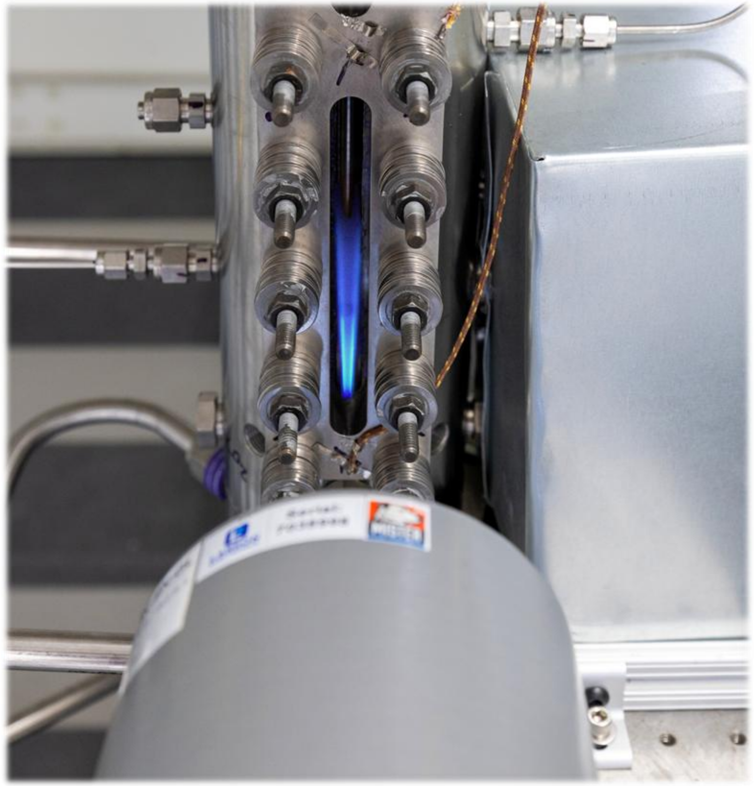
Investigation of Ignition and Stabilization of CO_2-Diluted Methane-Oxygen Flame Above Carbon Dioxide Critical Pressure



sCO_2 Symposium

March 3th, 2026

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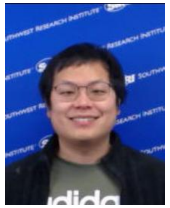
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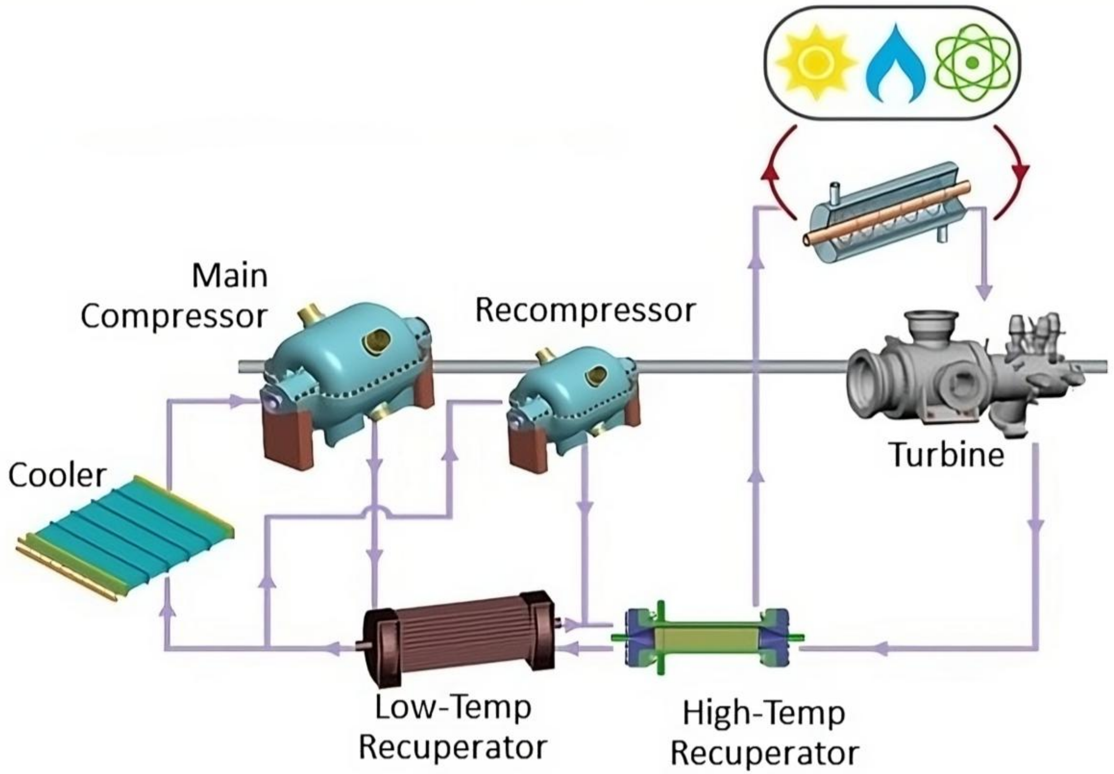
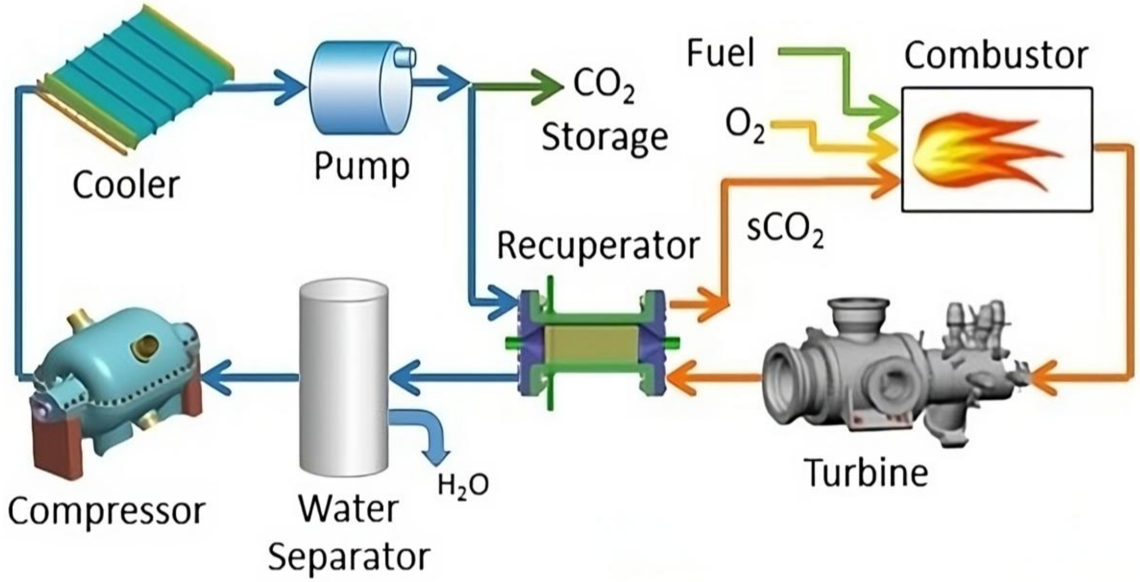
Introduction to Direct Fired sCO_2 Power Cycles



