Improving NOx Entitlement with Axial Staging

DE-FE00312227

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PM: Dr. Seth Lawson

Industry Partner: General Electric (Drs. Carlos Velez, Keith McManus)

Kickoff Meeting
October 27th, 2017

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Agenda

- Motivation & Research Objectives
- Experimental Rig - Headend
- Experimental Rig – Axial Stage
- Test Conditions
- Experimental Measurements
- Jet-in-Crossflow Correlation
- CFD Validation

Roles of Participants

Scott Martin, PI: Administrative Tasks, Jet-in-Crossflow Correlation, CFD Validation

<u>Co-PI's</u>
Kareem Ahmed: High Pressure Experiments

Subith Vasu: High Pressure Experiments

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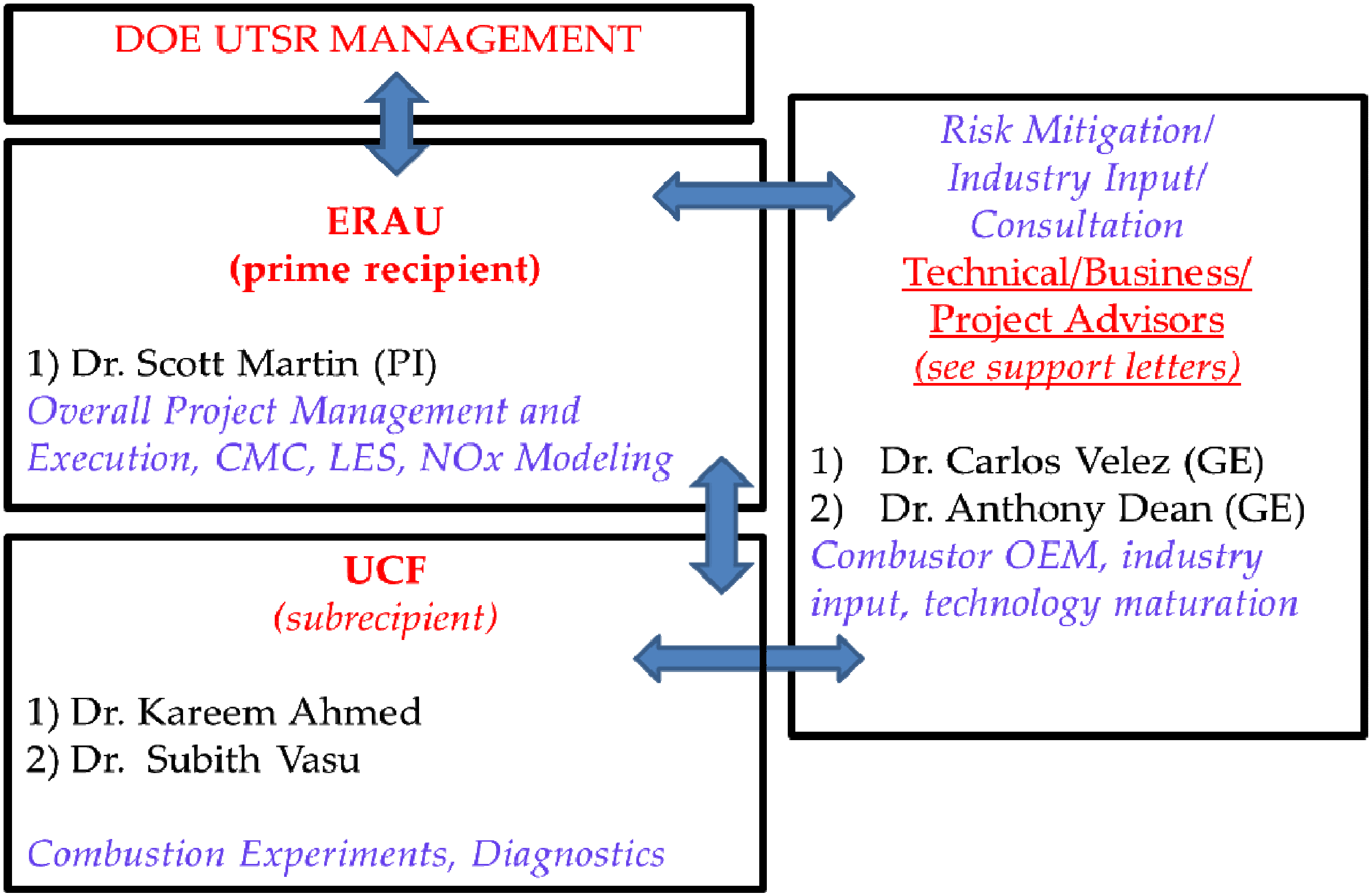
Project Management

