Investigation of Flame Structure for Hydrogen Gas Turbine Combustion

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- Project funded under Funding Opportunity Announcement DE-FOA-0002397.
- Start date 1 August 2021.
- The objective of the project is to advance hydrogen combustion technology from the current technology concept and/or application formulated stage (TRL 2) to a component and/or system validation in laboratory environment (TRL 4).
- At present, most gas-turbine manufacturers advertise engines capable of between 10-30% volume fraction of H_2 in the fuel. All OEMs indicate plans to extend this range to 100% over the next decade, primarily through the generation of hydrogen from a combination of fossil fuels and renewable energy sources.
- The potential use of ammonia as a carbon-free fuel and carrier of hydrogen is of significant interest but research on its viability from the aspect of combustion efficiency, NOx emissions, and dynamics is still in a nascent stage, especially at engine relevant operating conditions.

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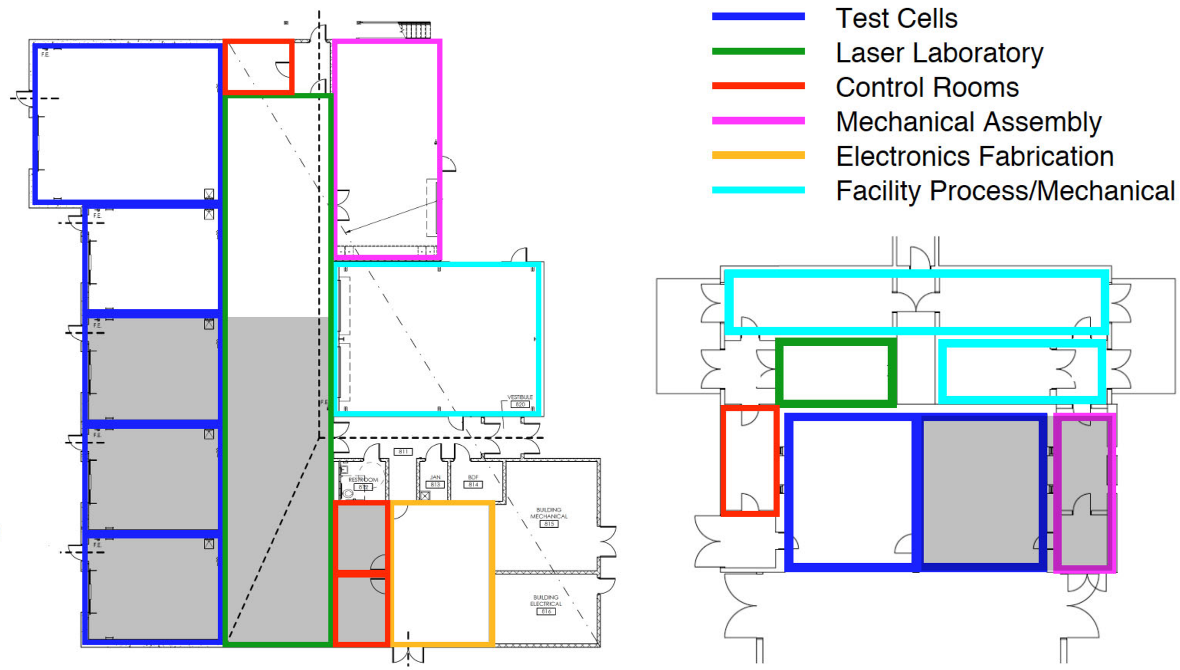
- Flame structure and dynamics for gas turbine combustion with hydrogen, ammonia, and mixtures of these fuels with natural gas will be explored.
- Our proposed research will focus on multi-stage, multi-tube, micromix (M3) injectors.
- The experiments will be performed in the Combustor Rig for Advanced Diagnostics (COMRAD) test rig. The test rig is designed to operate at pressures up to 40 bar and inlet air temperatures up to 1080 K. Two test article configurations will be developed:
  - Steady-state configuration for emissions, LBO, flashback.
  - Unsteady configuration for studies of self-excited combustion instabilities.
- Advanced diagnostic methods will be used to study flame structure and dynamics:
  - High-speed particle imaging velocimetry (PIV)
  - Dual-pump coherent anti-Stokes Raman scattering (CARS) for T, species.
  - Planar laser-induced fluorescence (PLIF) imaging for OH, NO, and NH concentrations.

