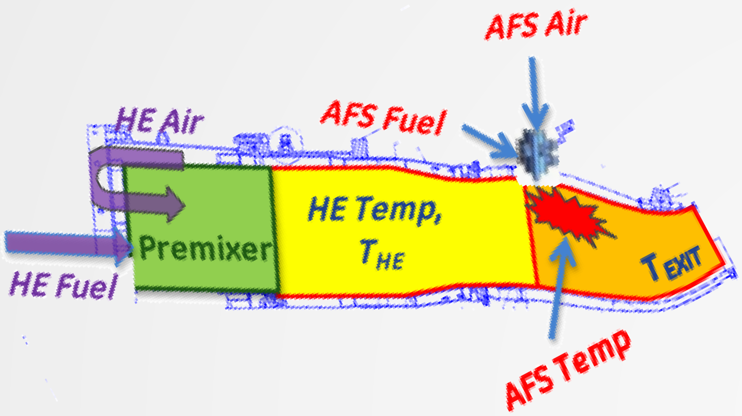
Outline

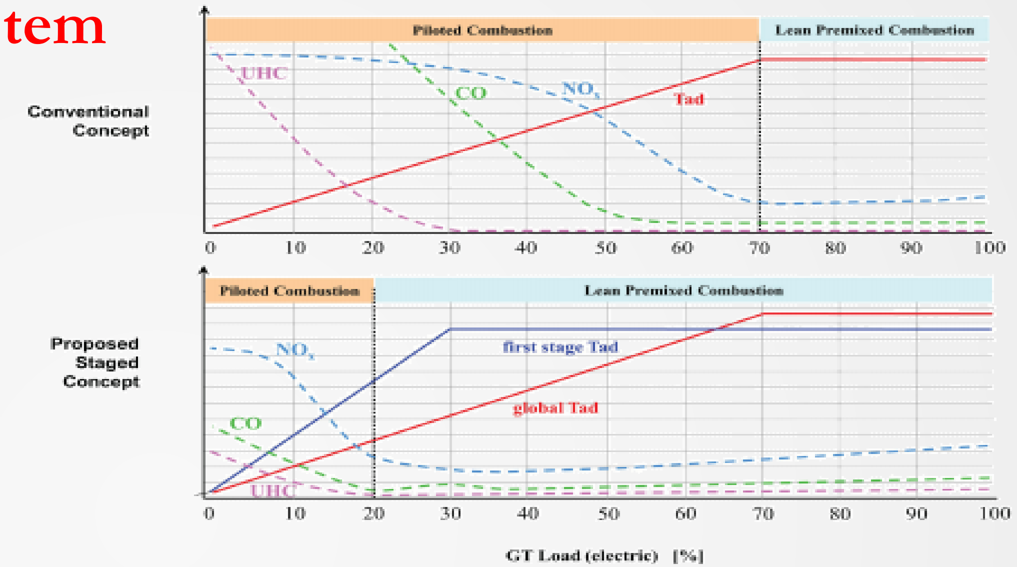
- Introduction
  - Motivation of Study
  - Recent Investigations
- Objectives
- Experimental Facility
  - Design and Concept
  - Target Conditions
  - Optical Diagnostics and Measurement
- Future Work

INTRODUCTION

Axial Stage Combustion System



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

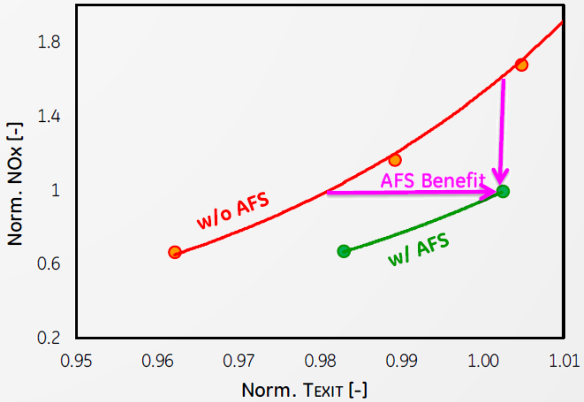


D.Winkler *et al.* GPPS Journal 2017

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

Minimize NOx with increasing turbine inlet temperature

AFS NOx Benefit



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

Motivation of Study

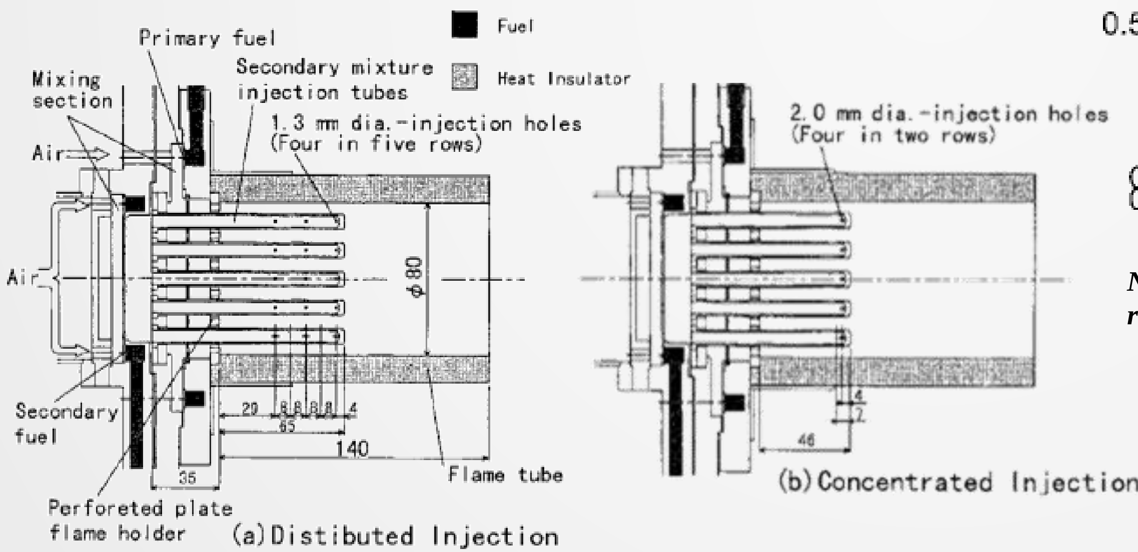
- Gas Turbine OEM's are under pressure to increase efficiency without increasing emissions.
- Increasing turbine inlet temperature is one method to increase efficiency, but with a large NOx penalty.
- By injecting some of the fuel late in the combustor (axial staging) it burns with a shorter residence time, minimizing the NOx 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.

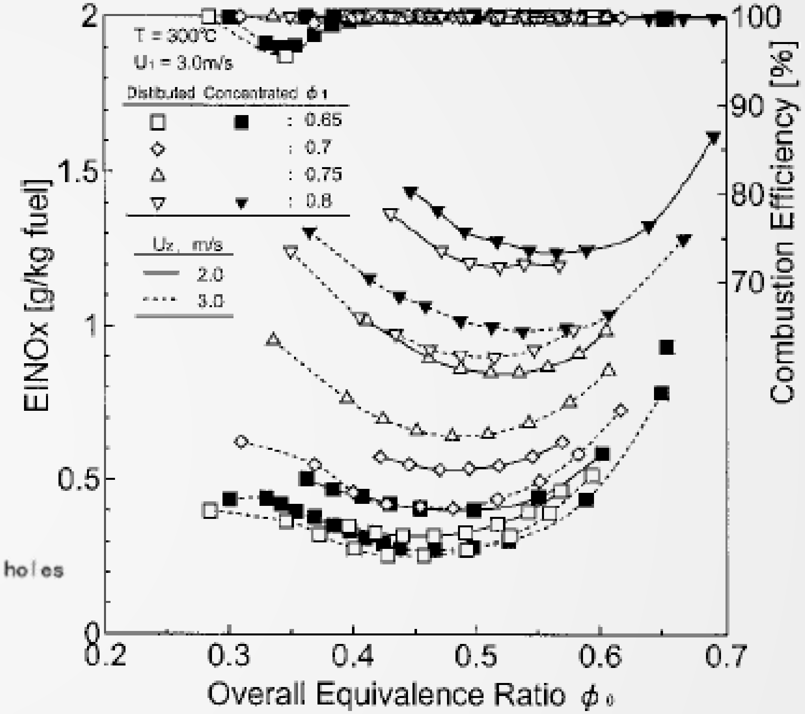
Axial Stage Combustion System Applications

- Power Generation
- Potential for Aircraft Engines

S. Hayashi et al., National Aerospace Laboratory, Japan
Combustion Symposium, 2000

- Lean-lean two stage combustion system
- Atmospheric test combustor
- Perforated-plate flame holder for primary flame stabilization
- Fuel/air mixture as quenching medium