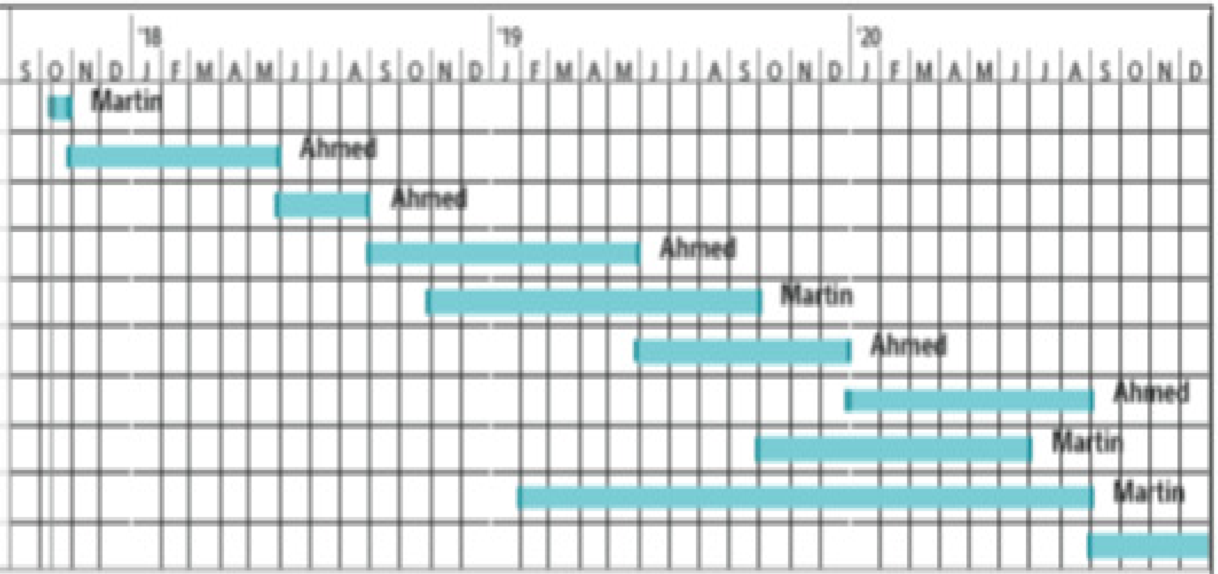


Lists of Tasks

1.0 Project Management and Planning
2.0 High Pressure Combustion Facility
2.1 Modify High Pressure Combustion Facility
2.2 Tune Rig Headend to Give Similar NOx Curve as Current Engines
3.0 Fuel and Air Axial Mixtures
3.1 Perform Initial Test of Axial Stage System
3.2 Explore Axial Stage System for Targeted Operability
4.0 Fuel and Diluent Axial Mixtures
5.0 Axial Stage Modeling
5.1 Develop Reacting Jet in Crossflow Correlation
5.2 Validate Existing Reacting CFD with Experimental Data

Project Timeline

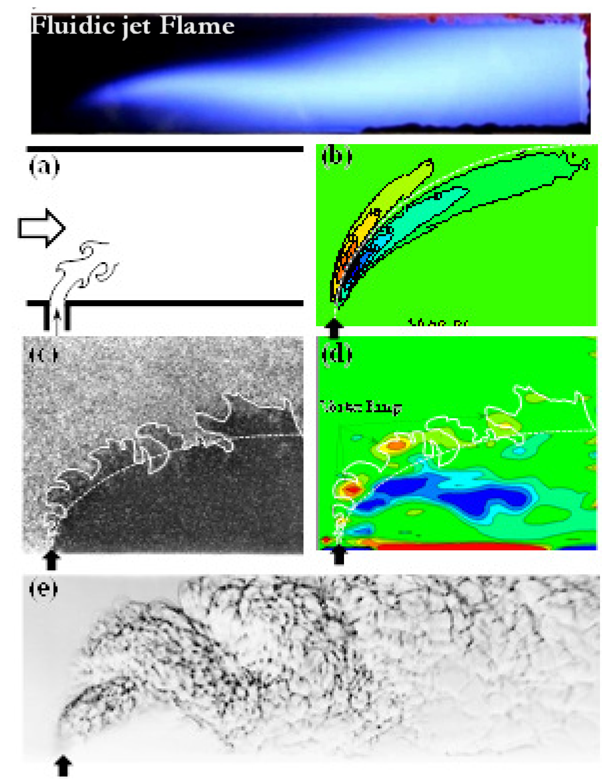
Task Name	Start	Finish	Resource Names
M1	10/12/17	10/30/17	Martin
M2	10/30/17	5/30/18	Ahmed
M3	5/30/18	8/30/18	Ahmed
M4	8/30/18	5/30/19	Ahmed
M5	10/30/18	9/30/19	Martin
M6	5/30/19	12/30/19	Ahmed
M7	12/30/19	9/1/20	Ahmed
M8	9/30/19	7/1/20	Martin
M9	1/30/19	9/1/20	Martin
M10	9/1/20	12/31/20	



Motivation and Research Objectives

Explore novel configurations to implement axial staging with direct involvement of original equipment manufacturers (OEMs). Develop reacting Jet-in-Crossflow correlation and validate existing CFD capabilities.