High Pressure Combustion Laboratory

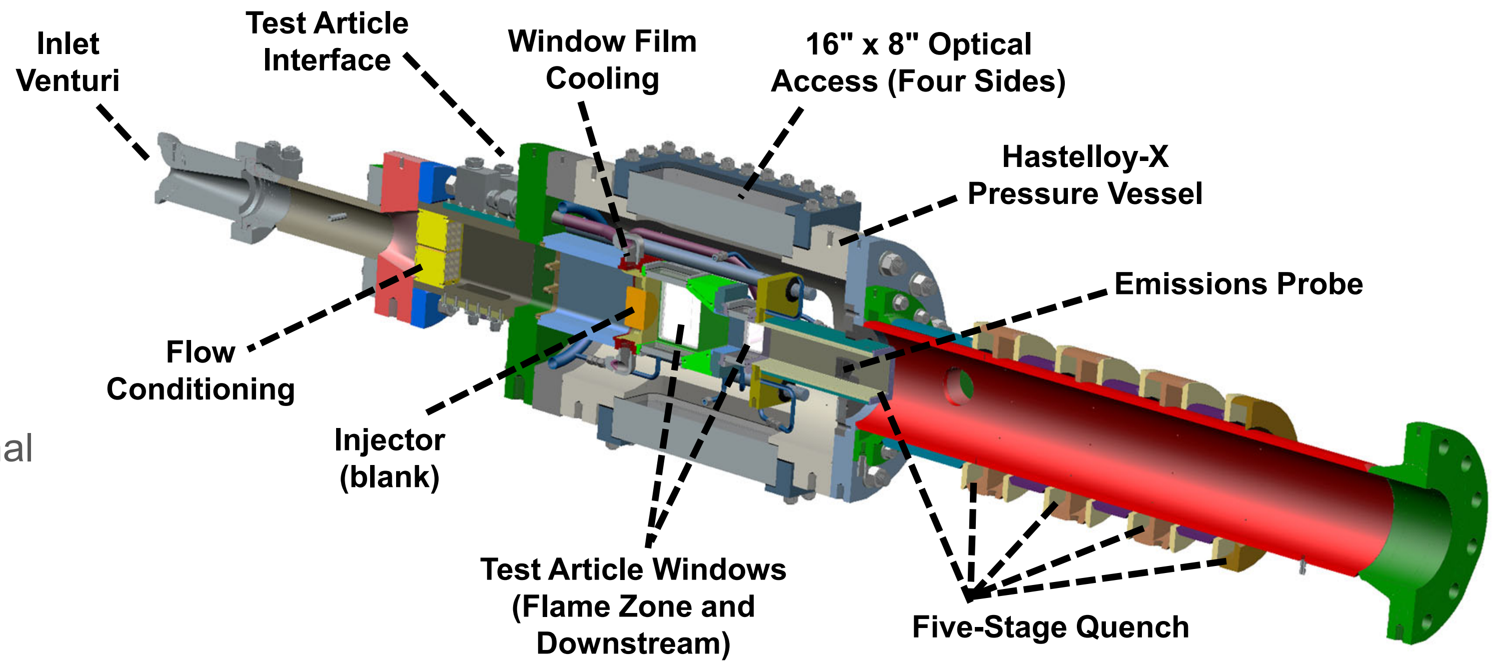
- Our gas turbine combustion work is housed within the Zucrow Laboratory Complex, in the high pressure facilities.
- The High Pressure Combustion Laboratory was constructed specifically for high pressure gas turbine combustion testing and for the application of advanced laser diagnostics for measurements in high-pressure optical rigs.
- The facility is capable of supplying heated air at pressures up to 60 bar (880 psia), temperatures up to 1100 K (1500°F), and a flow rate of 4 kg/s (8 lbm/s).

Aerial View



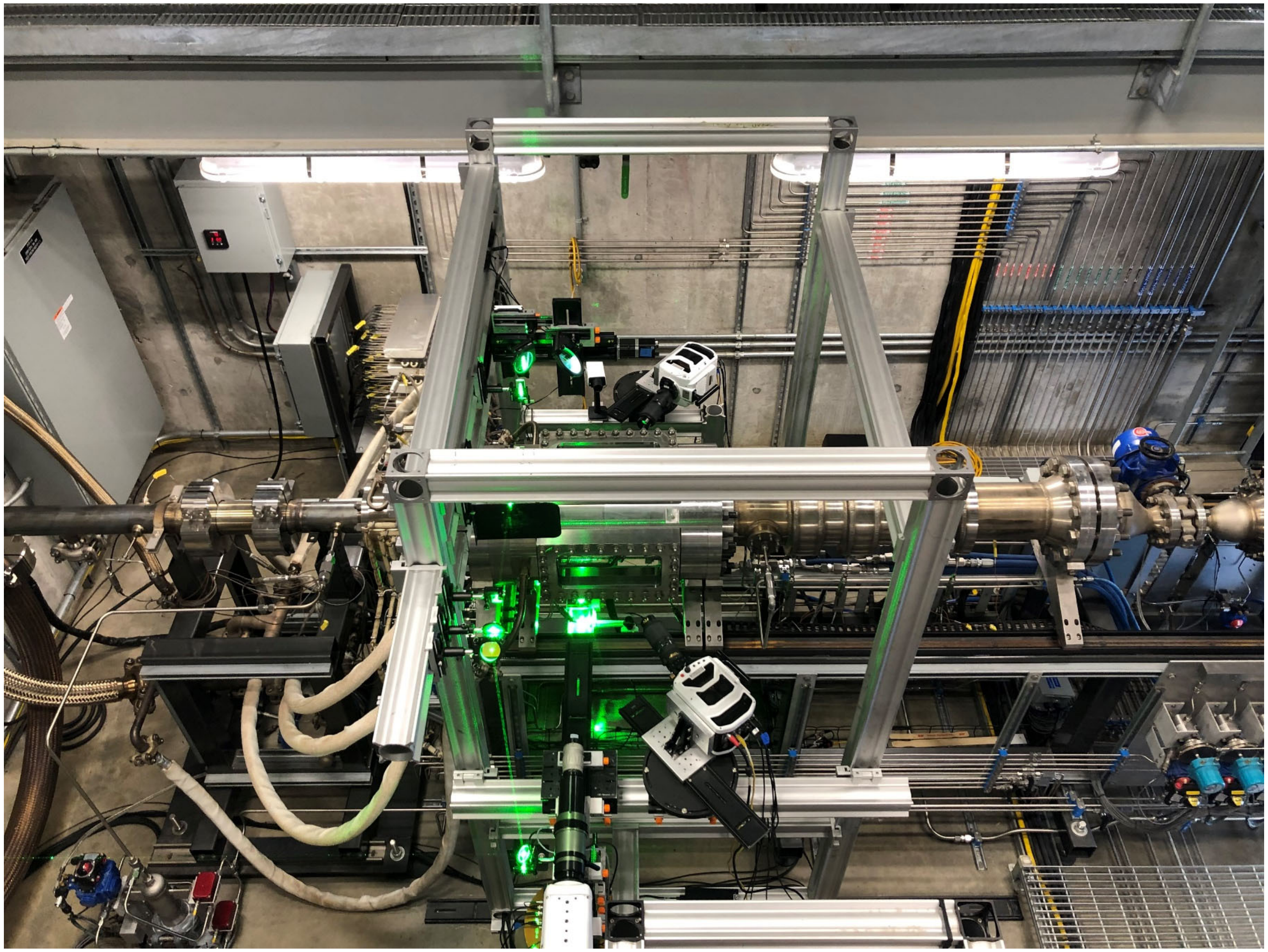
Advanced Gas Turbine Combustion Test Rig