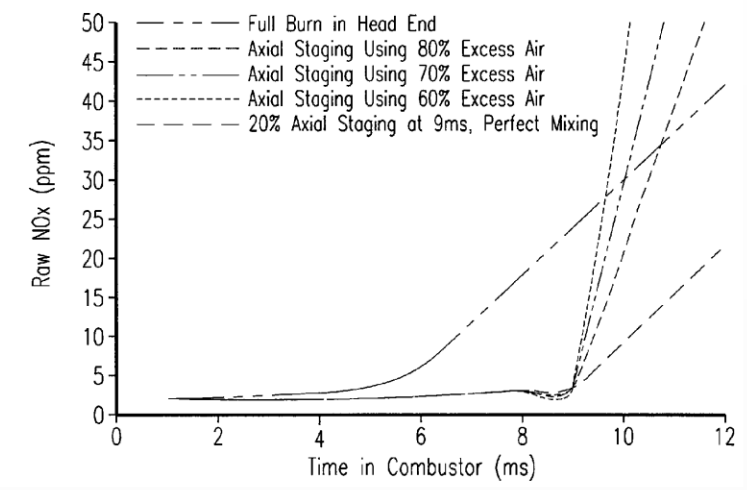


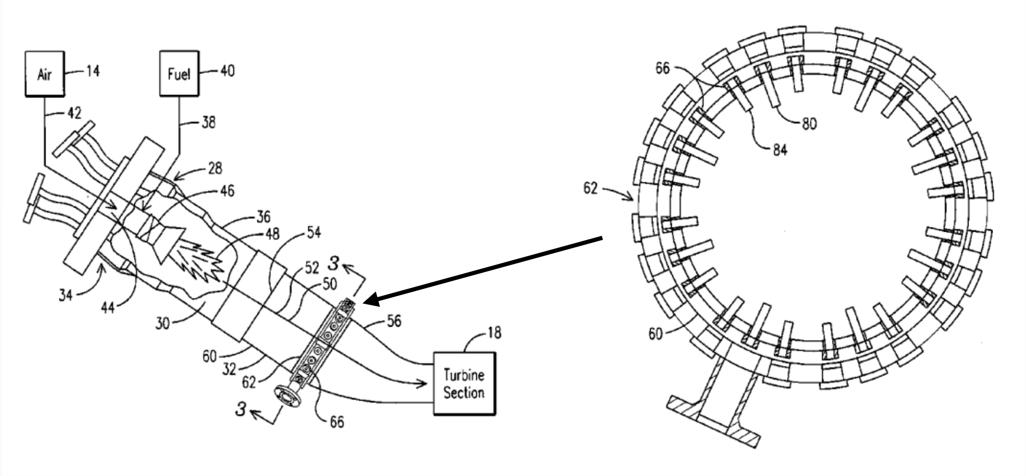


NOx and efficiency for different first stage equivalent ratios in concentrated and distributed injection

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

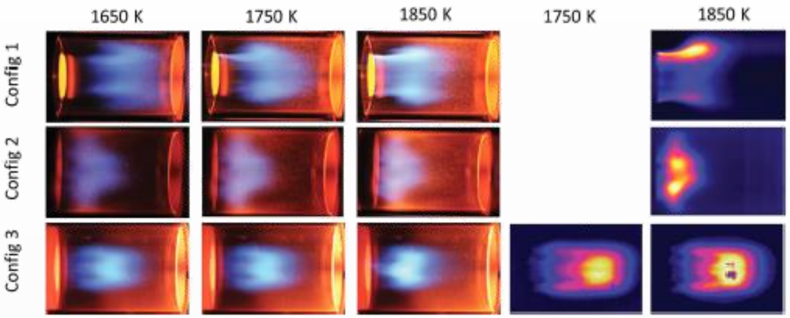
- Apparatus and method for controlling the secondary injection of fuel.
- Adds multiple fuel nozzles in the transition.
- Can be used to improve temperature pattern factor entering the turbine.

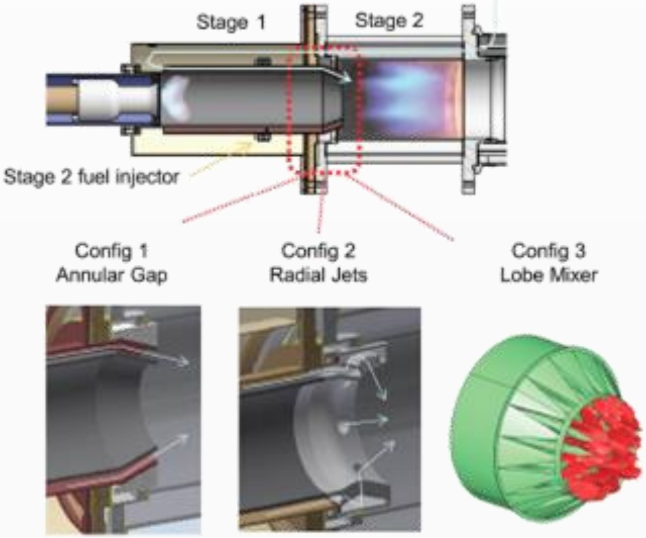


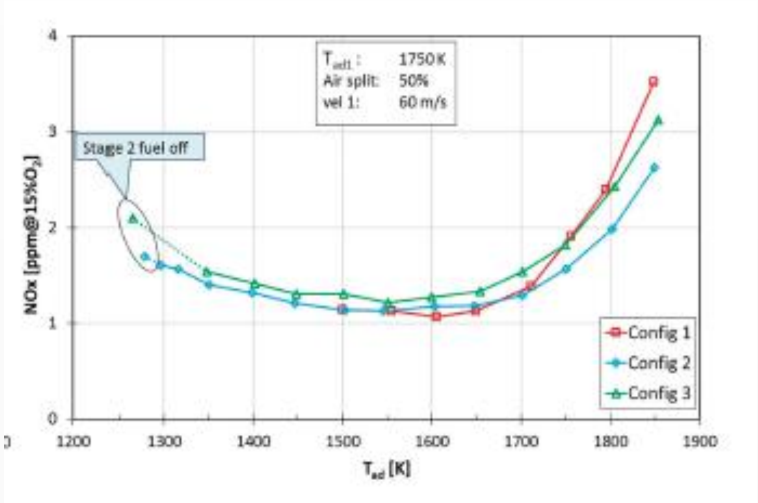


D. Winkler et al., Switzerland
Journal of the Global Power and Propulsion Society, 2017

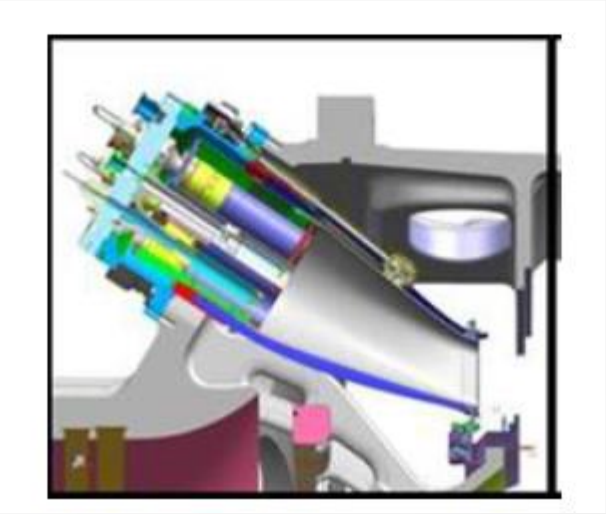
- Lean-lean two stage combustion system
- Atmospheric test combustor
- Secondary mixture injection between first and second stage
- Air as quenching medium



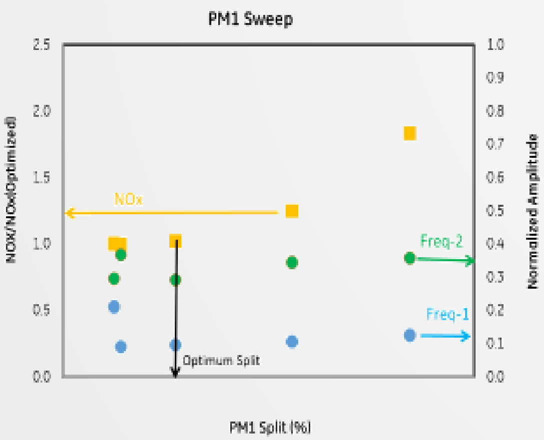


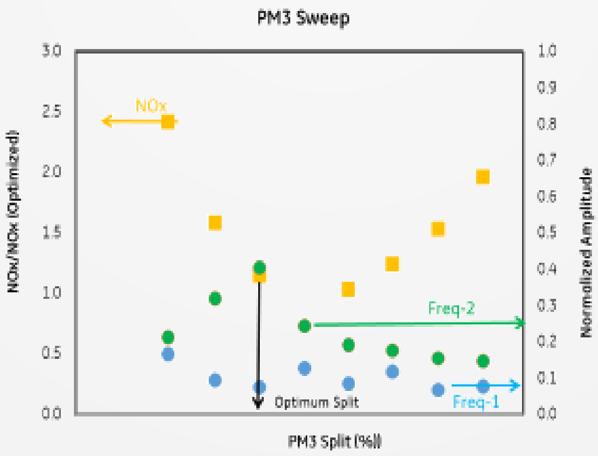


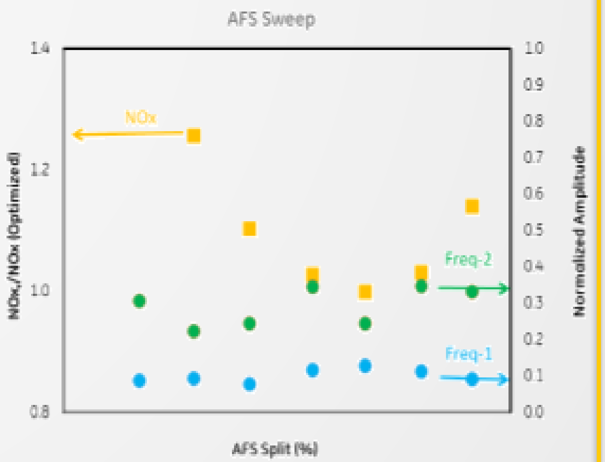
H. Karim et al., GE power, Greenville, SC
ASME Turbo Expo, 2017