- **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 premixed and non-premixed designs.**
- **Axial Stage Modeling : Jet-in-crossflow correlation and CFD validation**



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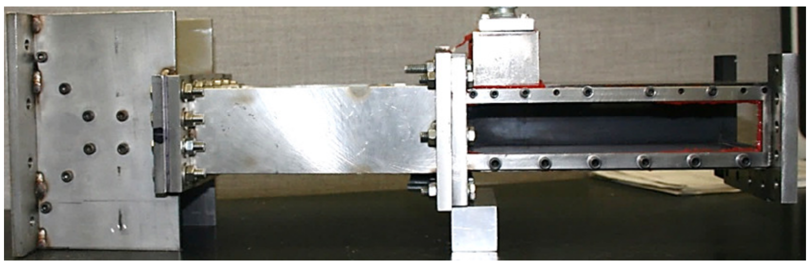
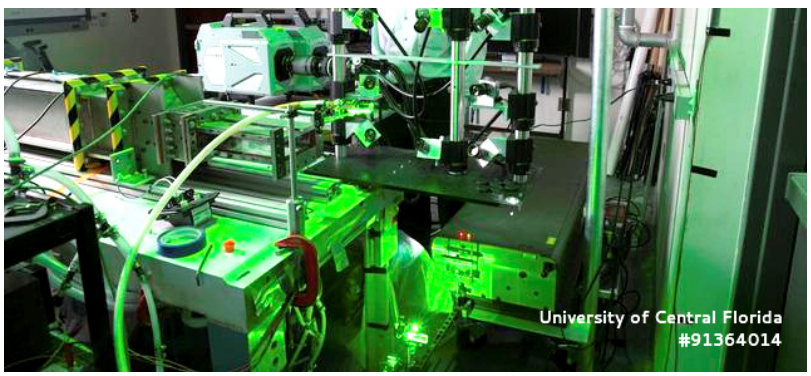
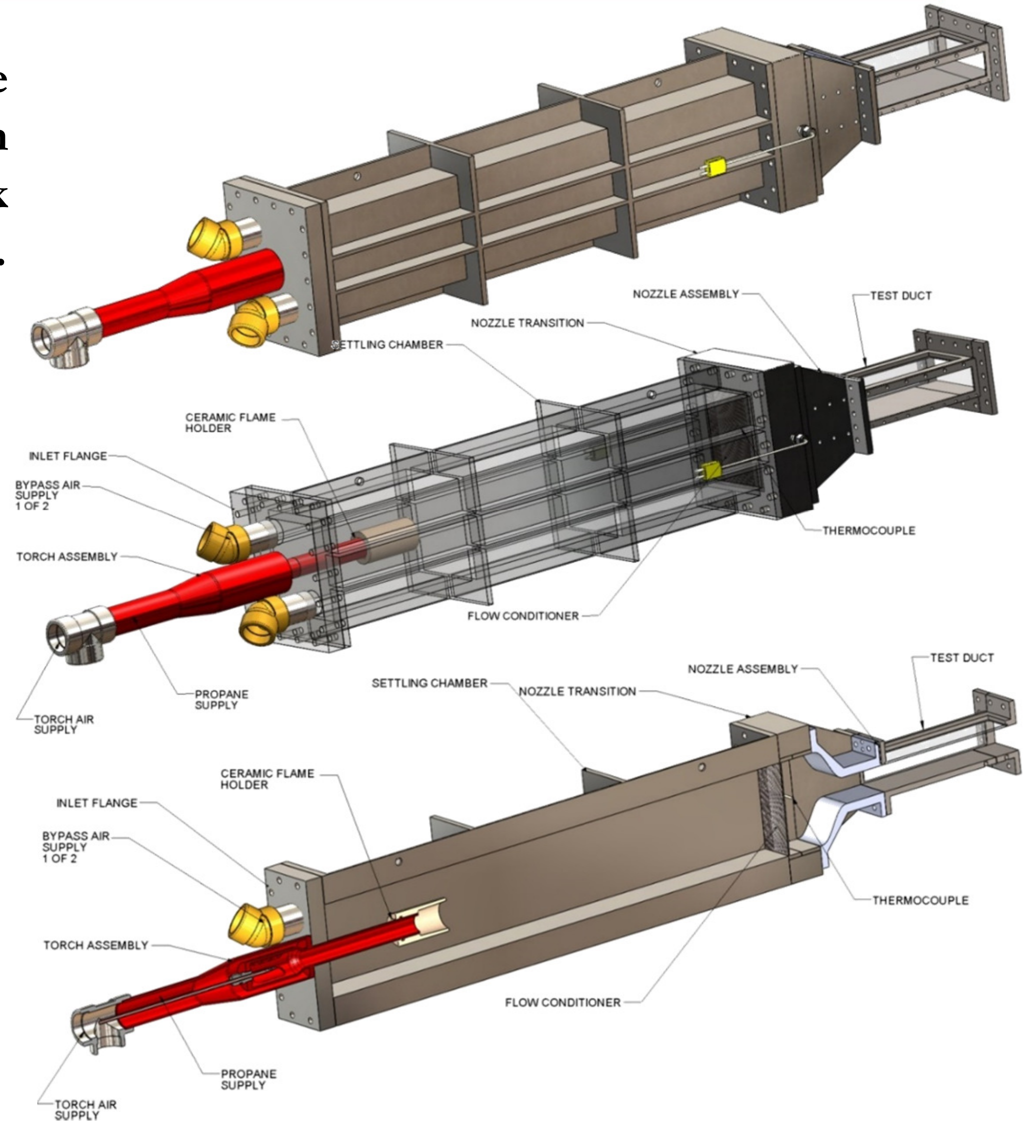
Experimental Rig - Headend