- Rig designed to simulate engine cycle conditions
  - 8 MW steady-state thermal power
  - 40 bar P3
  - 1000 K T3
  - Water-cooled
  - Film-cooled windows
- Excellent optical access to the flow, including flame zone and boundary conditions
- Will also accommodate traditional probe-type instrumentation
  - Emissions sampling
  - Acoustics



Advanced Gas Turbine Combustion Test Rig

COMRAD test rig pictured with stereo PIV diagnostic system in operation



Fluid System Summary

Airbreathing Combustion and Propulsion Lab

Operational Parameters	Maximum Operation (Steady State)
Heated air (or N_2) supply 1	5 kg/s at 58 bar and 1093 K (7 kg/s at 723 K)
Heated air (or N_2) supply 2	3.6 kg/s at 41 bar and 813 K (540 ºC)
Heated air (or N_2) supply 3	0.75 kg/s at 41 bar and 813 K (540 ºC)
Unheated air	0.45 kg/s (compressor discharge) with 9000 kg storage at 150 bar
Oxygen	2 kg/s and 8 kg/s at 150 bar
Bottled oxidizers	2 circuits at 1 kg/s and 150 bar
Nitrogen	0.05 kg/s (pump discharge) with 9000 kg storage at 400 bar
Bottled inert gases	2 circuits at 1 kg/s and 150 bar
Bulk fuel	Natural gas, hydrogen, and liquid fuels to support >10 MW (steady)
Bottled fuels	4 circuits at 1 kg/s and 150 bar
Water	5 kg/s at 83 bar (pump discharge) with 350 L reserve

Project Timeline

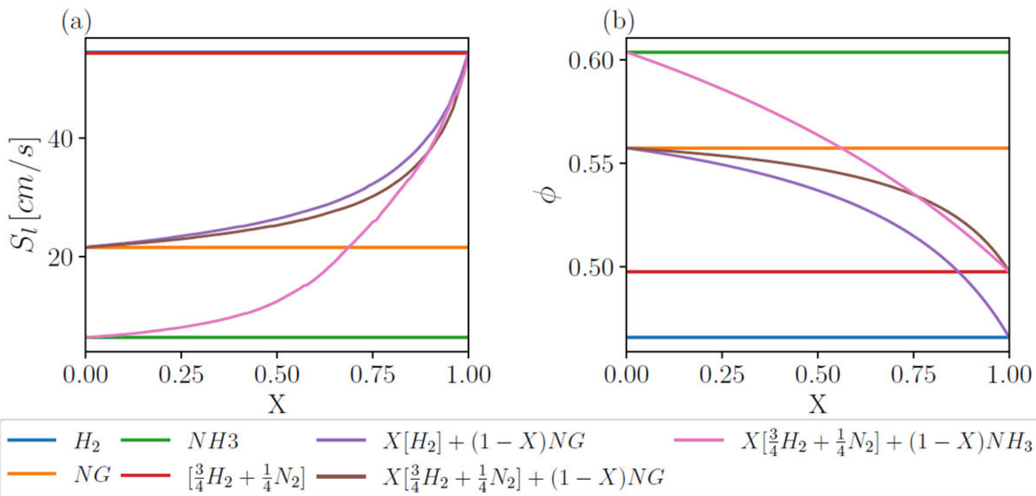
		Year 1				Year 2				Year 3			
Task 1.0 Project Management and Planning													
Task 2.0: Reconfigure Experimental Hardware and Validate Operation													
2.1	Develop M3 Injector		M1										
2.2	Develop Modular Combustion Chamber		M2										
2.3	Develop High-Pressure Ammonia Supply			M3									
2.4	Complete Final Assembly, Integration, and Verification Testing			M4	M5								
Task 3.0: Complete Parametric Map of Global Combustion Performance													
3.1	Characterize Combustion Emissions								M6				
3.2	Measure Points of Lean Blowout								M7				
Task 4.0: Complete Parametric Survey of Combustion Stability													
4.3	Configure Hardware for Dynamics Testing							M08					
4.4	Develop Parametric Stability Map with Baseline Instrumentation								M09				
Task 5.0: Perform Advanced Diagnostics of Flow-Flame Structure and Dynamics													
5.1	Perform Simultaneous High-Speed PIV and OH PLIF Measurements								M10				
5.3	Perform Ultrahigh-Speed PIV and OH-PLIF Measurements									M11			
5.3	Perform NO PLIF Measurements										M12		
5.2	Perform NH PLIF Measurements for Fuels with Significant NH3 Fractions										M13		
Task 6.0: Acquire High-Fidelity Measurements of Flow Temperature and Mixing													
6.1	Perform "Point" Dual-Pump CARS Measurements										M14		
6.2	Demonstrate and Deploy Dual-Pump "Line" CARS												M15
Task 7.0: Curate Measurement Database													
7.1	Assemble and organize all data, metadata, and processing tools												M16

Task 2.3: Design Envelope

Test Condition Mapping

- Initial fuel fraction (X) sweep from 0.5 to 1.0
- Ammonia decomposition efficiency (η) sweep from 0.4 to 1.0
  - Rate of ignition delay increase requires unreasonable combustor lengths at $\eta < 0.4$
- Equivalence ratio determined at a fixed adiabatic flame temperature of 1980 K (DOE target for 65% combined cycle efficiency GTs)