- 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)







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OBJECTIVES

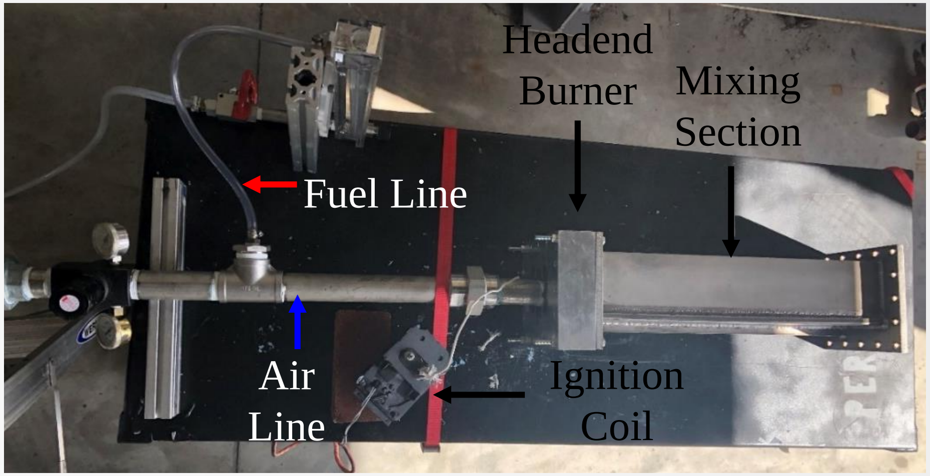
Objectives

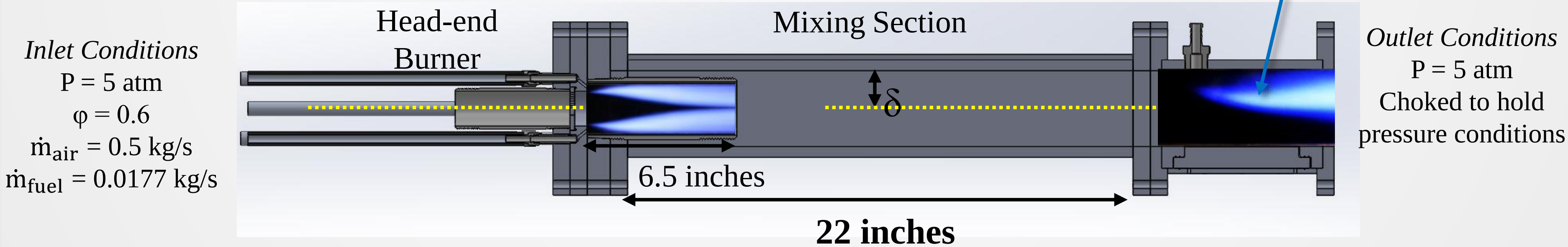
Develop a high pressure axial stage combustion test facility and explore novel configurations to implement axial staging with direct involvement of original equipment manufacturers (OEMs).

- **Conduct experiments using the 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

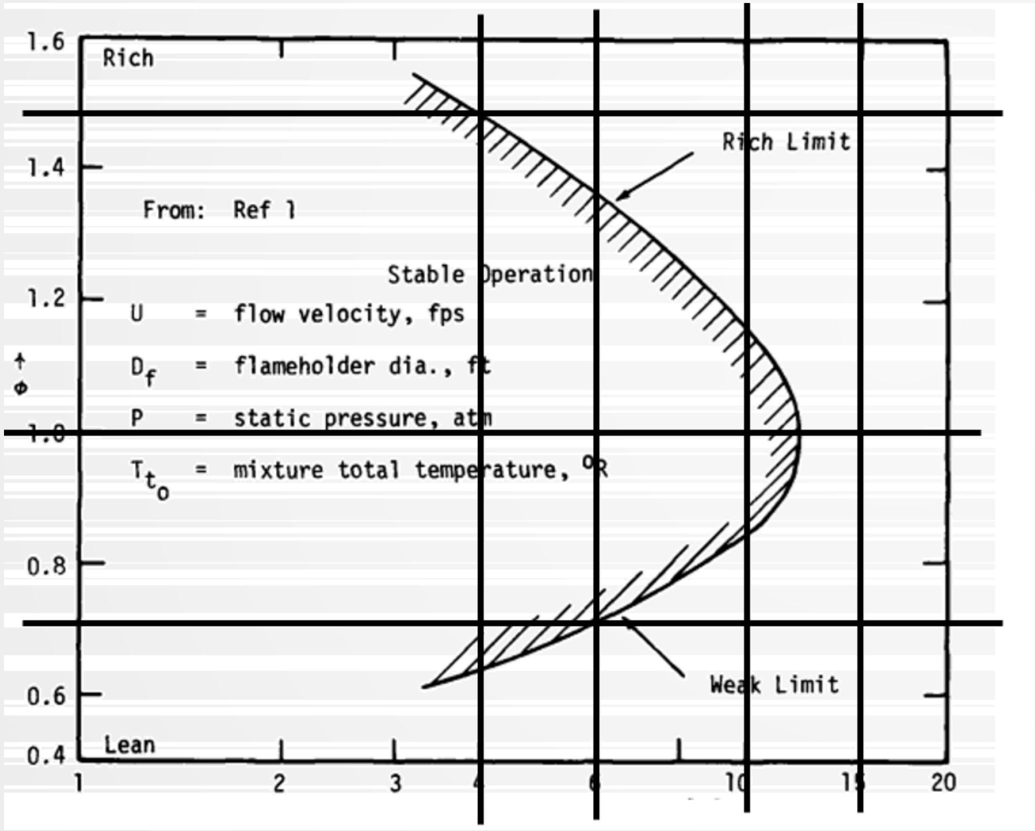
- Experimental setup consists of 3 main components
  - First Stage Burner
  - Mixing Section
  - Test Section
- Axial staged burner will be injected with various mixtures (fuel, fuel/air, fuel/air/CO_2) to characterize the secondary flame

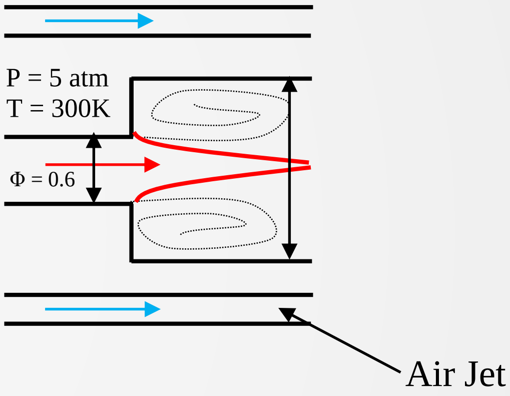




Cut-out view of head-end burner and mixing section

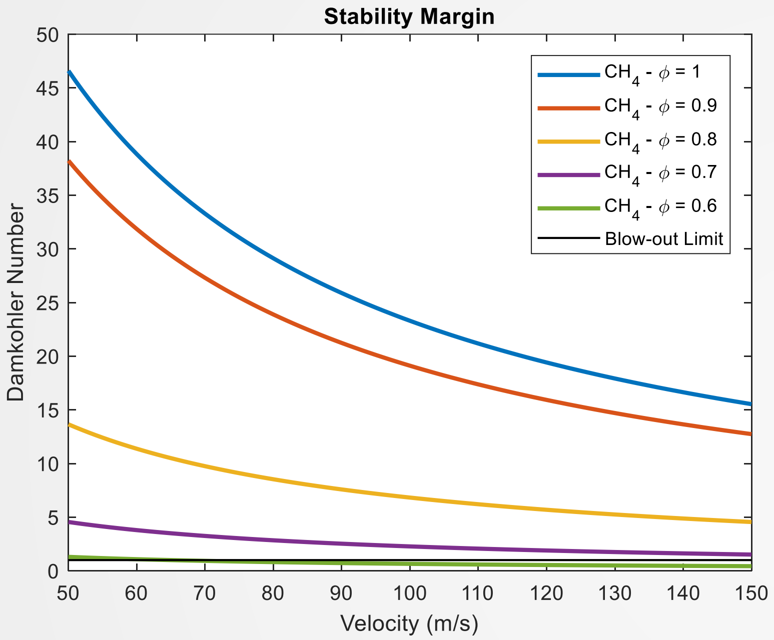
- $\textit{Stability Correlation Parameter} = \frac{V}{d}\frac{d}{d_e}\frac{P_o}{P}\left(\frac{1000}{T_{t_o}}\right)^{1.5} 10^{-3}$