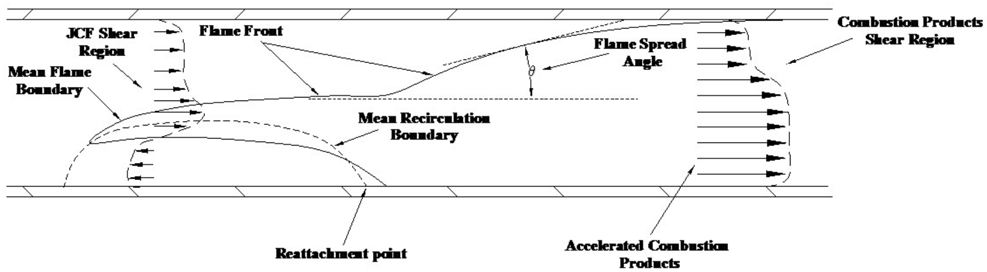
High Speed and High Temperature Combustion Chamber (vitiated with full optical test section): 2.5in x 3in x 6in, 100 m/s, 5 bar, 1kg/s (2 kg/s max).

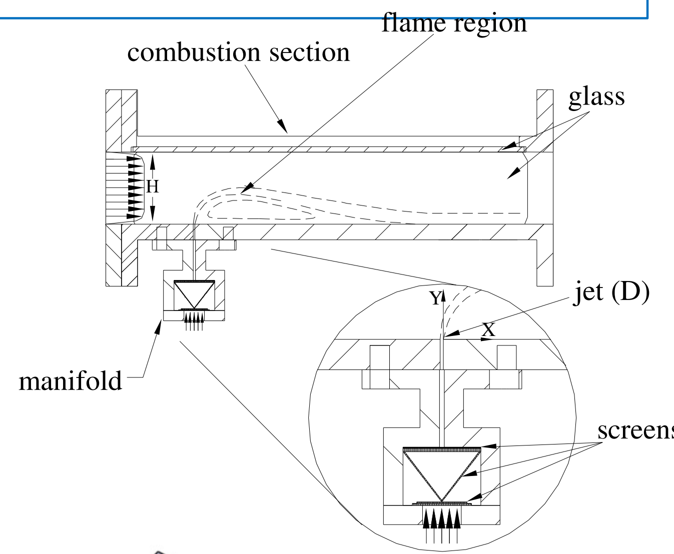


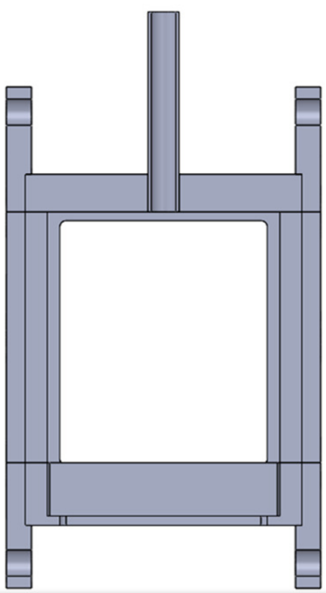


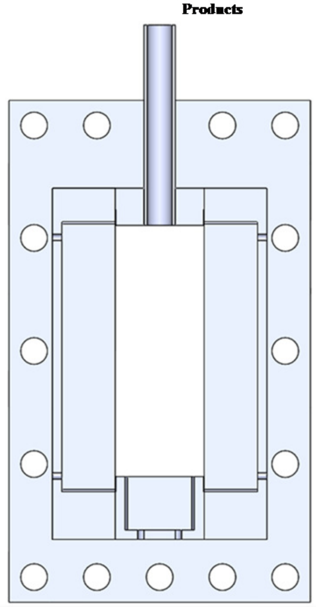


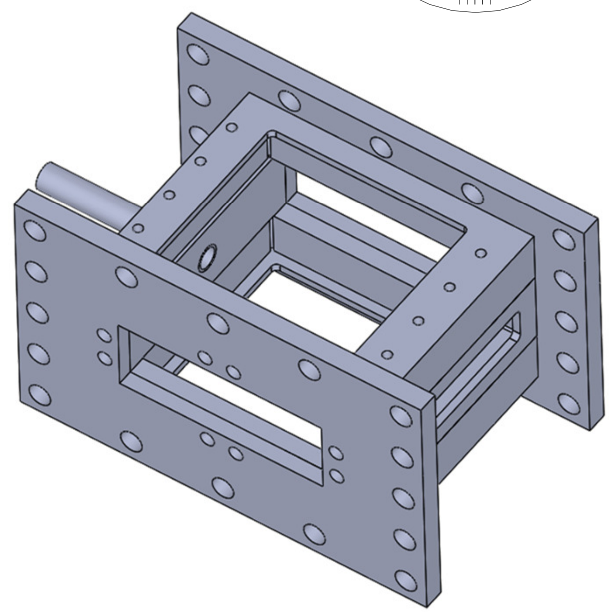
Experimental Rig - Axial Stage



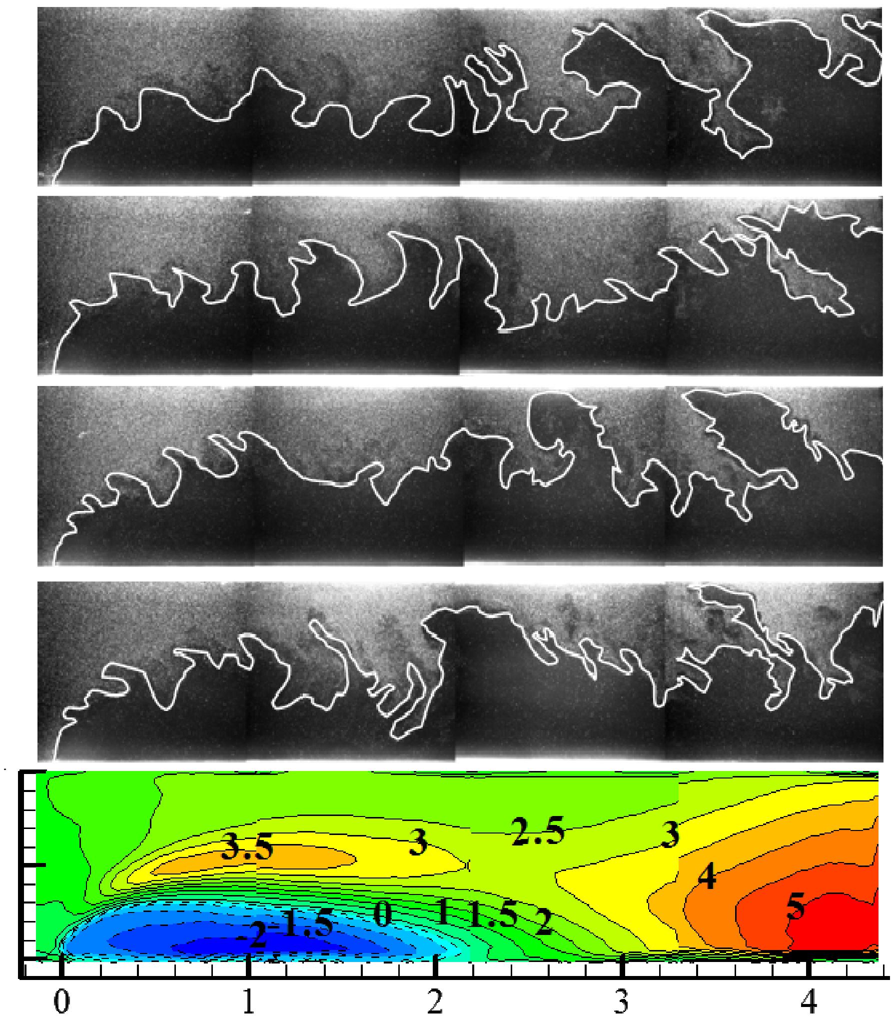


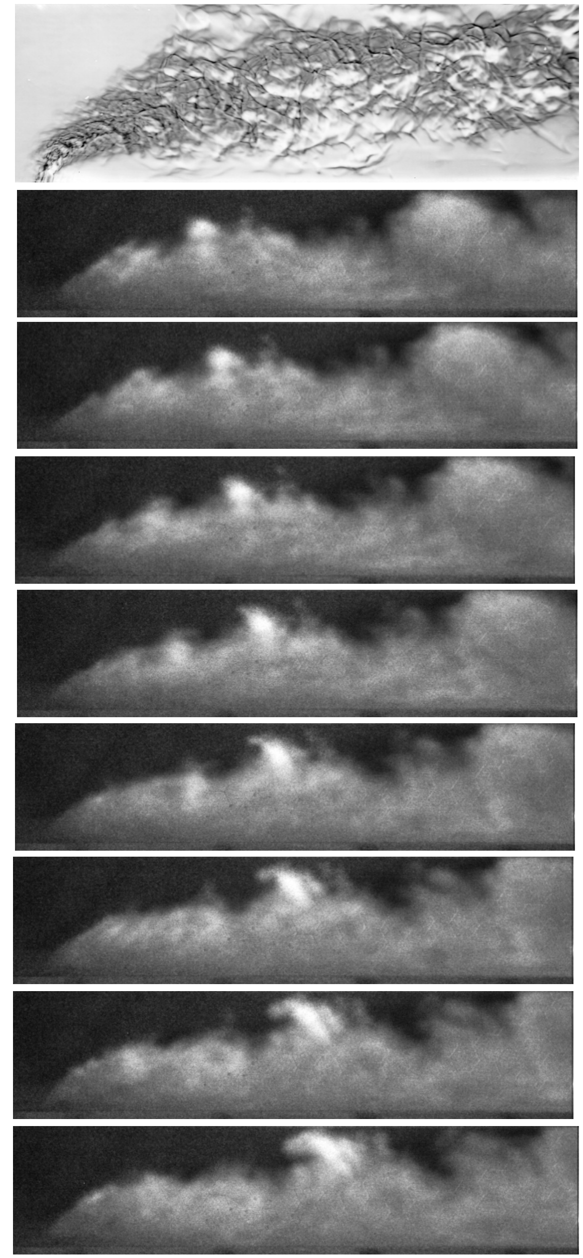




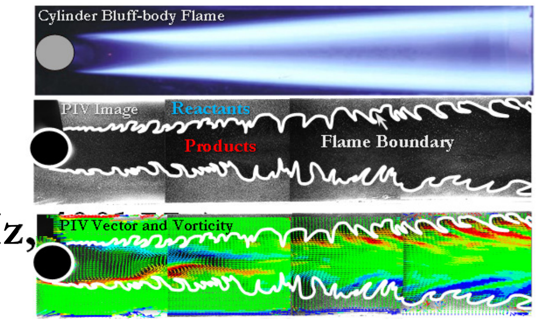


Axial Stage Example Data

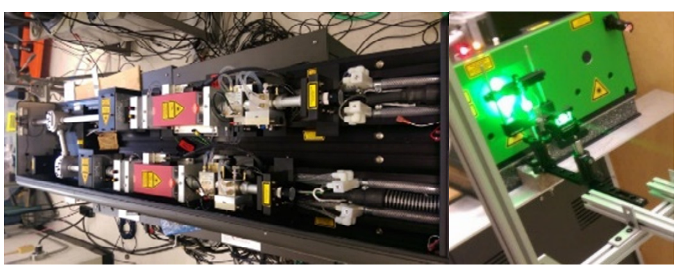




Experimental Measurements: PIV and Chemiluminescence

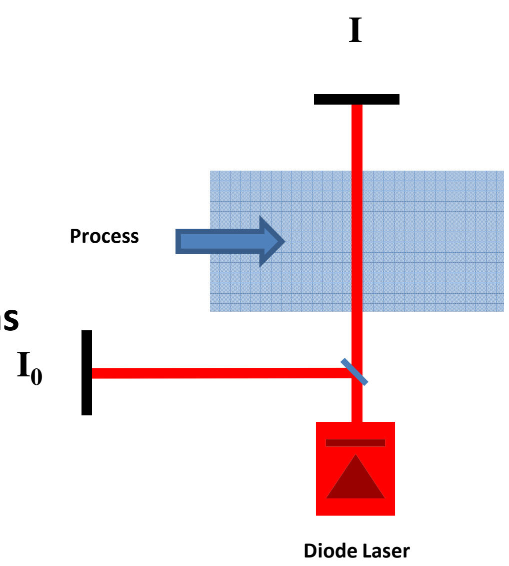


- High-speed PIV system (20kHz, 40kHz, 60kHz, 100kHz)
- High speed cameras 21,000-2,100,000 frames per second