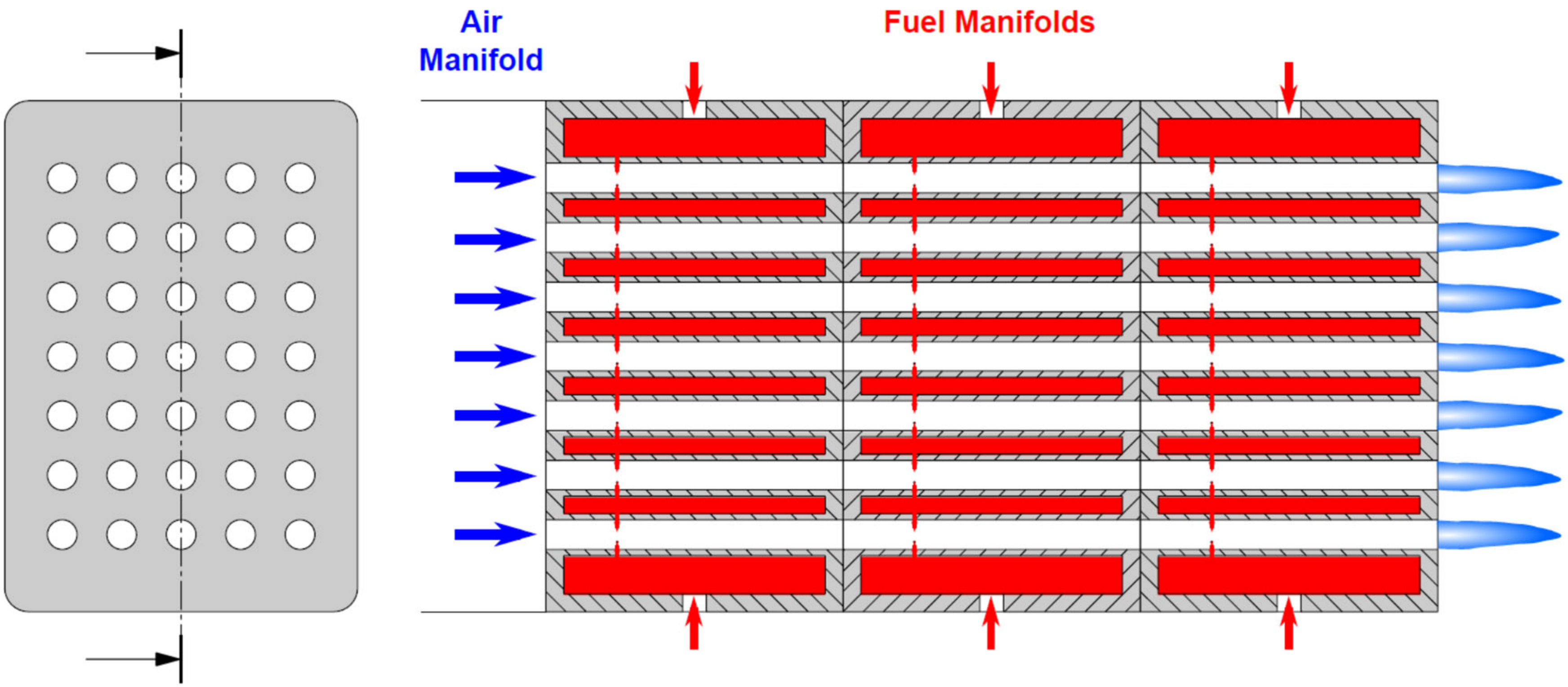
$$X\left[\eta\left(\frac{3}{2}H_2 + \frac{1}{2}N_2\right) + (1-\eta)NH_3\right] + (1-X)NG$$



Premixed laminar flame speed (a) and variation in equivalence ratio for an adiabatic flame temperature of 1705 °C (3100 °F).

Fluid	X	η	$\dot{m}_{max}\,[kg/s]$	$P_{bulk,min}\,[bar]$
H_2	1.0	1.0	0.03	55
N_2	1.0	1.0	0.13	47
NG	0.0	N/A	0.04	47
NH_3	1.0	0.4	0.09	N/A
Air	N/A	N/A	2.2	62

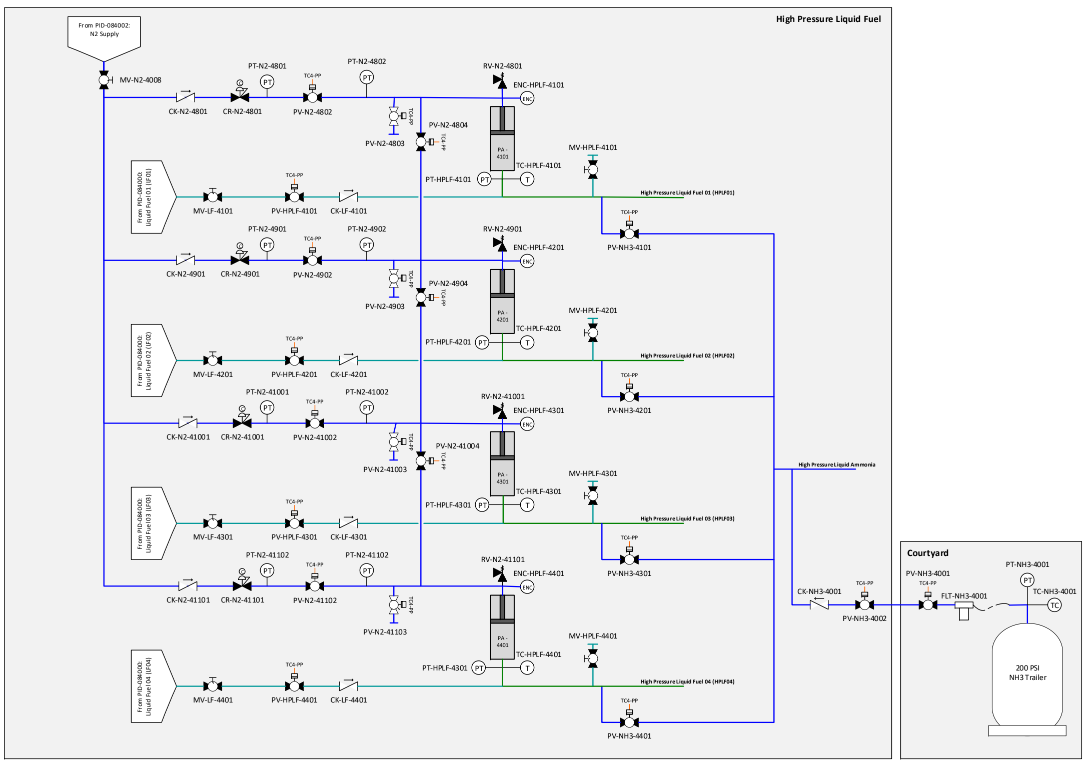
Task 2.1: Multi-Stage, Multi-Tube Micromixing (M^3) Injector