Cycle Diagram of Indirect Cycle

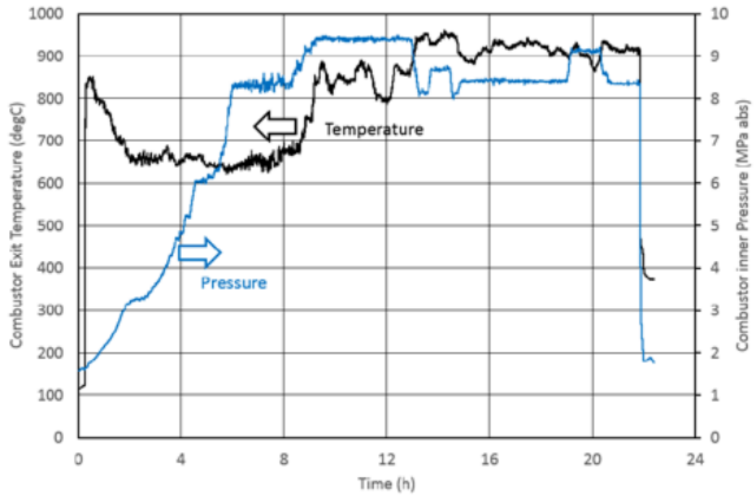


Cycle Diagram of Direct (Allam-Fetvedt) Cycle

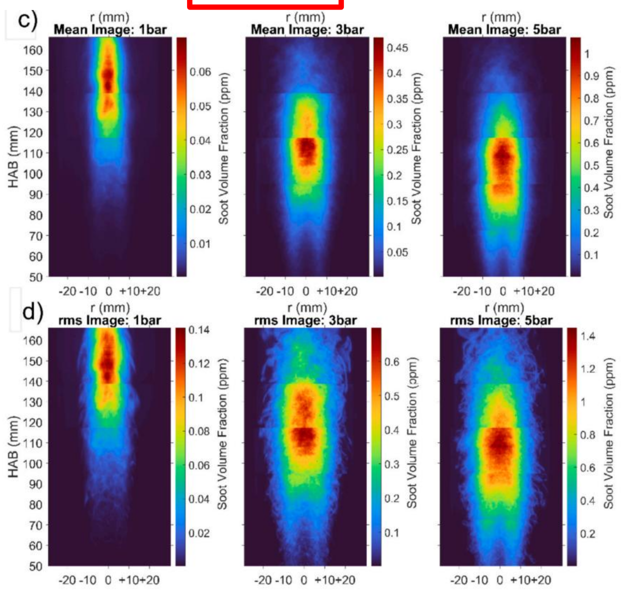
Source: U.S. Department of Energy

Previous Work

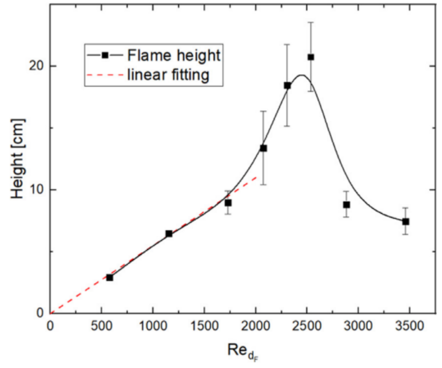
- **Suzuki et. al. (Toshiba)** – demonstration of 50 MW_{th} oxy-fuel combustor for Allam-Fetvedt cycle up to ~90 bar
- **Bukar et. al. (KAUST)** – Pressure effects on soot formation in turbulent flames up to 5 bar
- **Lee et. al. (KAIST)** – Flame stabilization and soot emissions for methane jet flames with CO_2-diluted oxy-fuel combustion up to 5 bar
- **Many more!**



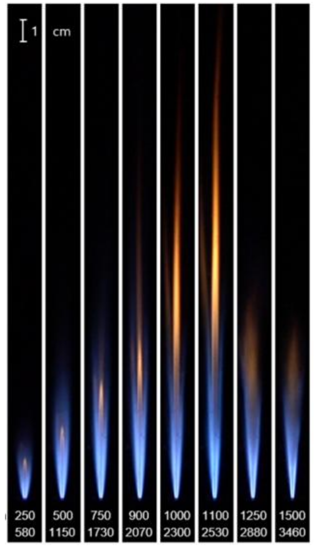
Suzuki et al., 2019



Bukar et al., 2025



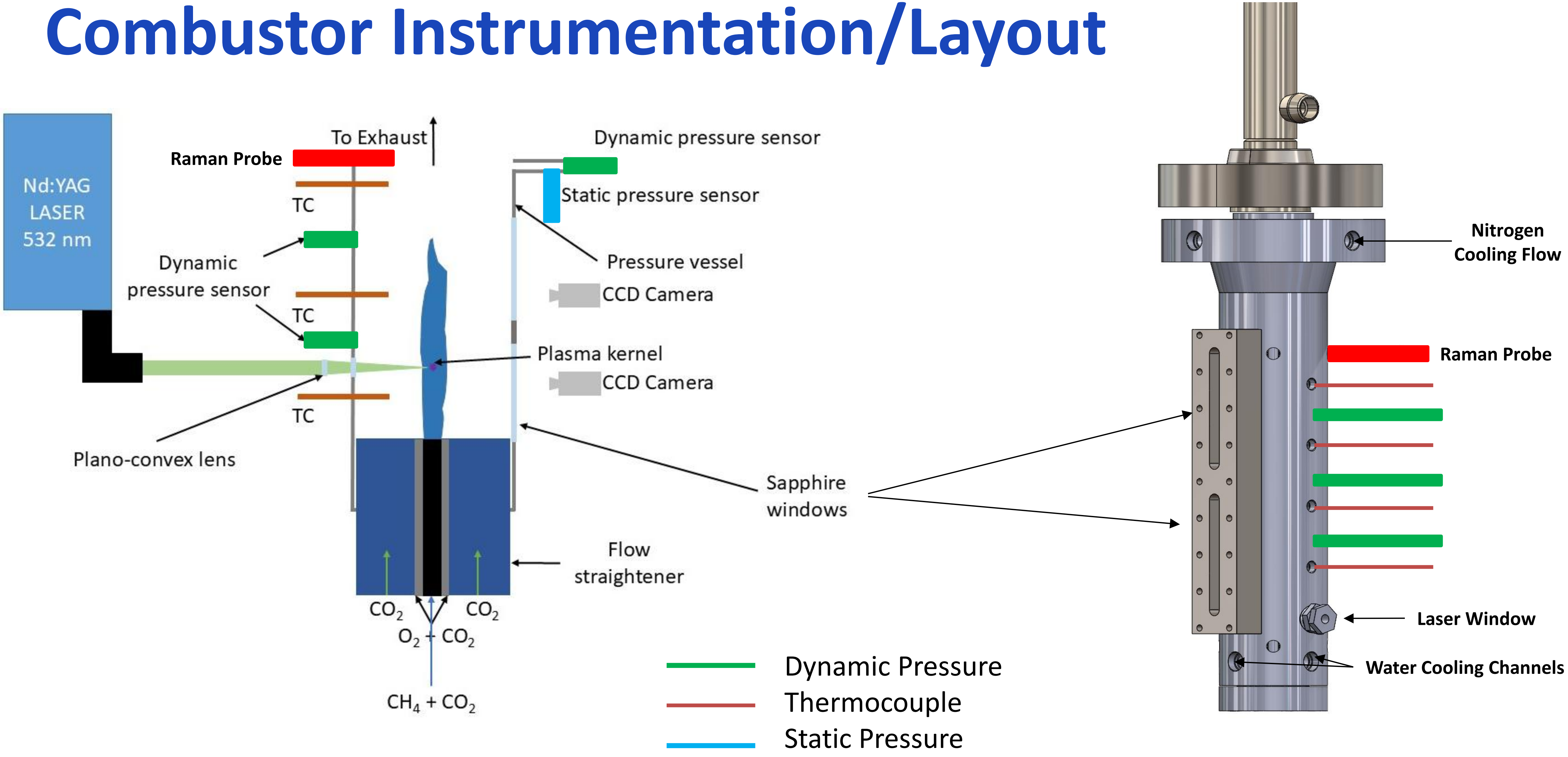
Lee et al., 2021



Scientific Objectives

1. Verify operability at high acid gas concentrations above critical point of CO_2
2. Examine ignition characteristics and pressure effects on CO_2-diluted methane flames
3. Develop and validate a numerical model to simulate this combustor configuration – the results of this validation are not part of this presentation