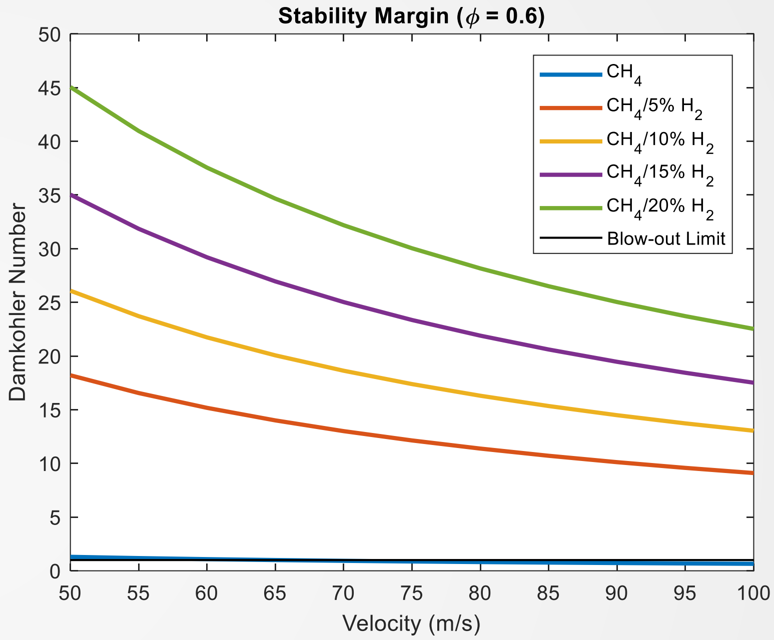


Premixed center section is mixed with outer air jets

Methane/Air



Methane/Hydrogen*/Air

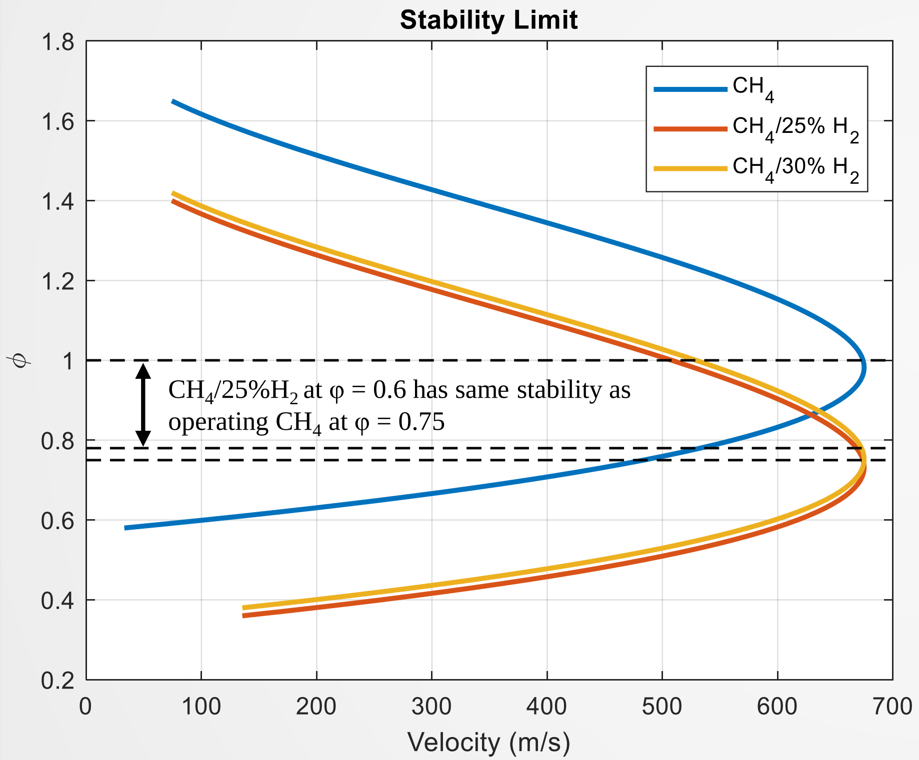


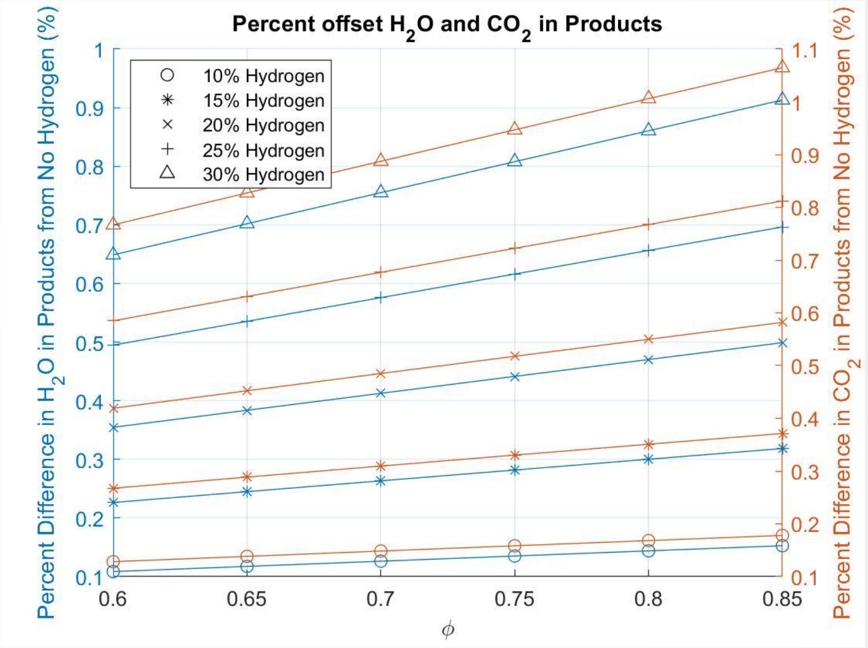
*Adding small quantities of hydrogen increases the stability of burning methane at $\Phi = 0.6$

- $\tau_{chem} = \frac{L_f}{S_L}$ ← Flame Thickness, ← Laminar Flame Speed
- $Da = \frac{\tau_{conv}}{\tau_{chem}}$, want Da > 1

Design and Concept - Headend Stability

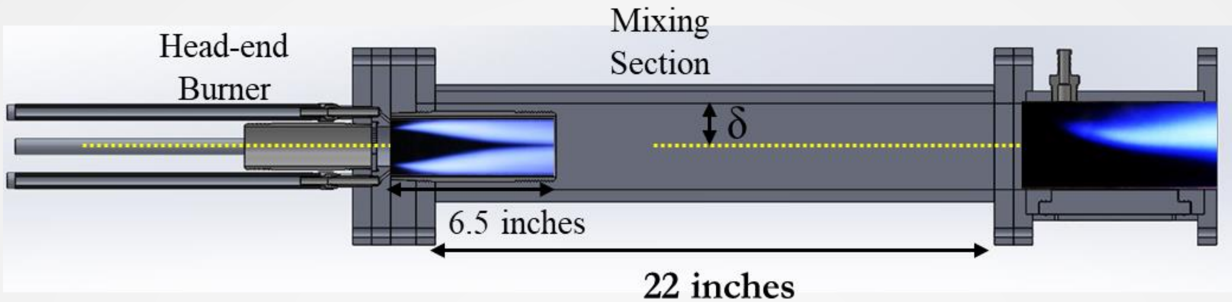
- High pressure-lean conditions are on the blow-out limit of the stability curve
- Adding hydrogen pilots will increase flame stability, but increases H_2O and decreases CO_2 produced





- CH_4/30% H_2 (φ = 0.6) equivalent of CH_4 at φ = 0.78
- Adding 30% H_2 results in a φ = 0.03 difference when compared to 25% H_2

Design and Concept – Flame Speed

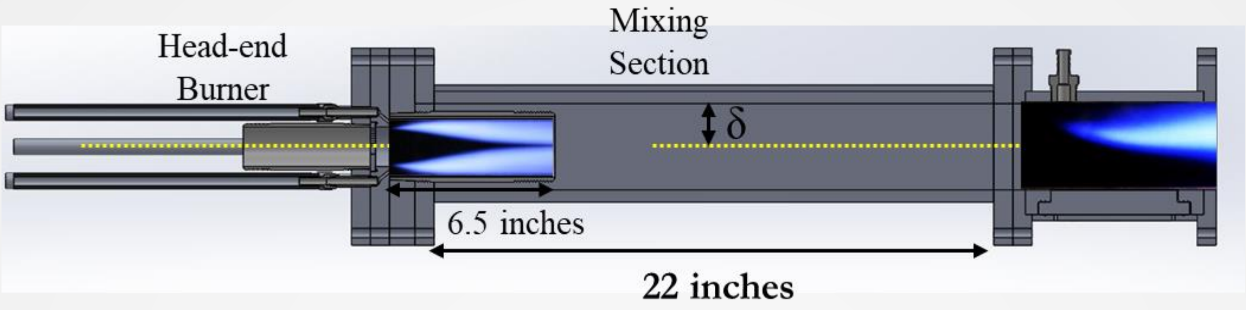


Methane Pilot

Turbulence (%)	*Laminar Flame Speed (m/s)*	*Turbulent Flame Speed (m/s)*	*Flame Angle (deg.)*	$\vec{V}_{lip}$ *(m/s)*	$\vec{V}_{air}$ *(m/s)*	$\vec{V}_{products}$ *(m/s)*	*Mach Number*	*Mixing Length (in)*
5	0.257	3.1	2.8	60.3	24.1	180	0.43	9
10		5.9	6.0					
15		8.8	8.9					

Hydrogen Pilot

Turbulence (%)	*Laminar Flame Speed (m/s)*	*Turbulent Flame Speed (m/s)*	*Flame Angle (deg.)*	$\vec{V}_{lip}$ *(m/s)*	$\vec{V}_{air}$ *(m/s)*	$\vec{V}_{products}$ *(m/s)*	*Mach Number*	*Mixing Length (in)*
5	0.257	3.1	2.8	63.9	8.6	192	0.55	7
10		5.9	6.0					
15		8.8	8.9					



Methane Pilot

Percent Bypass (%)	$\vec{V}_{lip}$ (m/s)	$\vec{V}_{air}$ (m/s)	$\vec{V}_{pilot}$ (m/s)	$\vec{V}_{products}$ (m/s)	Mach Number	m_{fuel} bypass (kg/s)	m_{air} bypass (kg/s)	m_{air} core (kg/s)	m_{fuel} core (kg/s)
5	63.7	10.7	10.3	363	0.57	0.0011	0.0248	0.4752	0.0166
10	60.3	21.4	18.6	344	0.54	0.0020	0.0498	0.4502	0.0157
15	57.0	32.1	26.9	325	0.51	0.0028	0.0748	0.4252	0.0149