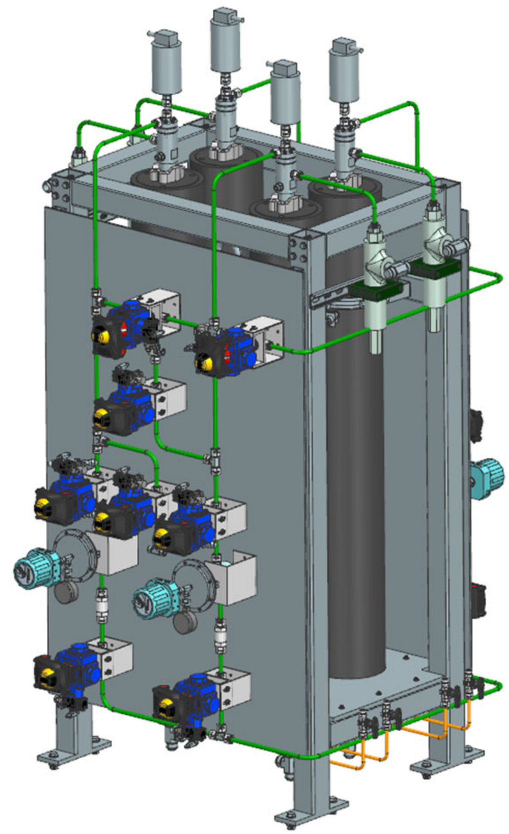
Schematic representation of the proposed M3 injector

Task 2.3: Ammonia Feed System

- Ammonia delivered in saturated state pressurized to target conditions in a piston tank
  - 70 kg of ammonia available per test
  - Maximum supply pressure of 345 bar



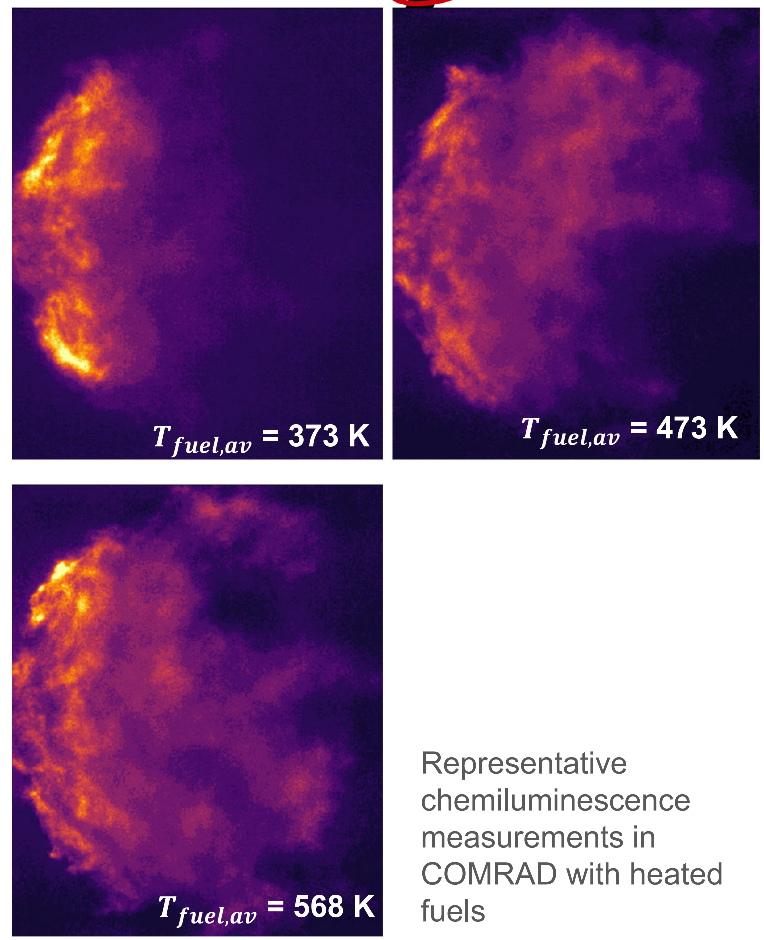
- Ammonia delivered to steady state vaporizer prior to injection
  - Also accommodates liquid ammonia injection



Task 2.3: Ammonia Vaporizer

- 54 kW capacity liquid fuel heater will serve as a vaporizer for liquid ammonia at high pressure for the UTSR experiments
- Fuel heater has been demonstrated to heat FT-SPK (Jet-A surrogate) up to 570 K at 50 bar