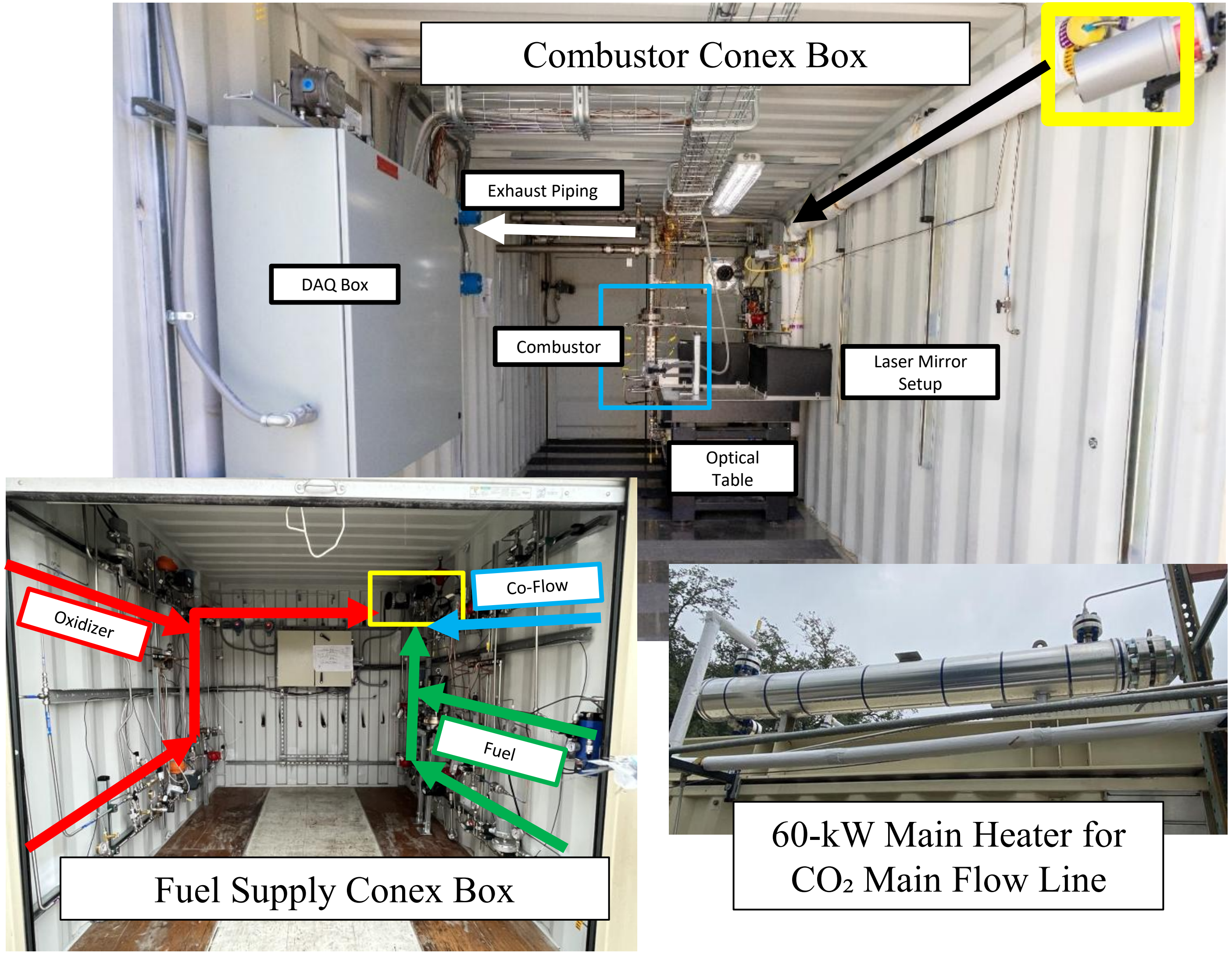
Combustor Instrumentation/Layout



SwRI kW-Scale Oxy-Fuel Combustion Test Facility

Current Rig Capabilities:

- Up to ~0.15 kg/s CO_2 at ~1600 psig
- Up to 150-kW_{th} Power
- Fuel & Oxidizer Mixing Capabilities
- Laser Ignition, Optical Access
- In-Situ Emissions Measurements
- Multiple Heaters (up to 60-kW)
- Combustor Pressures up to 100 bar



Testing Methodology

1. Ignition Testing
   - Laser ignition light off
   - CO_2 dilution in oxidizer and fuel lines
   - Ignition pressure rise

2. Steady State Combustion Testing
   - CO_2 dilution in oxidizer and fuel lines
   - Explore methodology to climb in pressure at steady state
   - Explore flame characteristics (soot, length, shape)

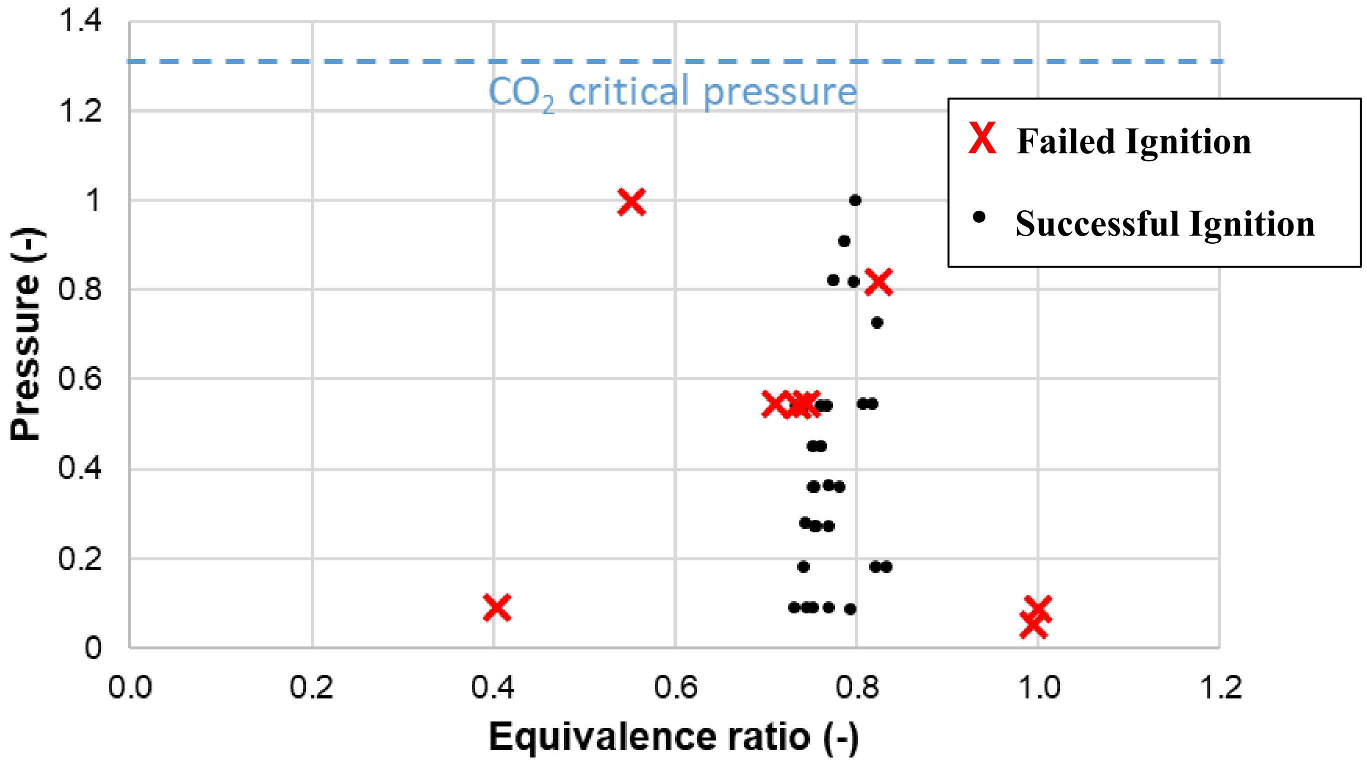
Variable	Collection Rate	Time of Collection
Static Pressure	1 Hz	All Day
Temperature	1Hz	All Day
Dynamic Pressure	10 kHz	At Ignition
Flame Natural Luminosity	~100 fps	At Steady State Conditions