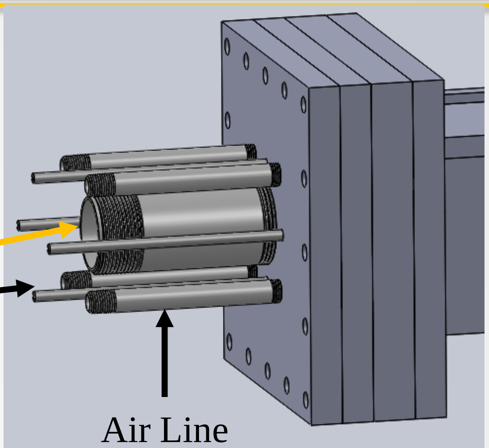
Hydrogen Pilot

% Hydrogen (by mole)	$\vec{V}_{lip}$ (m/s)	$\vec{V}_{air}$ (m/s)	$\vec{V}_{pilot}$ (m/s)	$\vec{V}_{products}$ (m/s)	Mach Number	m_{H_2} bypass (kg/s)	m_{air} bypass (kg/s)	m_{air} core (kg/s)	m_{CH_4} core (kg/s)
5	66.6	5.61	1.40	383	0.61	0.00011	0.0033	0.4967	0.0173
10	66.1	11.8	2.92	380.	0.61	0.00024	0.0068	0.4932	0.0170
15	65.5	18.5	4.57	378	0.60	0.00037	0.0108	0.4892	0.0167

First Stage Burner

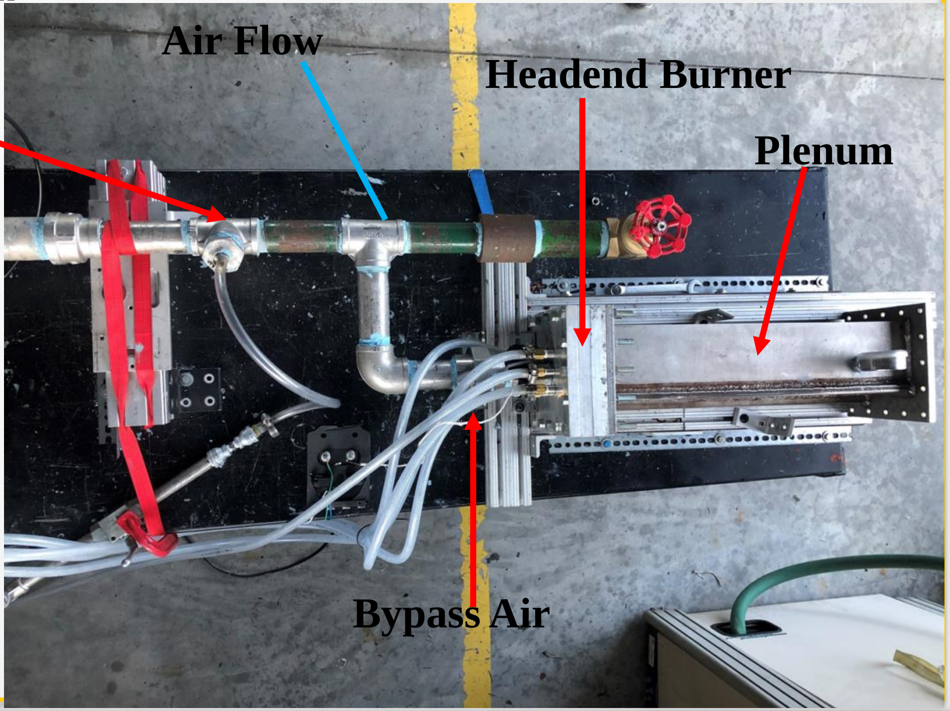
Design Parameters

- Duct Area : 3 x 3.5 in
- 4 air bypass lines
- Single flame holder
  - Step: ~0.5”
- Perforated plate for uniform flow and prevent flashback



Testing Conditions

- Inlet Flowrate : 60 $\frac{m}{s}$
- Primary Fuel : Premixed methane/air
- Φ : 0.6
- Pressure : 1 atm. (initial, working up to 5 atm.)
- Outlet Flowrate : 146 $\frac{m}{s}$
- Outlet Temperature : 1665K

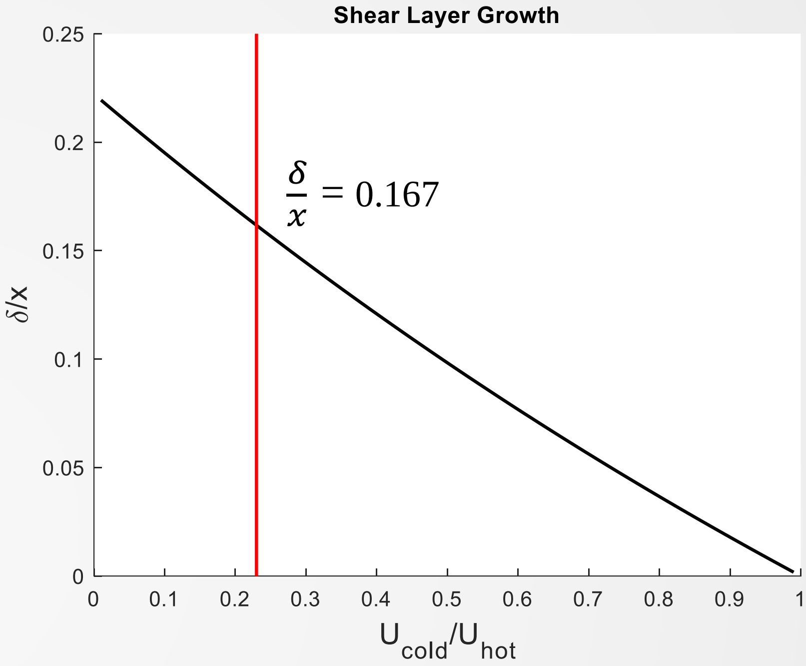


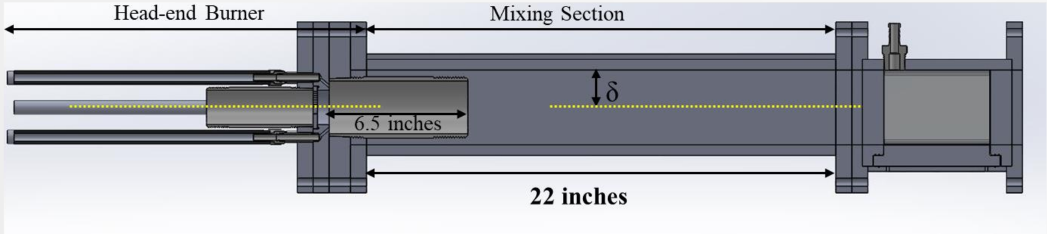
Mixing Section

- Need an appropriate mixing length to allow cold and hot flows to have a uniform temperature profile for axial jet

$$\frac{\delta}{x} = C_\delta \frac{(1-r)(1+\sqrt{s})}{2(1+r\sqrt{s})}\left[1 - \frac{(1-\sqrt{s})/1+\sqrt{s})}{1+2.9(1+r)/(1-r)}\right]$$

- Velocity Ratio, r = $\frac{\vec{U}_{cold}}{\vec{U}_{hot}}$
- Density Ratio, s = $\frac{\rho_{cold}}{\rho_{hot}}$
- δ = shear layer height
- x = mixing length
- C_δ = constant



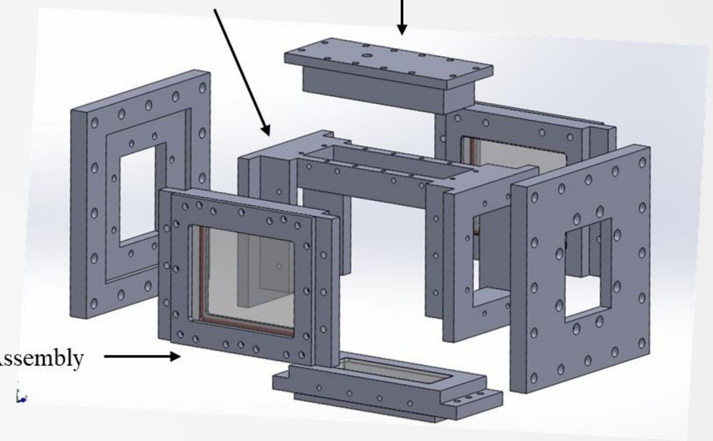


Cut-out view of head-end burner and mixing section

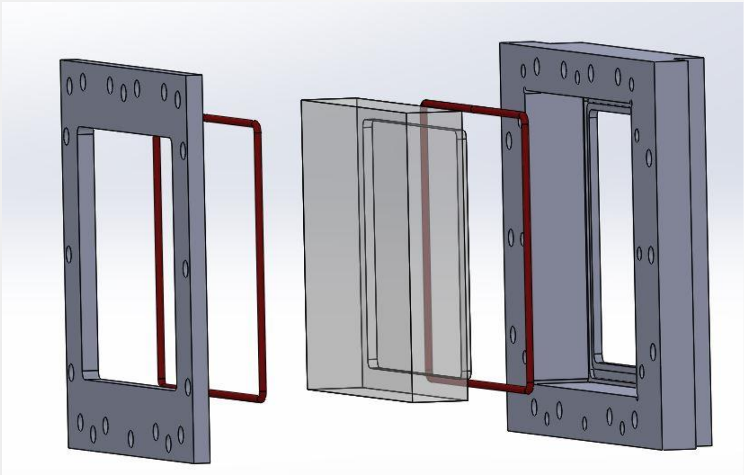
- Glass thickness determined with following correlation:

$$t = \sqrt{\frac{P \times A \times SF}{21000}}$$

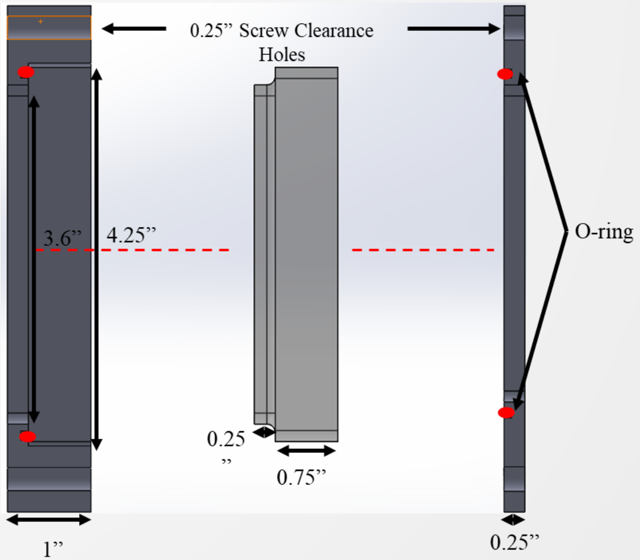
- P = Pressure
- A = Surface area of glass
- SF = Safety factor (10)
- 1" thick glass design can hold 91 psi with a SF of 10



Test section 3.5" tall and 3" wide

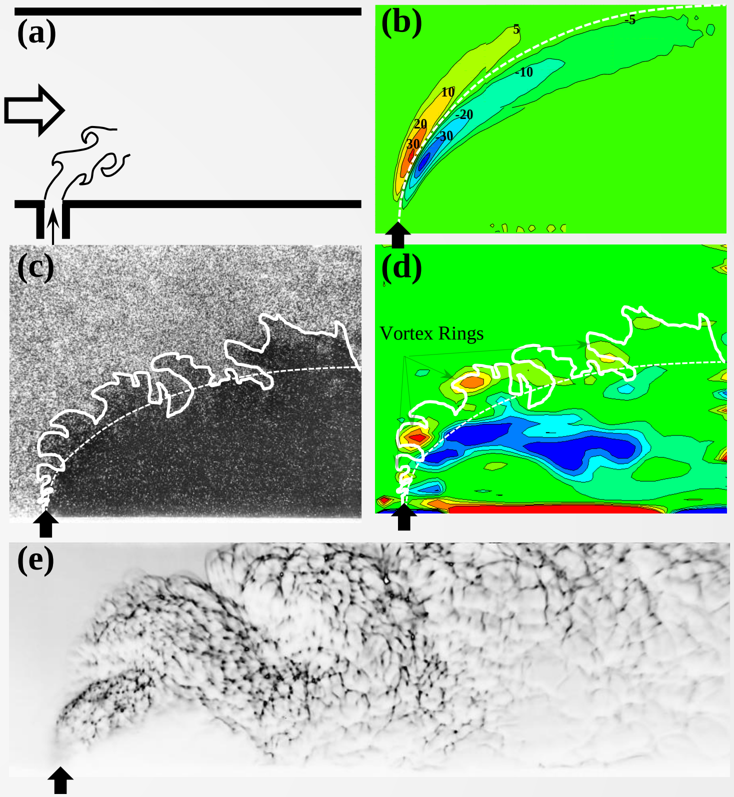


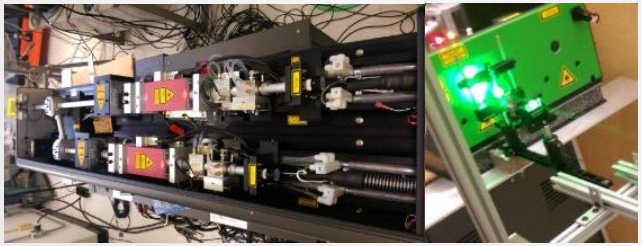
Side view for side plate, glass, and window plate integration

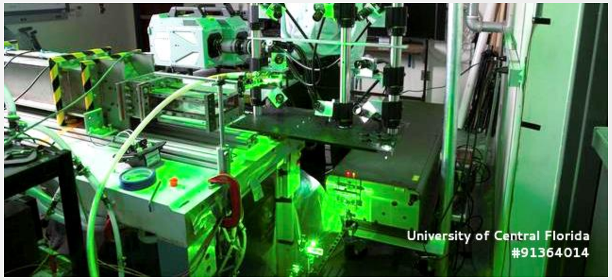


Advanced Optical Diagnostics and Measurements

- High-speed PIV system (20-40kHz)
- High-speed Schlieren (100 kHz)
- High-speed CH* and CH2O (40 kHz)
- LabVIEW control hardware and software
- Dynamic pressure transducers (PCB)

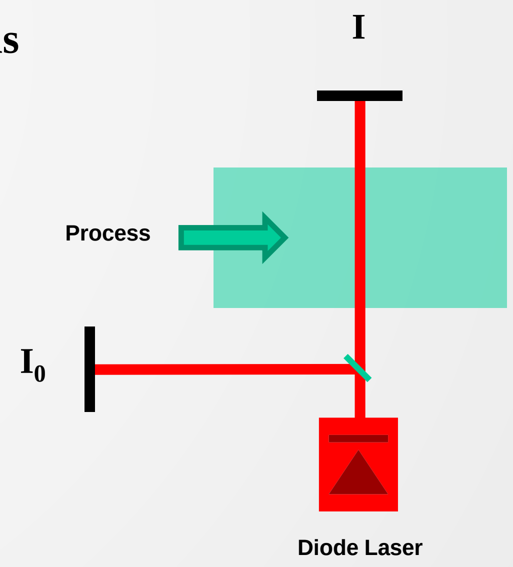






Tunable Diode Laser Absorption Spectroscopy (TDLAS)

- **Measure NOx and CO in the flame**
- **TDLAS Overview**
  - **Measure Process Transmittance (I/I_0) at Specific Wavelength(s)**
    - Diode Laser + 2 Photodetectors
  - **Apply Photon Conservation**
    - Beer-Lambert Law: $-\ln\left(\frac{I}{I_0}\right) = \sum_i \sum_j S_{ij}(T) X_j P L \phi_{ij}\left(\nu - \nu_{0_{ij}}\right)$
  - **Infer Process Path-Integrated Thermodynamic, Flow Conditions**
    - Time-Resolved Composition, Temperature, Pressure, Speed
    - Non-Uniformity Along Line-of-Sight



I = *Transmitted Intensity* $\left(\frac{W}{cm^2 sr Hz}\right)$
I_0 = *Incident Intensity* $\left(\frac{W}{cm^2 sr Hz}\right)$
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*)
ϕ_{ij} = *Lineshape Function* (*cm*)

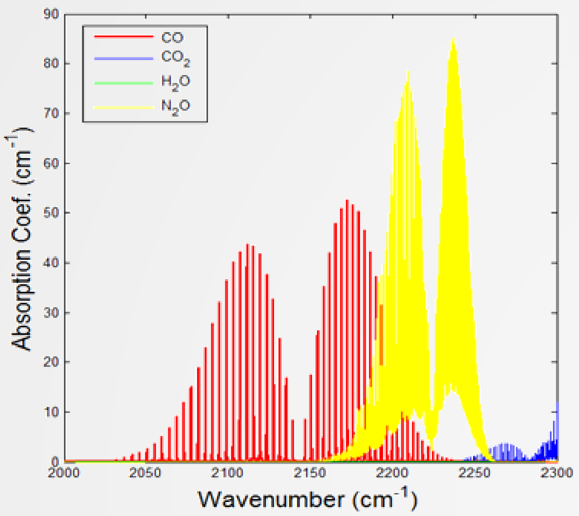
ν = *Optical Frequency* (*Hz*)
$\nu_{0_{ij}}$ = *Line Center Optical Frequency* (*Hz*)