Fuel heater stand



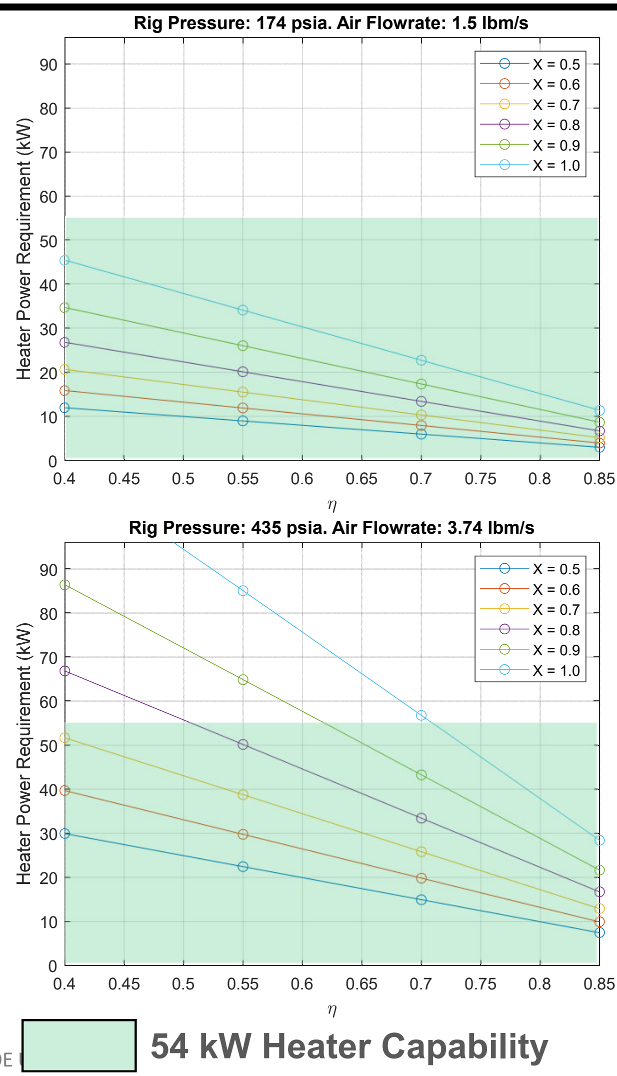
Representative chemiluminescence measurements in COMRAD with heated fuels

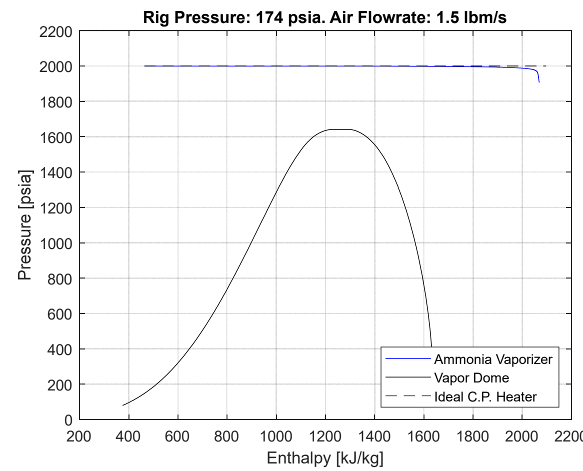
Task 2.3: Ammonia Vaporizer

Power Balance

- High ammonia flowrate conditions (large X, small η) require more power through the vaporizer
- Current configuration of the COMRAD fuel heater can support up to 54 kW in a single circuit
- At OPR ~30, we can simulate an ammonia catalytic decomposition efficiency of 71% with fuel made up of entirely NH_3 and H_2
- Ammonia pressurized up to 345 bar, heated, and expanded down to the target experiment conditions
  - Avoid transition through vapor dome in heater to circumvent phase change and associated instabilities

$$\underbrace{X}_{=1}\left[\eta\left(\frac{3}{2}H_2+\frac{1}{2}N_2\right)+(1-\eta)NH_3\right]+\overset{=1}{\cancel{(1-X)NG}}$$