Data Collection Rates for Various Measurements

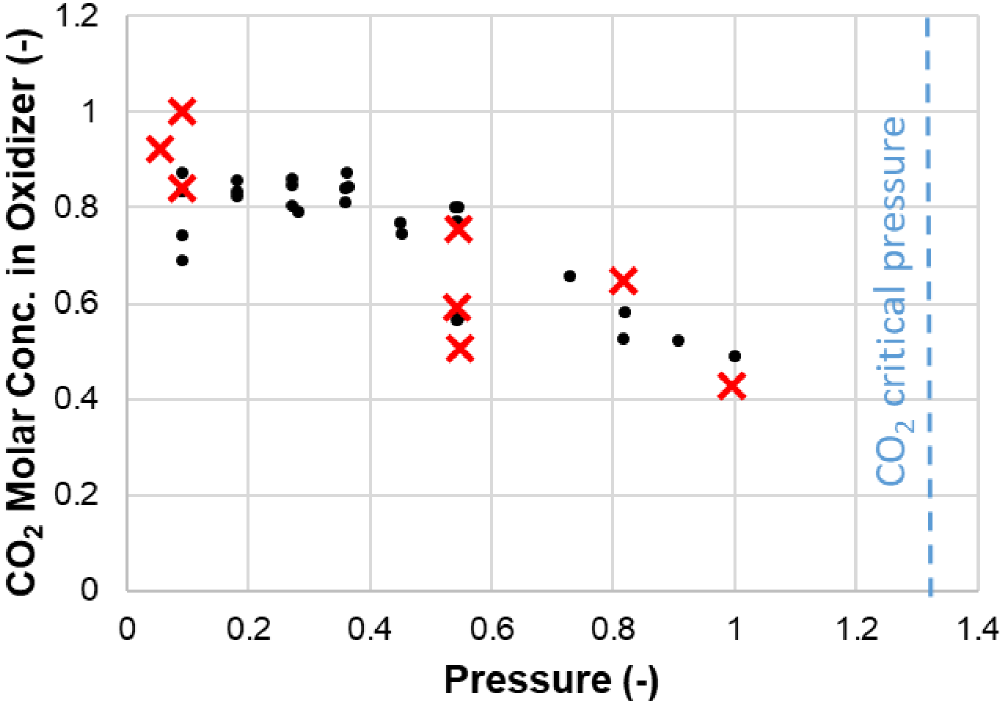
Ignition Test Results

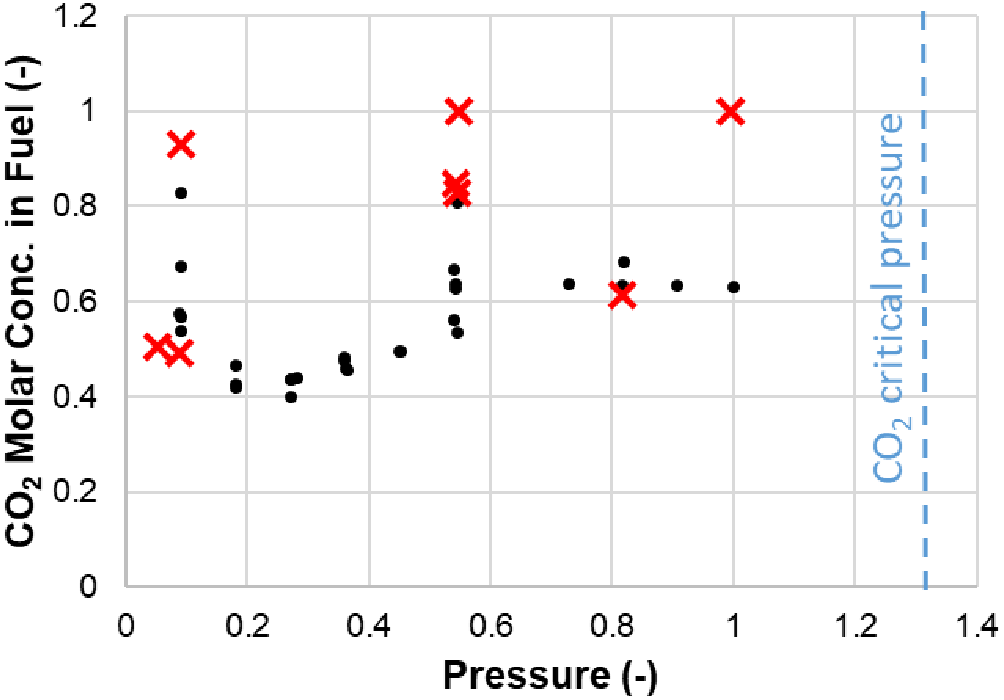
Ignition Test Data: Equivalence Ratio

- Ignitions around the equivalence ratio relevant to power cycles were most successful
- Failed attempts deviating from average successful E.R. likely due to reduced reactivity
- **Ignition success appears to be more dependent on equivalence ratio than pressure**