- High-speed chemiluminescence CH*, OH* (40 kHz, 80kHz,
- Light-field focusing system for flow measurements and visualization
- LabVIEW control hardware and software
- Dynamic pressure transducers (PCB)
- Codes: DMD, POD, PIV, Turb, Physics-Based Models (Matlab/Fortran)



Tunable Diode Laser Absorption Spectroscopy (TDLAS)

- **TDLAS Overview**
  - **Measure Process Transmittance (I/I_0) at Specific Wavelength(s)**
    - Diode Laser + 2 Photodetectors
  - **Apply Photon Conservation**
    - Beer-Lambert Law: $\mathbf{I/I_0 = \mathit{f}(X,T,P,V)}$
  - **Infer Process Path-Integrated Thermodynamic, Flow Conditions**
    - Time-Resolved Composition, Temperature, Pressure, Speed
    - Non-Uniformity Along Line-of-Sight



Tunable Diode Laser Absorption Spectroscopy (TDLAS)

- **TDLAS Overview**
  - **Beer-Lambert Law (Detail)**
    - Equation of Radiative Transfer → Limiting Case of Dominant Stimulated Absorption
    - Valid at each optical frequency ν across targeted region of EM spectrum

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

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

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

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

$T = Static\ Temperature\ (K)$

$X_j = Mole\ Fraction$

$P = Static\ Pressure\ (atm)$

$L = Path\ Length\ (cm)$

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

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

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

Subscripts

$i = Quantum\ Transition$

$j = Atomic/Molecular\ Species$

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Tunable Diode Laser Absorption Spectroscopy (TDLAS)