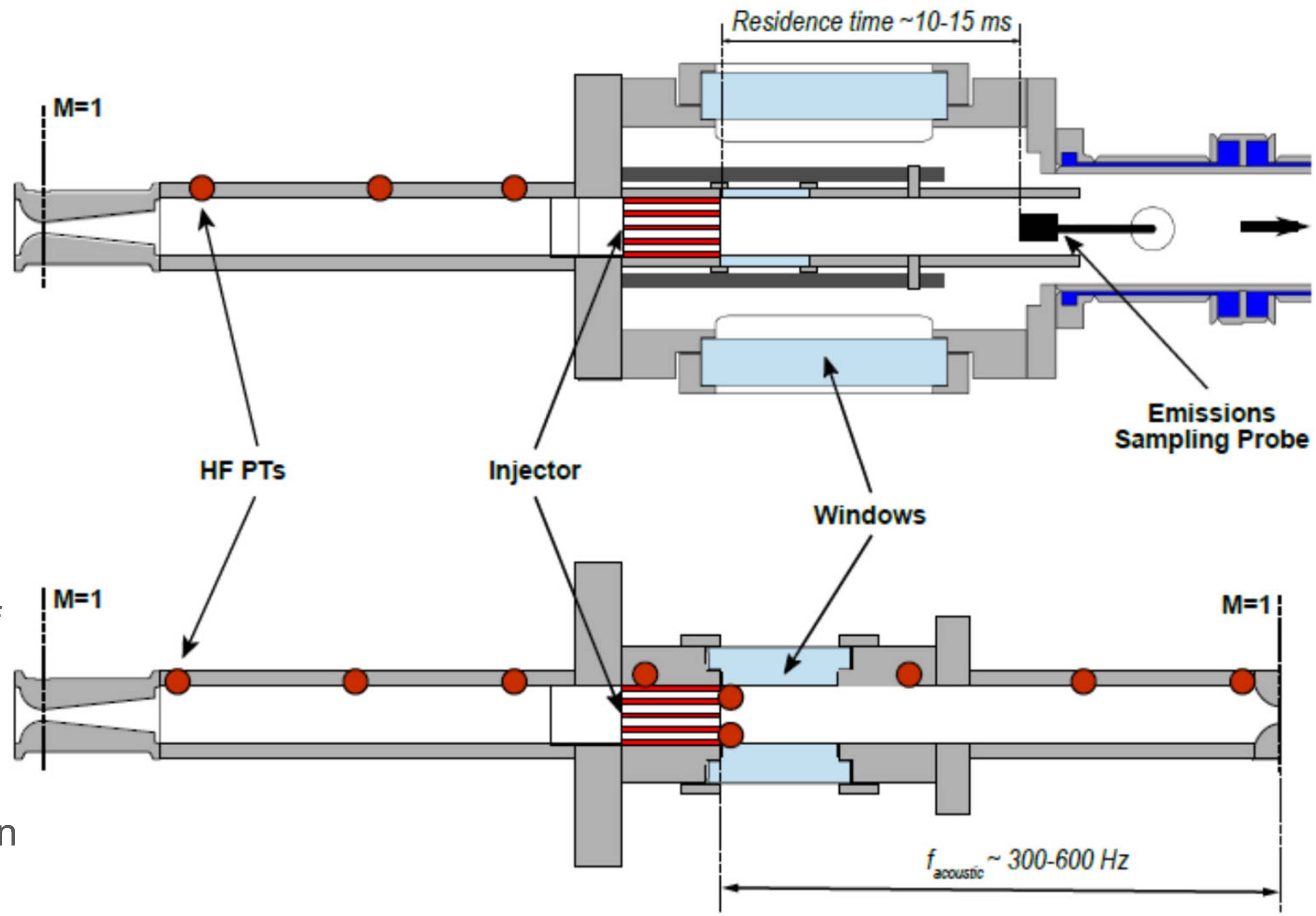
Task 3.0/4.0: Test Configurations

Emissions Configuration

- Steady-state operation for emissions and flame structure characterization with target fuels and operating conditions
  - Large optical access for application of laser based diagnostics
  - FTIR/FID emission characterization system

Dynamics Configuration

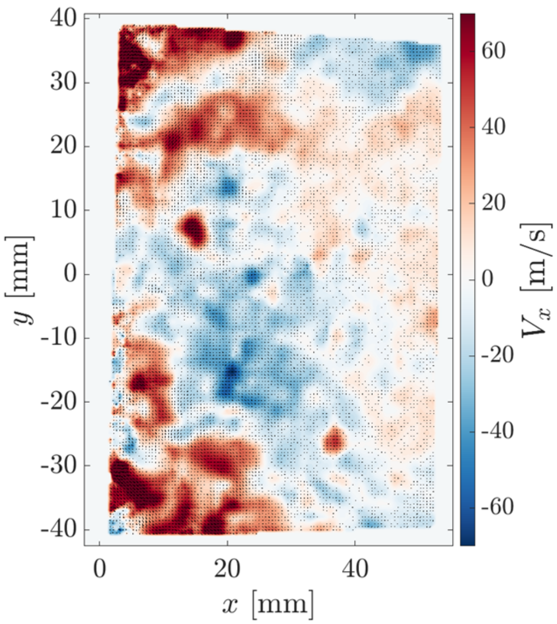
- Modular geometry to tune frequency and amplitude of dynamics with fuels of largely varying HRR and flame temperatures
  - Well-defined boundary conditions
  - Large optical access for application of laser based diagnostics