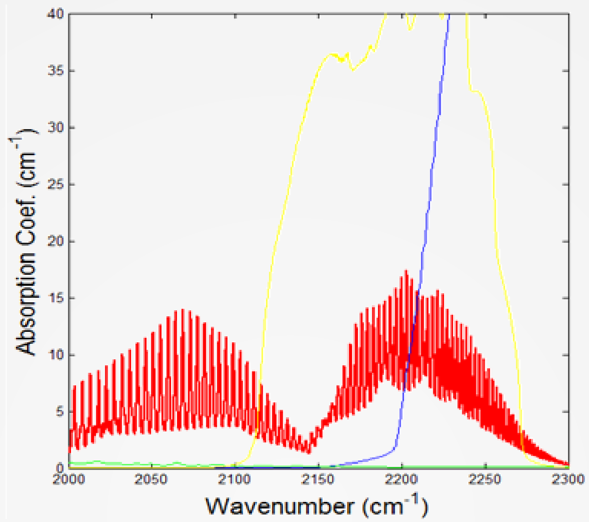
Subscripts

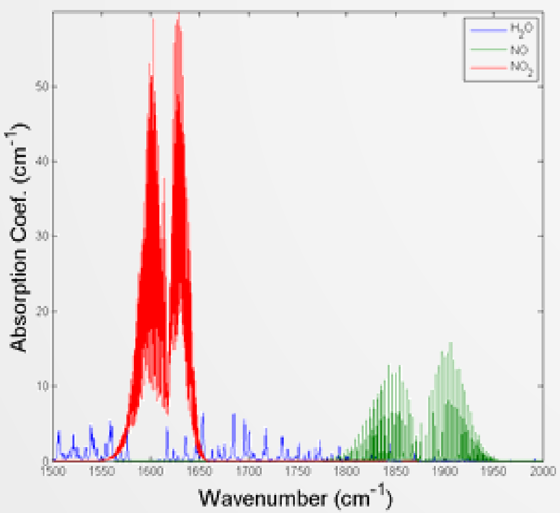
i = *Quantum Transition*

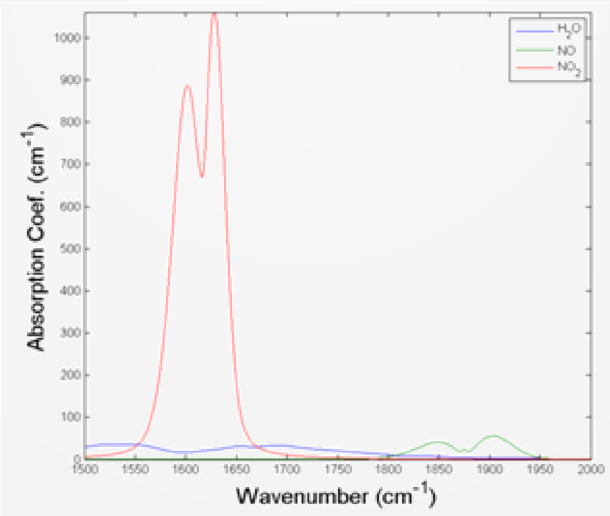
j = *Atomic/Molecular Species*

Experimental Measurements: TDLAS for NOx, CO









Spatial temporally resolved for understanding evolution of emissions

Carbon Monoxide (target) and common interfering species (CO_2, H_2O, N_2O) absorption features at T = 296 K and P =1 atm (**Left**); and T = 1500 K and P = 40 atm (**Right**).

NO, NO_2, and interfering water absorption features at $T = 296$ K and $P = 1$ atm (**Left**); and P =40atm (**Right**). Note the marked increase in absorption for NO and NO_2 at high pressures and the minimal water interference around 1600cm^{-1} and 1900cm^{-1}.

Diagnostics will be validated using shock tube and high temperature cells

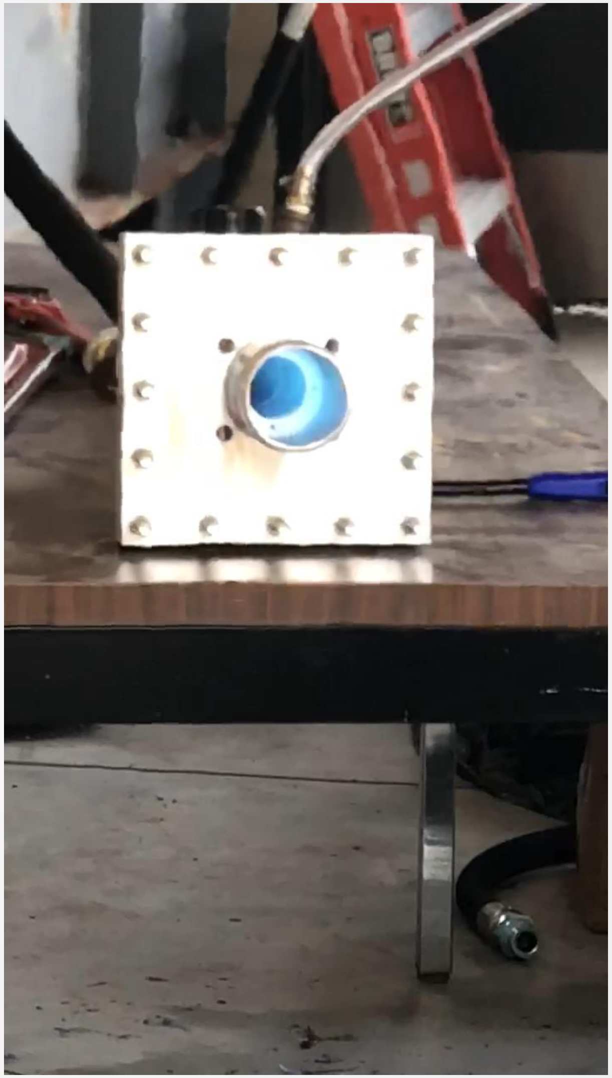
- Headend and axial fuel levels will be varied to explore the optimum fuel split for minimum NOx.

<table>
<tr><th colspan="14">Fuel Jet Test Points</th></tr>
<tr><td>φ (Headend)</td><td colspan="4">0.6</td><td colspan="4">0.63</td><td colspan="3">0.66</td><td colspan="2">0.69</td></tr>
<tr><td>Headend T (°C)</td><td colspan="4">1400</td><td colspan="4">1450</td><td colspan="3">1500</td><td colspan="2">1550</td></tr>
<tr><td>Axial ΔT</td><td>50</td><td>150</td><td>200</td><td>250</td><td>50</td><td>100</td><td>150</td><td>200</td><td>50</td><td>100</td><td>150</td><td>50</td><td>100</td></tr>
</table>

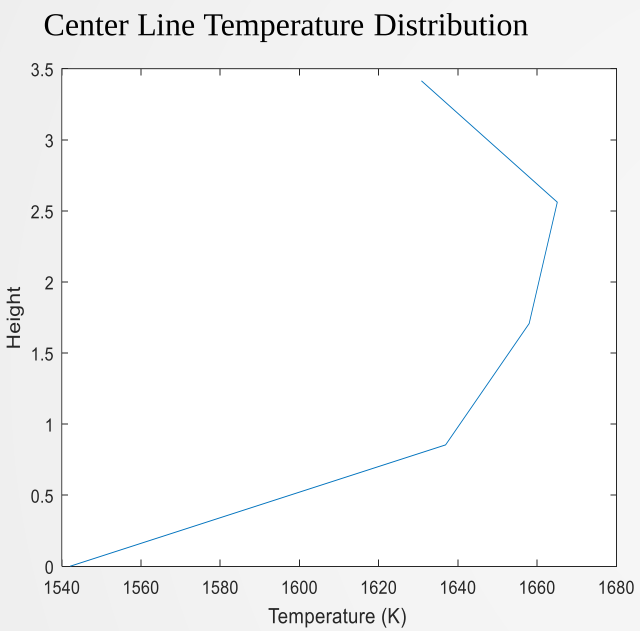
- Axial compositions, fuel only, fuel & air, and fuel/air & diluents.

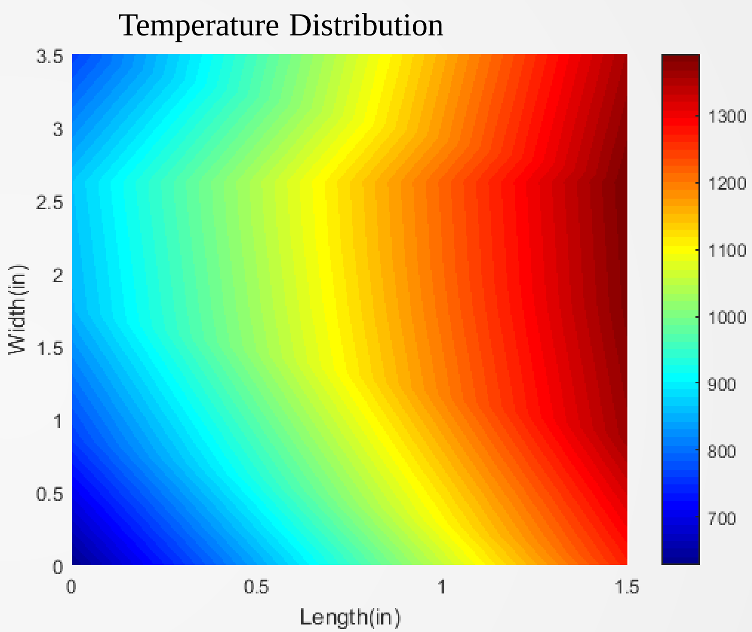
- Axial composition will be premixed, non-premixed and partially premixed. Straight and swirl jets will be tested.

Headend Test



Measured temperature profile at exit of mixing section.