Ignition Test Data: CO_2 Concentration

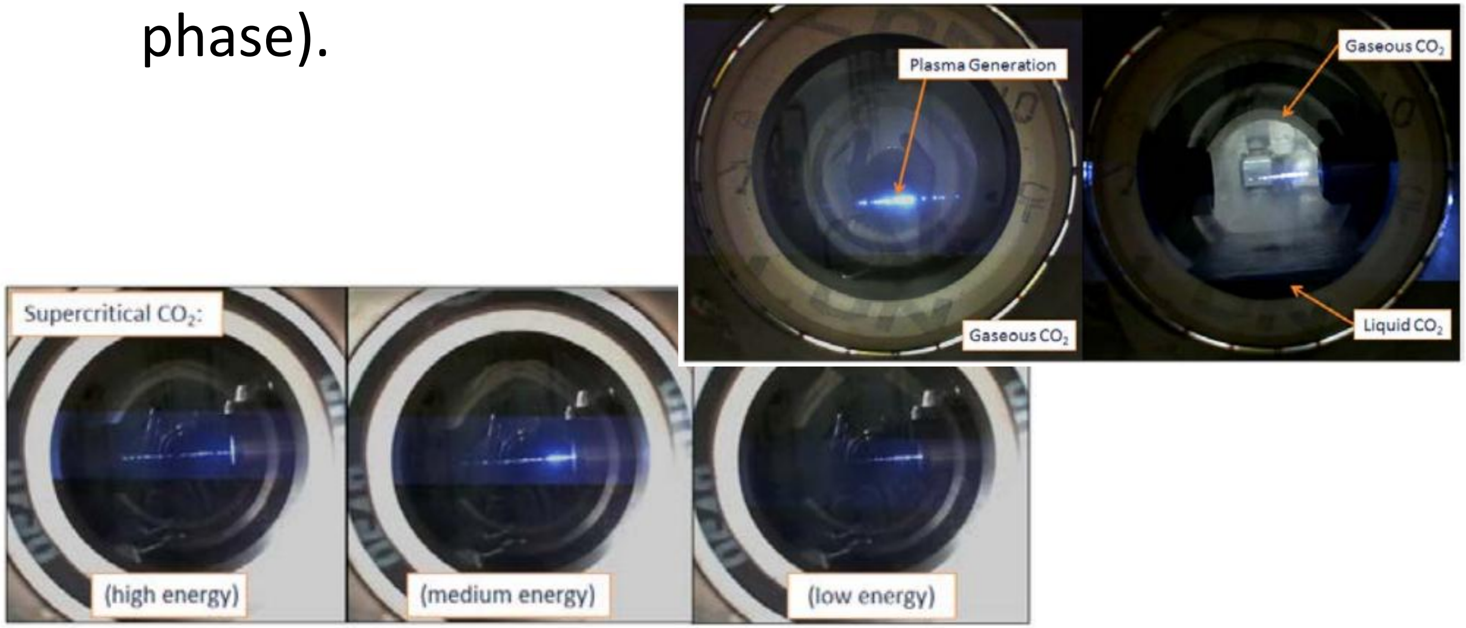




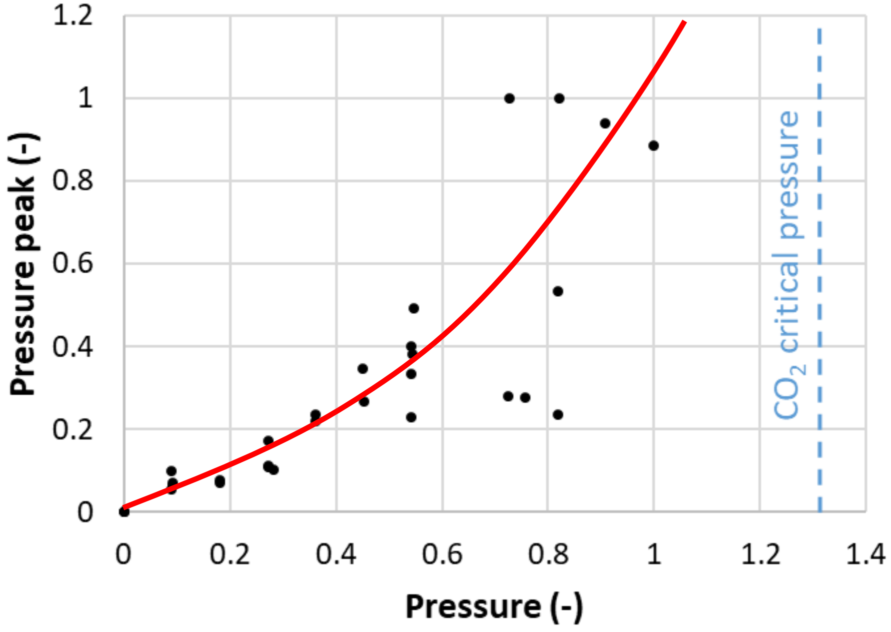
- Little dependence on CO_2 concentration in the oxidizer stream
- **Flame seems to be more sensitive to changes in CO_2 concentrations in the fuel stream** (>50% of failures above 0.6 CO_2-Fuel)

Ignition Test Data: Pressure Rise

- Results reproducible between test points
- Pressure rise at ignition remained below 1% of system pressure
- **As pressure increased, pressure rise became more variable** (possibly more stochastic post-ignition phase).