- **TDLAS Overview**
  - **Beer-Lambert Law (Detail)**
    - **Species Detection:**
      - All quantities known (or measured separately) other than X_j, solve for X_j
    - **Thermometry:**
      - Take a ratio of equation at two different optical frequencies while holding T, P, L, X_j fixed, resulting expression is a function of temperature only, solve for T
      - All quantities known (or measured separately) other than T, compare measurement with high-fidelity simulation, infer T
    - **Pressure Measurement:**
      - All quantities known (or measured separately) other than P, compare measurement with high-fidelity simulation, infer P
    - **Velocimetry: (laser beam must make an angle with flow)**
      - Compare position of spectral features $\nu_{0_{ij}}$ to high-fidelity simulation with no bulk flow (no Doppler shift), infer process velocity component along laser line of sight

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

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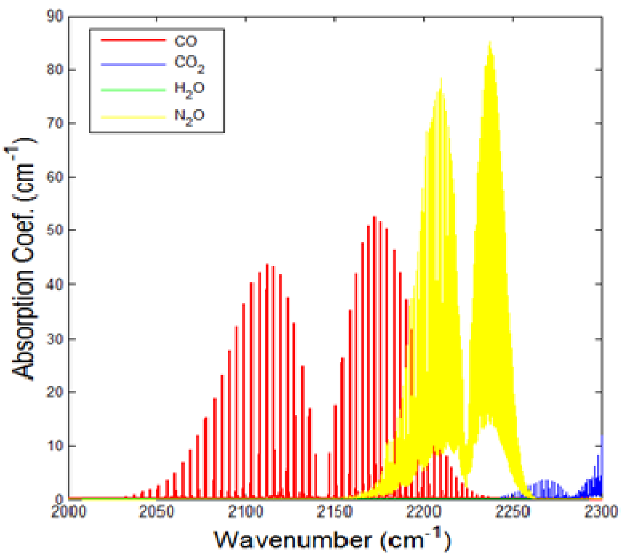
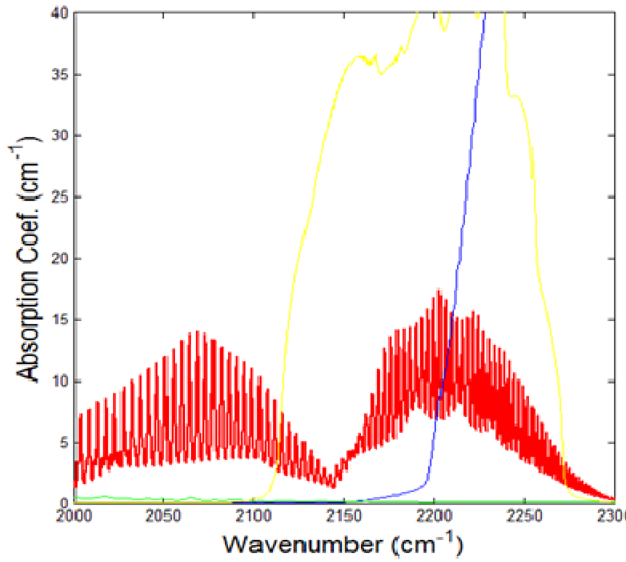
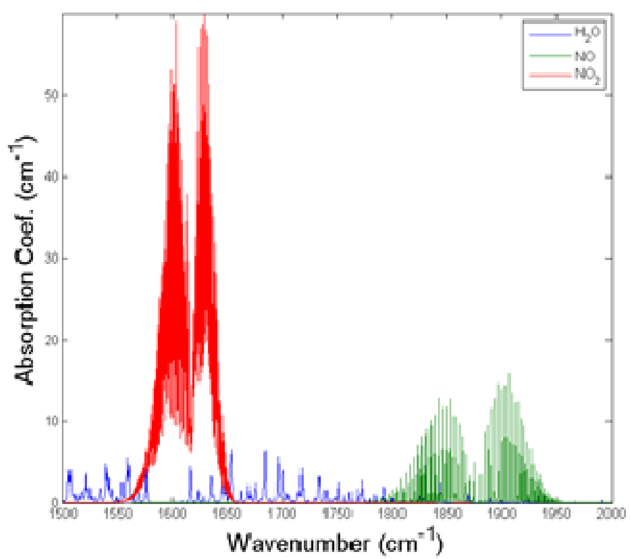
Experimental Measurements: TDLAS for NOx, CO

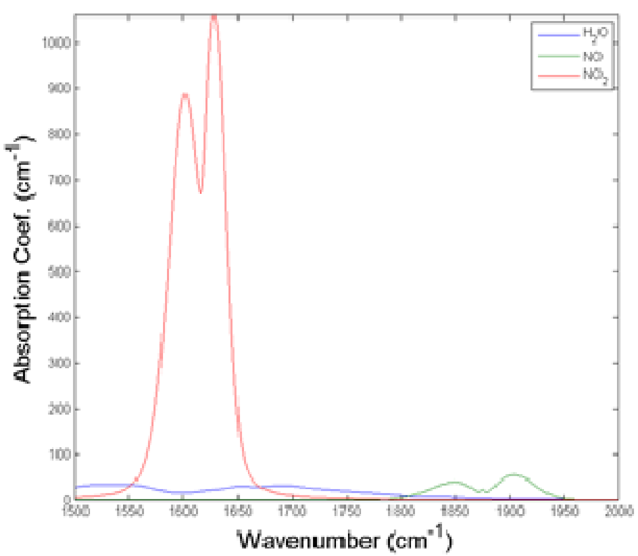




Spatio temporally resolved for understanding evolution of emissions

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 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