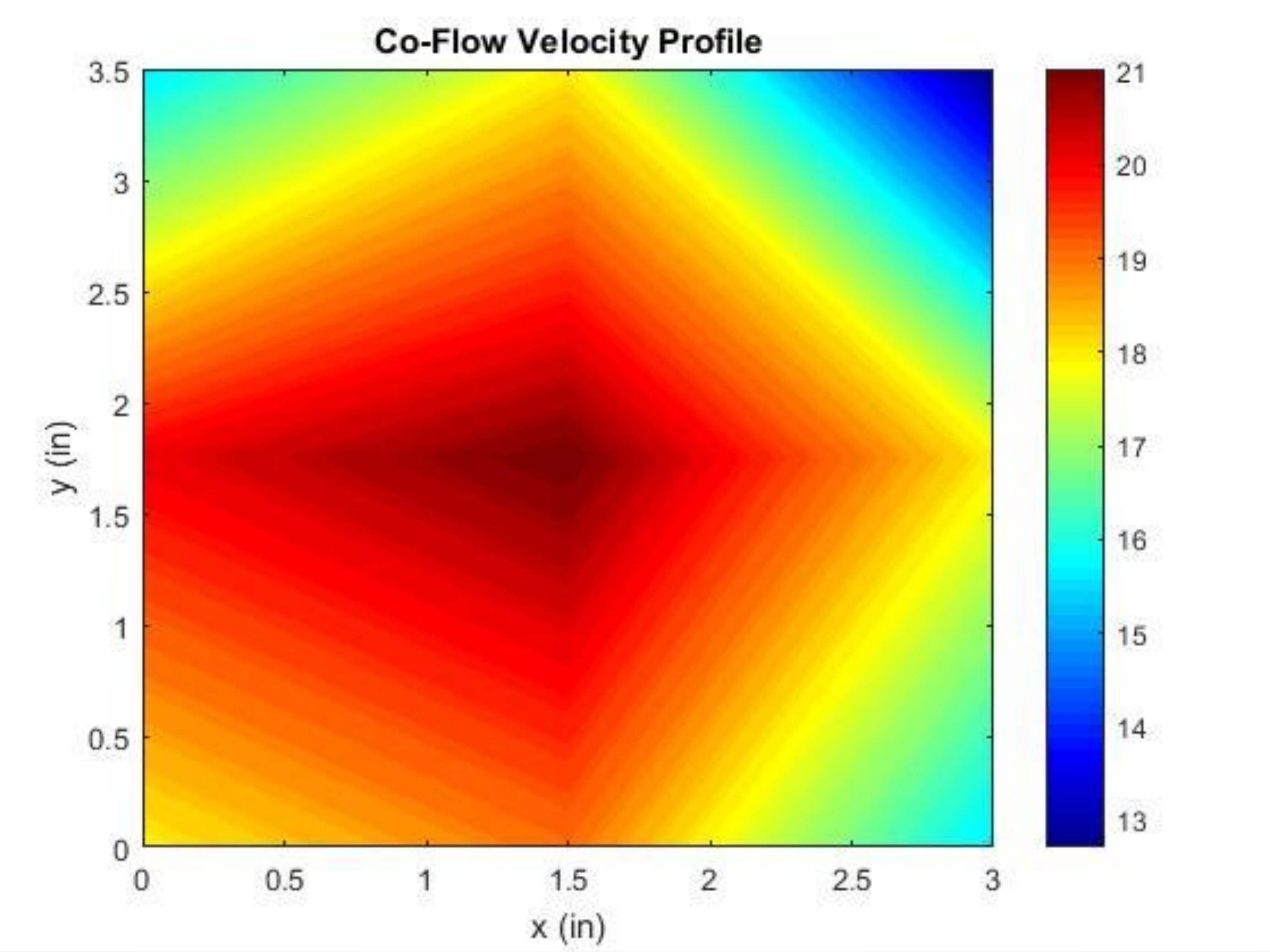




Pressure (atm)	$\dot{m}_{air}$ (kg/s)	$\dot{m}_{fuel}$ (kg/s)	ρ (kg/m^3)	Temperature (K)	Φ	Duct Height (in)	Duct Width (in)
1	0.094	0.0039	1.25	300	0.712	3.5	3

Velocity Profile

Measured velocity profile at exit of mixing section.



Jet-in-Crossflow Correlation

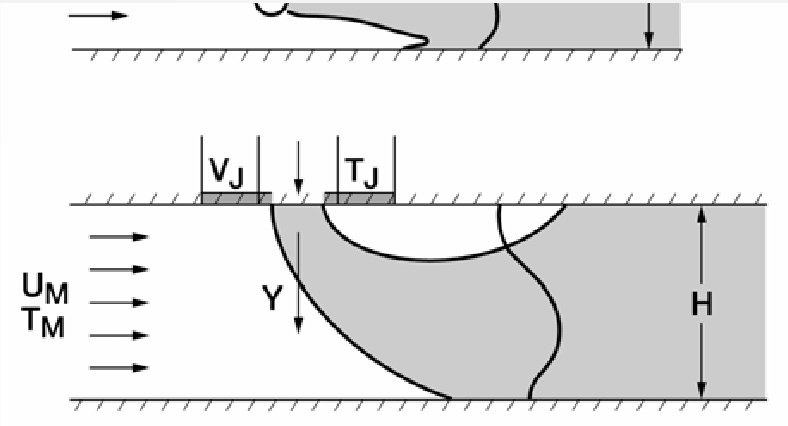


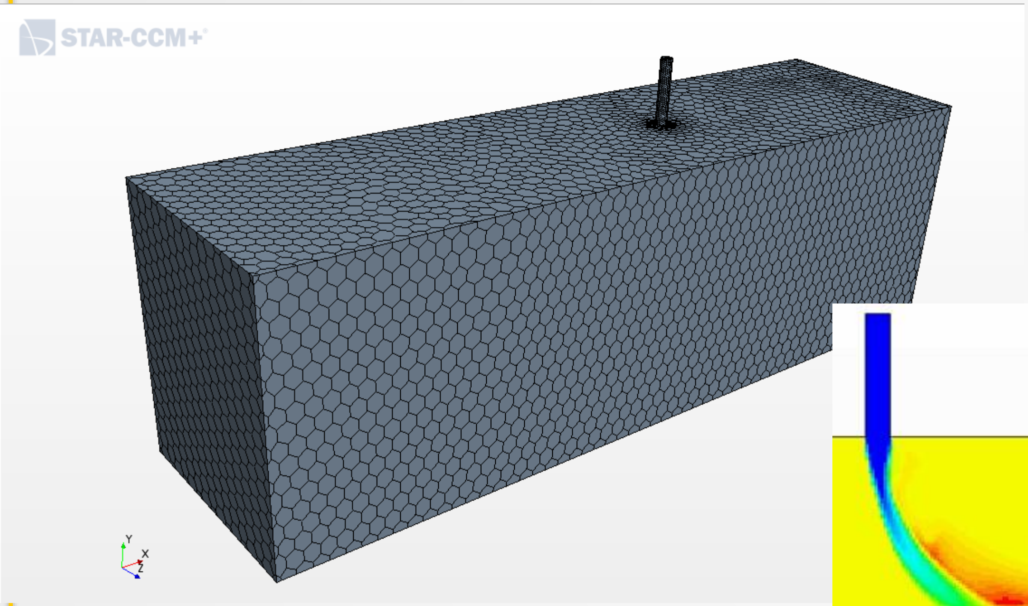
Figure 1.—Schematic of flow field for a confined jet in cross flow (shown for one-side injection of a single row of jets from the top duct wall).

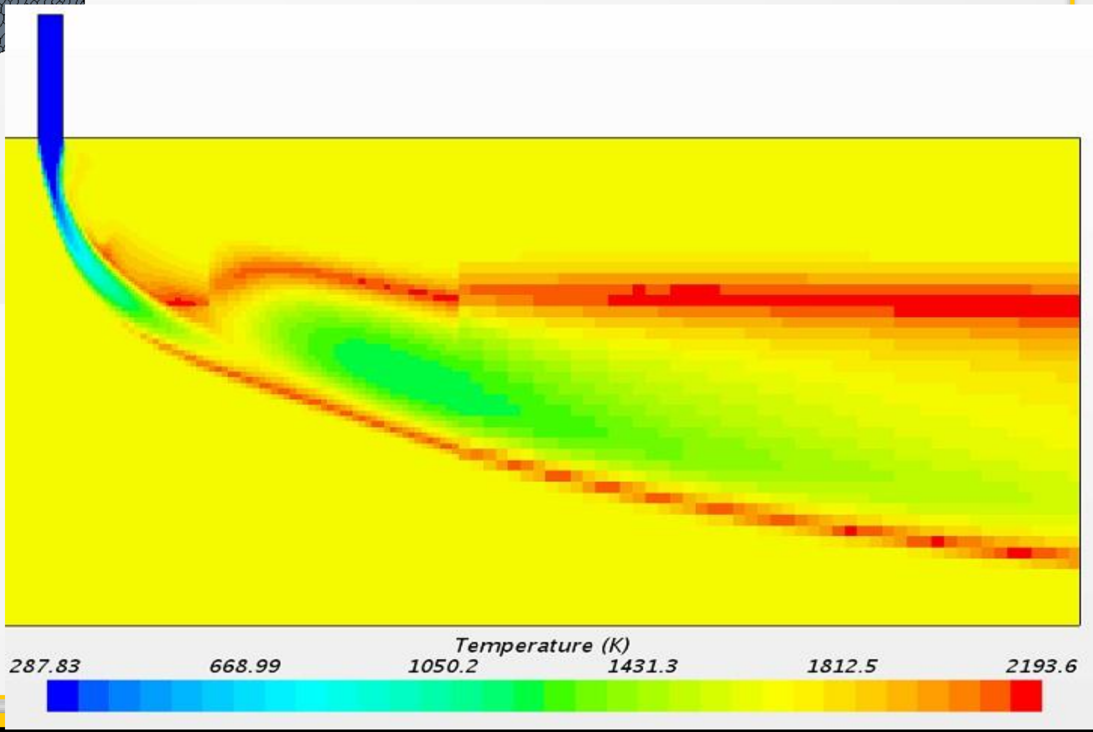
From Holdeman et al., NASA/TM—2005-213137

- Excel based tool to predict non-reacting jet-in-crossflow (JiC).
- The data obtained in this project will be used to create a reacting JiC correlation.

CFD

- Modeling test section with measured conditions at the inlet.
- Will evaluate different combustion models in Star-CCM, Fluent and OpenFOAM.





Questions