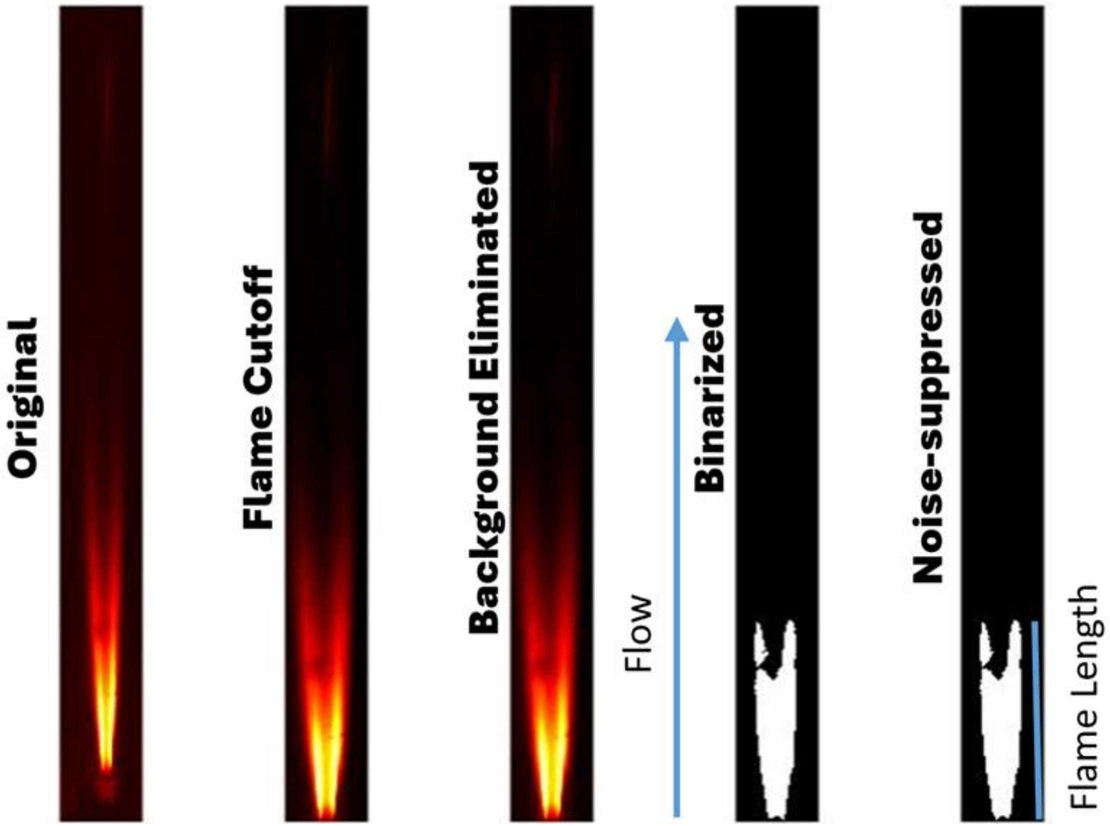
Katcher et al., 2019



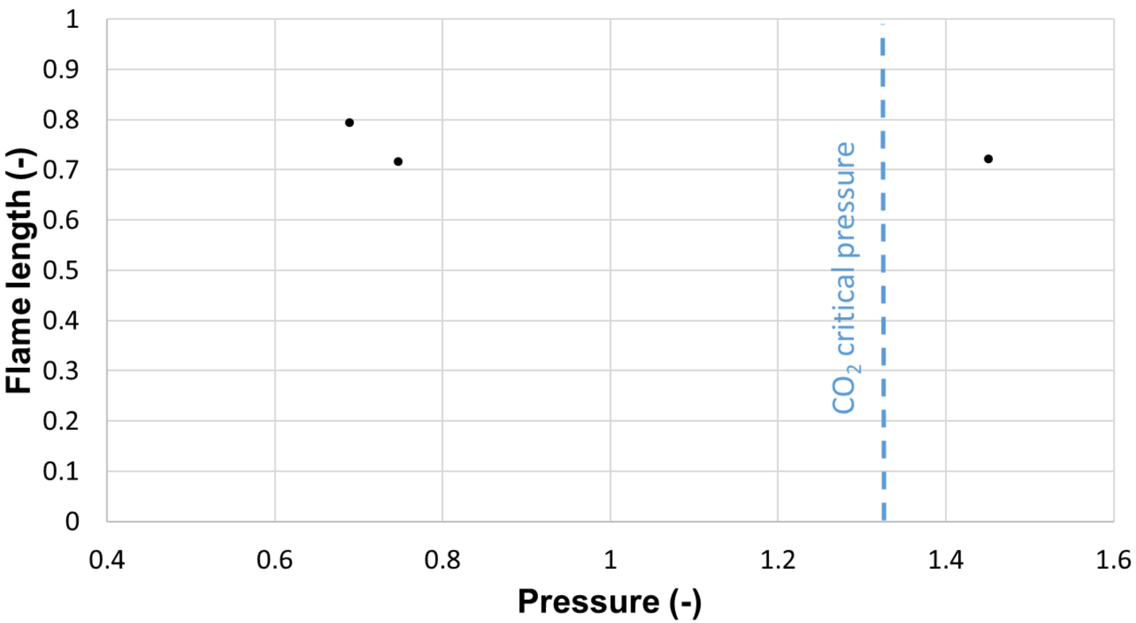
Ignition pressure was slowly increased to avoid overpressure event.

Steady State Combustion Test Results

Flame Length Data



Example of Flame Image Processing for Flame Length Measurement



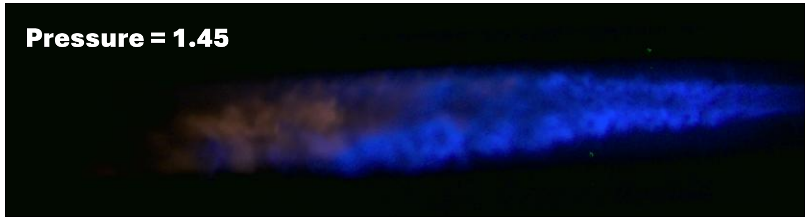
Flame Length at Constant Fuel-CO_2 Concentration

- **Pressure appears to be have minimal impact on flame length**
  - Likely due to thermal power scaling with pressure
- More data is needed to confirm this hypothesis

Flame Length Imaging

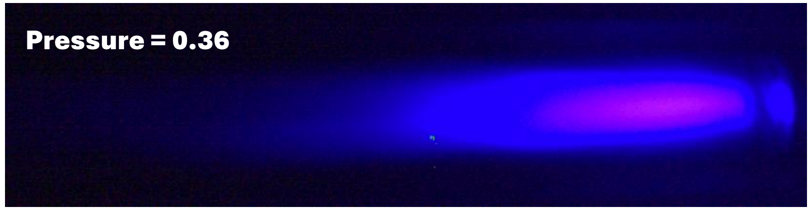
Variables During Image Capture:

- Camera Positioning
- Changes in Shutter Speed/Exposure
- Degradation of Camera
- Use of CH* filter

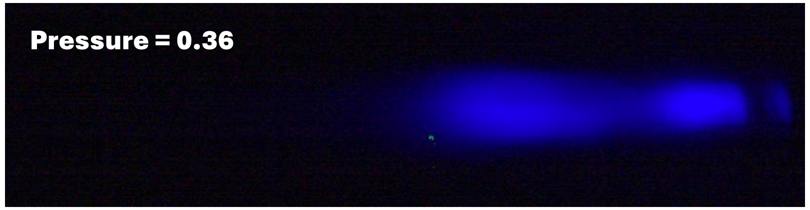


Exp: 25

Exp: 50

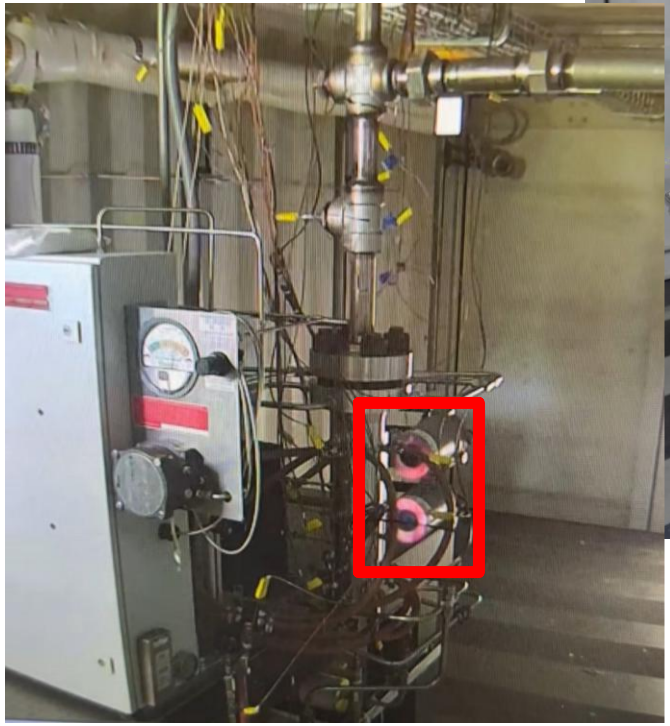


Exp: 30000*

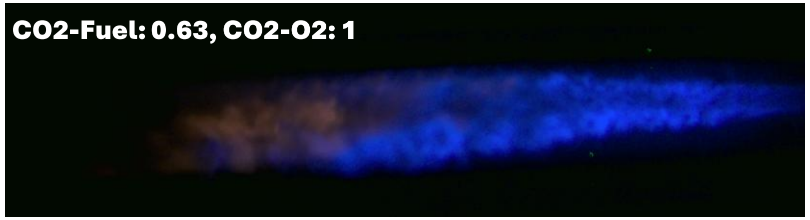


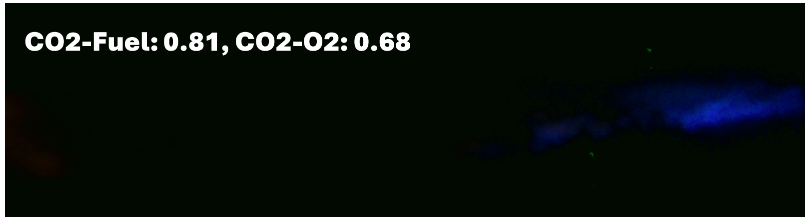
Exp: 25000*

Exp: 50000



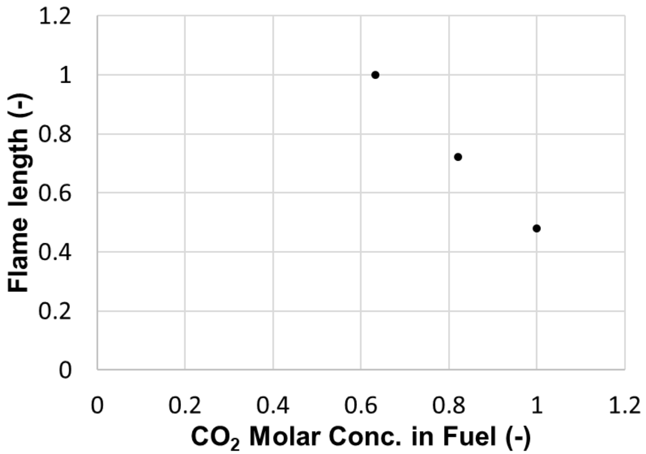
Flame Length vs CO_2 Concentration

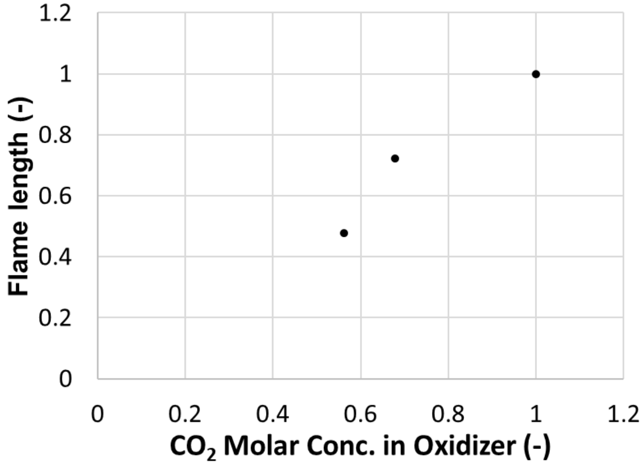




Above Conditions are Above CO_2 Critical Point

- **Flame length decreased with higher CO_2-fuel concentrations**
- More soot observed at lower CO_2-fuel concentrations
- Further investigation is needed to decouple effects of CO_2 concentrations in fuel and oxidizer