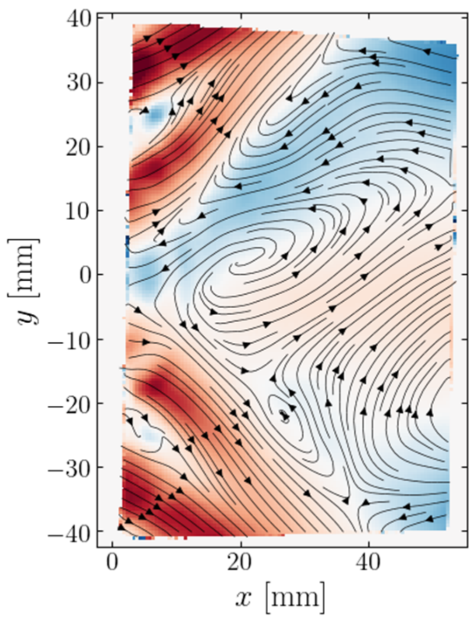
Task 5.0: Advanced Diagnostic Methods

Stereo PIV Vector Fields

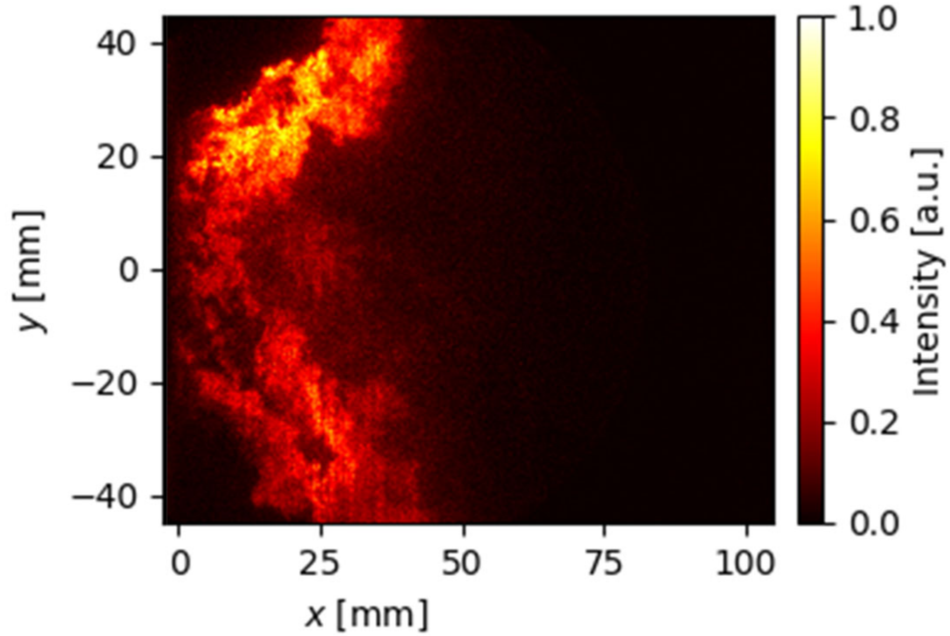
Instantaneous



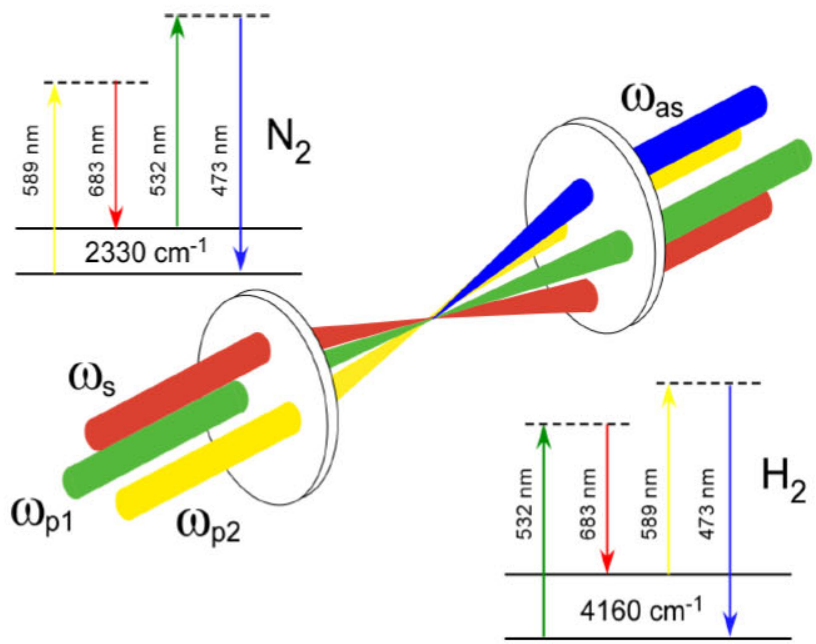
Averaged

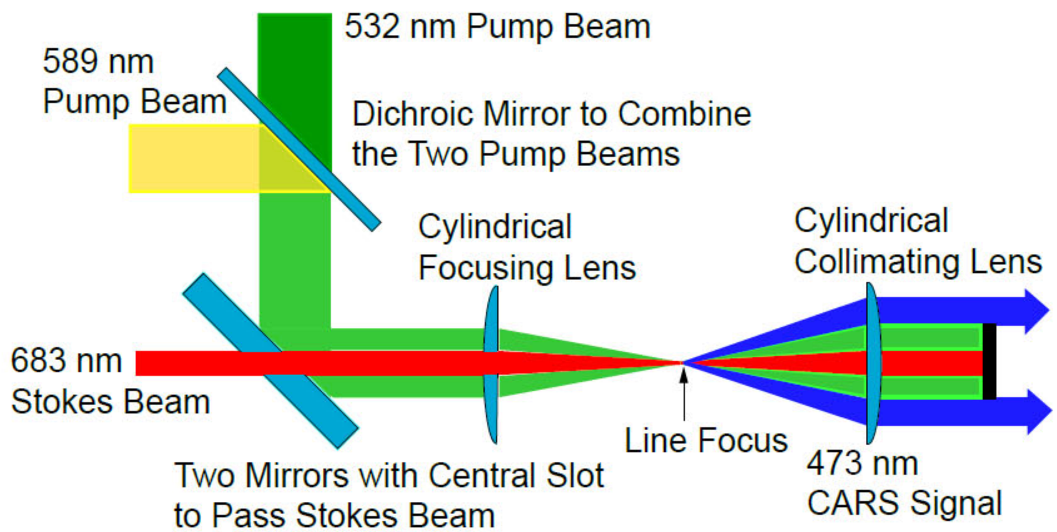


OH PLIF Instantaneous Image



Task 6.0: Dual-Pump CARS Measurements of T, H_2, N_2





External Collaborators

Letters of Support Received from GE, Air Products, and Velo3D

- General Electric: We anticipate receiving design guidance from GE regarding the M3 injector. "GE is supportive of this project for the following reasons
    - Validated combustion models
    - High pressure entitlement
    - CFD modeling accuracy
    - Validated chemical kinetics mechanisms for hydrogen and hydrogen-ammonia blends"

  Shailesh Potnis, Ph.D., Advanced Programs Leader, AEO Product Management, GE Aviation

- Air Products: "Air Products is pleased to support this project with its expertise on Hydrogen and Ammonia. Specifically, Air Products will support the project with guidance on ammonia handling and ammonia to hydrogen ratios to be used in the combustor. Engineers from Air Products will provide support through periodic teleconference meetings with researchers at Purdue." Ranjit Ghosh, Ph.D., Manager, Applications R&D & Growth

- Velo3D: "We anticipate personnel from Velo3D will interact closely with Profs. Lucht and Slabaugh by providing input on the design and manufacturability of the multi-stage micromix injectors. The proposed research program will be of great interest and value to future Velo3D efforts to promote additive manufacturing enabled solutions for hydrogen-based gas-turbine systems." Zach Murphree, Ph.D., Vice President of Global Sales and Development

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- COMRAD test rig is operational and laser diagnostics methods that will be used for the UTSR experiments are currently being applied in an aviation gas turbine experiment.
- Design of the new ammonia handling system and the ammonia vaporizer is complete.
- Design processes for the new emissions (steady state) and dynamics (unsteady) test sections are underway.
- Kickoff meetings with external collaborators have been scheduled.

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