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Jet-in-Crossflow Correlation

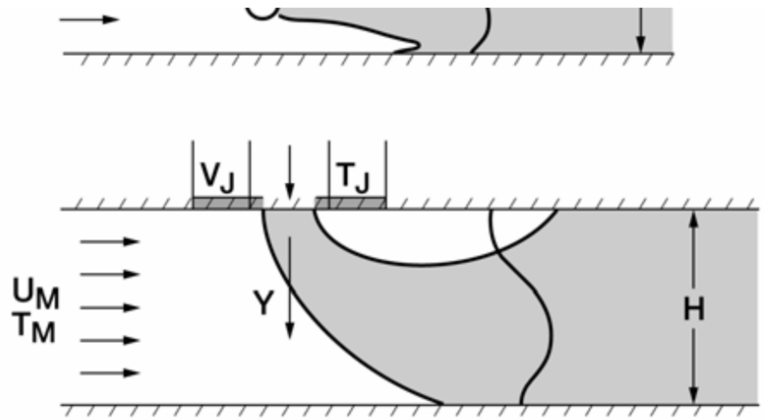
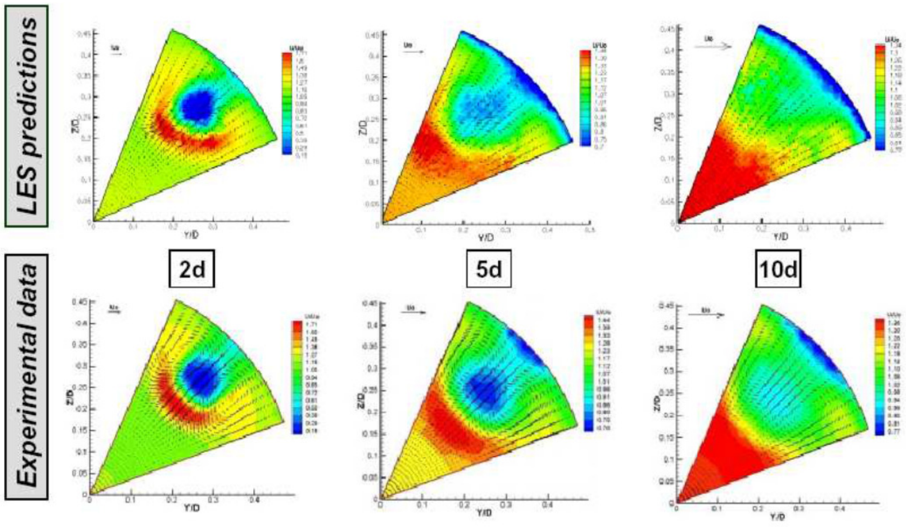


Figure 1.—Schematic of flow field for a confined jet in cross flow (shown for one-side injection of a single row of jets from the top duct wall).

From Holdeman, 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 Validation



Gajan et al.

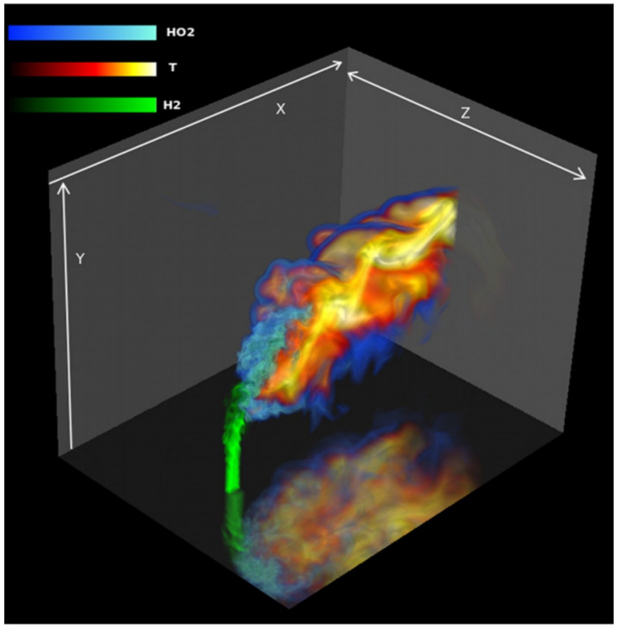


Figure 1: Volume rendering of temperature (black body colormap), HO2 (blue colormap), and H2 (green colormap) scalar fields at t=2.802ms from start of simulation. Opacity transfer functions adjusted to highlight the regions with high temperature, HO2, or H2 mass fraction. Grout et al.

Validate the capabilities of our OpenFOAM based CFD code and a commercial code to predict reacting jet-in-crossflow.