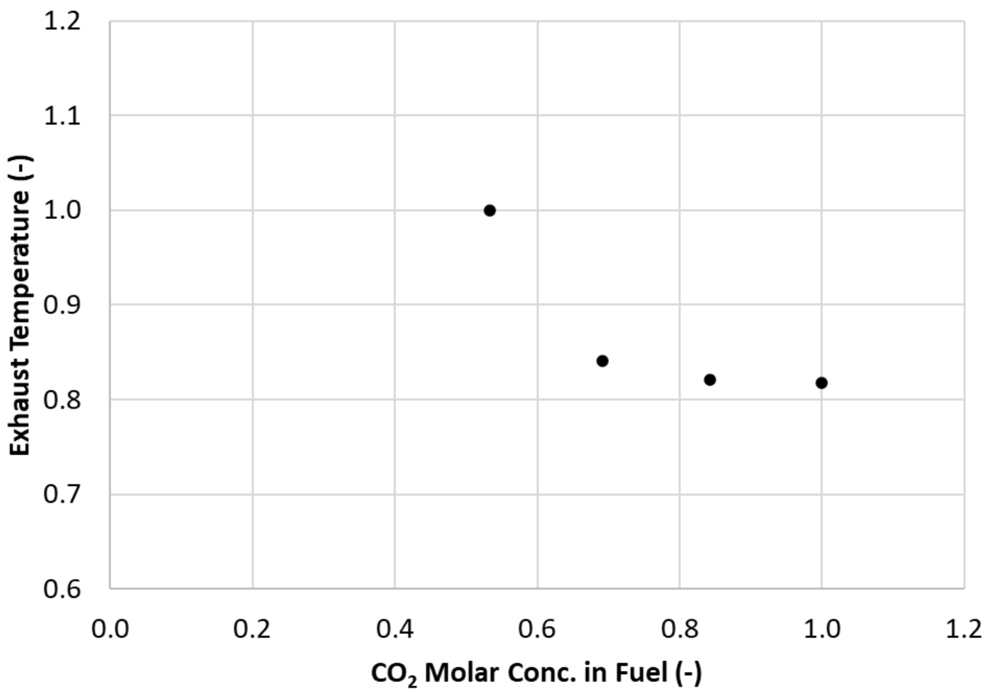


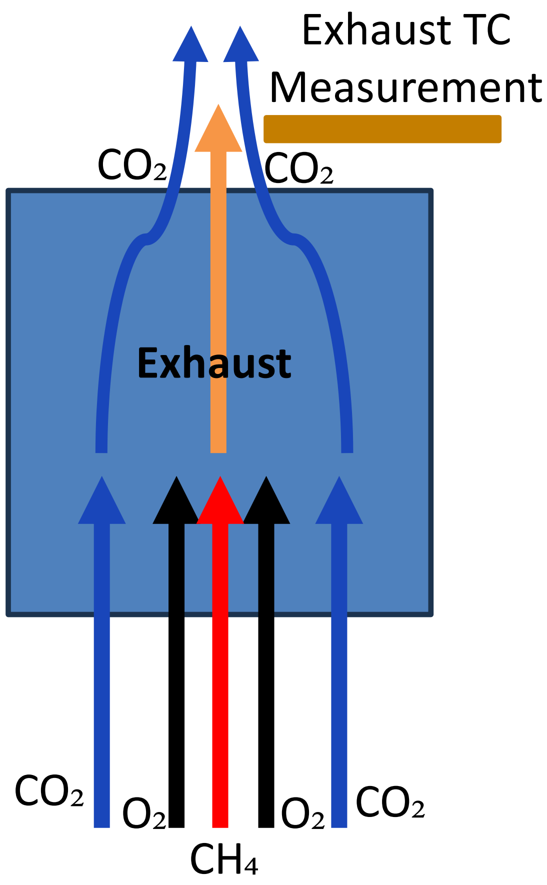
Exhaust Temperature vs CO_2 Concentration

- Higher CO_2 concentrations

→less combustion propensity

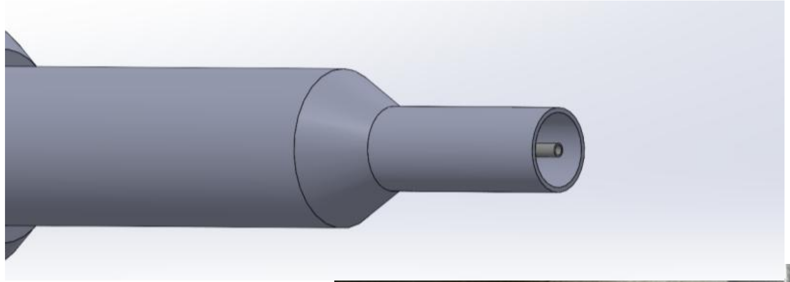
- Co-flow may have homogenized flow
- More data necessary to draw conclusions

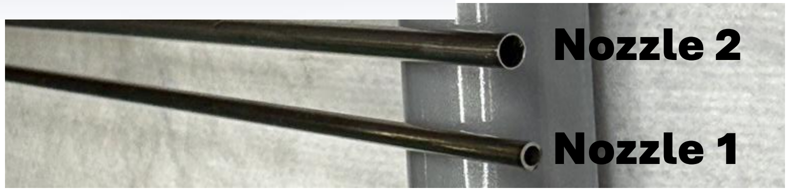


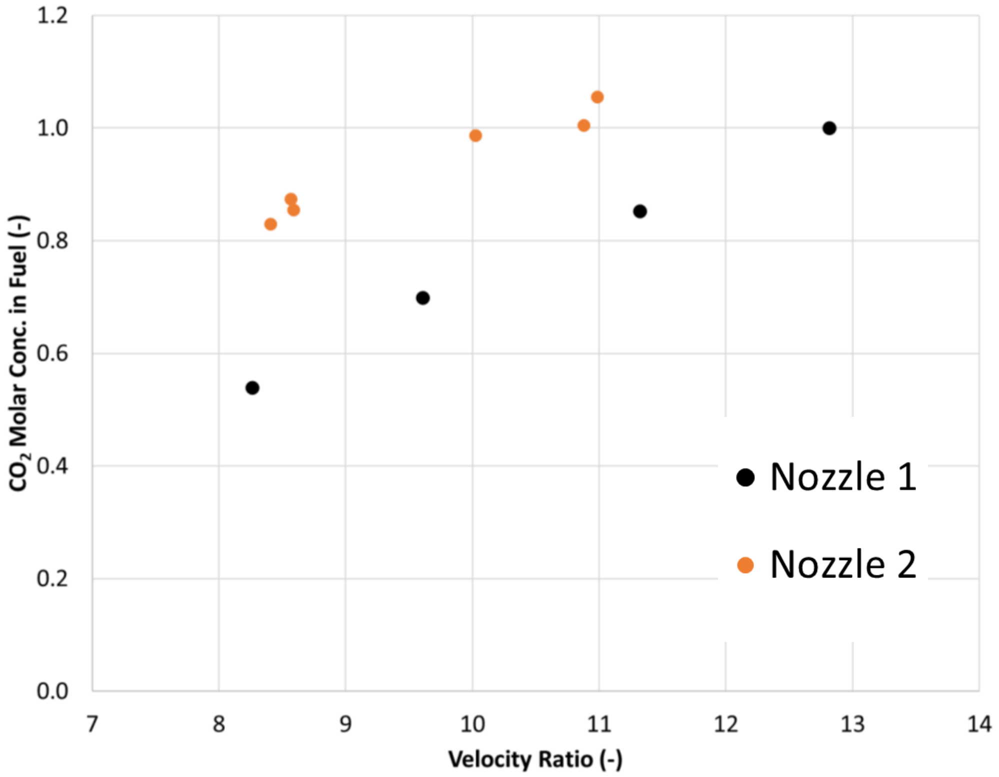


Velocity Ratio vs CO_2 Concentration

- Nozzle size drove exit velocity at constant CO_2 concentrations
- Increasing nozzle size allowed for higher CO_2 concentrations in fuel stream
- **Takeaway: Reactivity seems to be a bigger driver than mixing for flame stability**

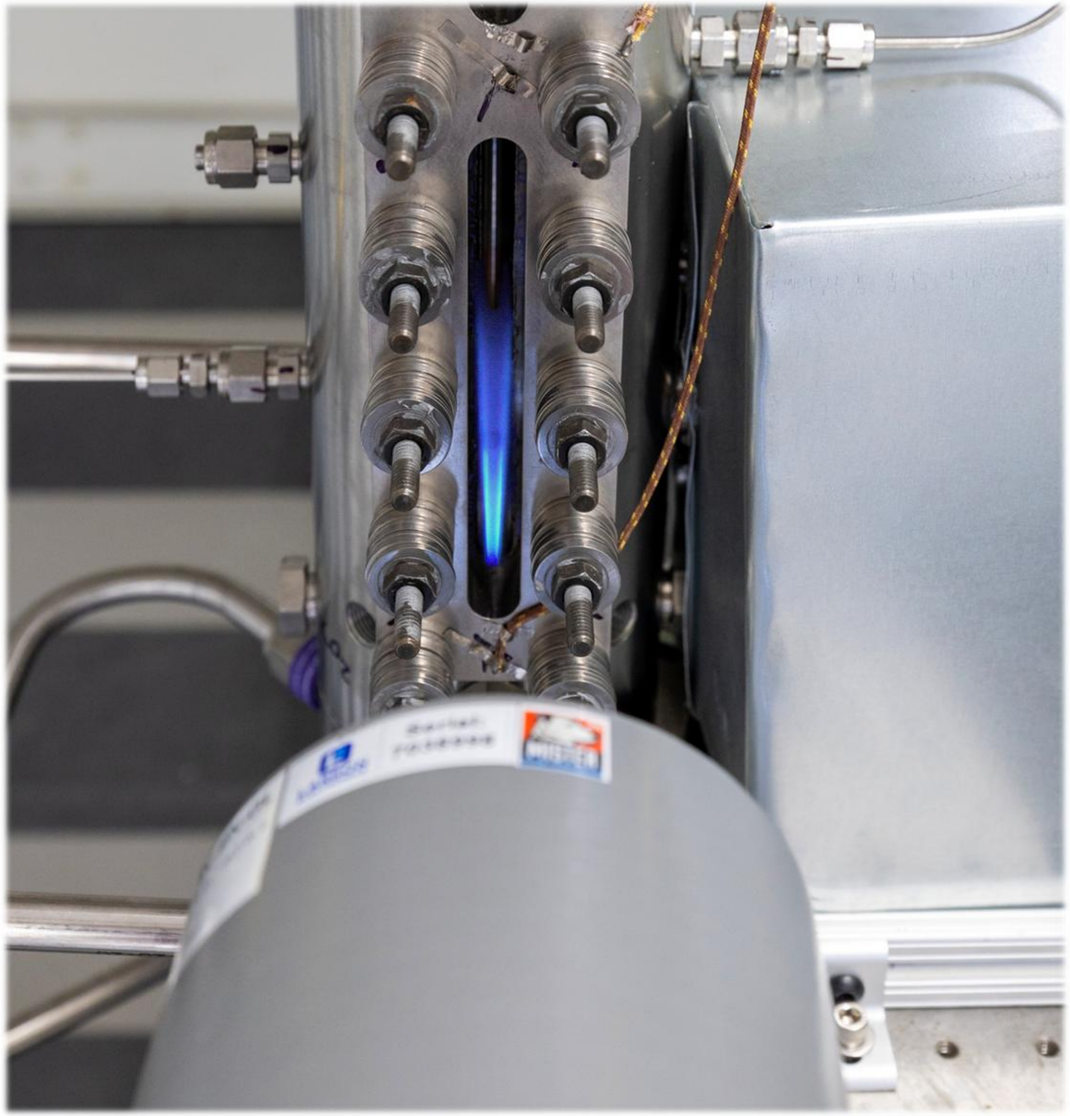






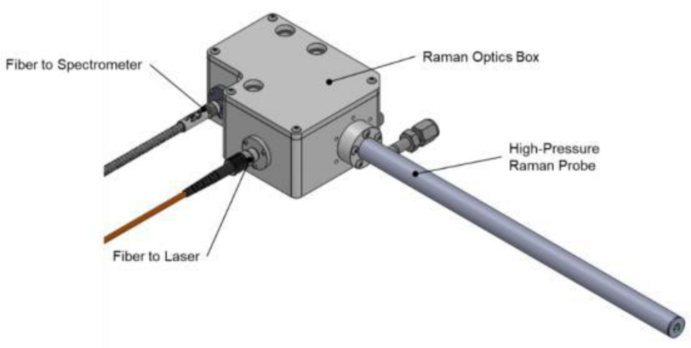
Conclusions

- The flame is more sensitive to CO_2 concentrations in fuel than oxidizer
- Ignition is sensitive to equivalence ratio
- Flame is more sensitive to reactivity than mixing
- Oxy-fuel combustion above the critical point of CO_2 is challenging to reach and maintain
- More testing is needed to gather data above the critical point

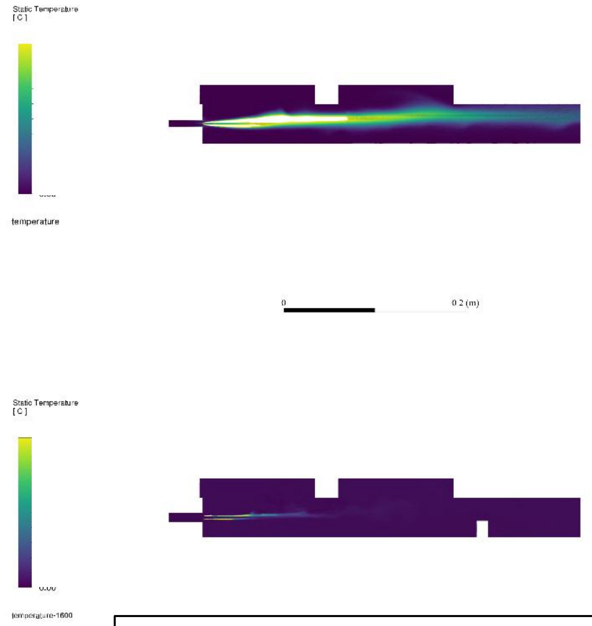


Future Plans

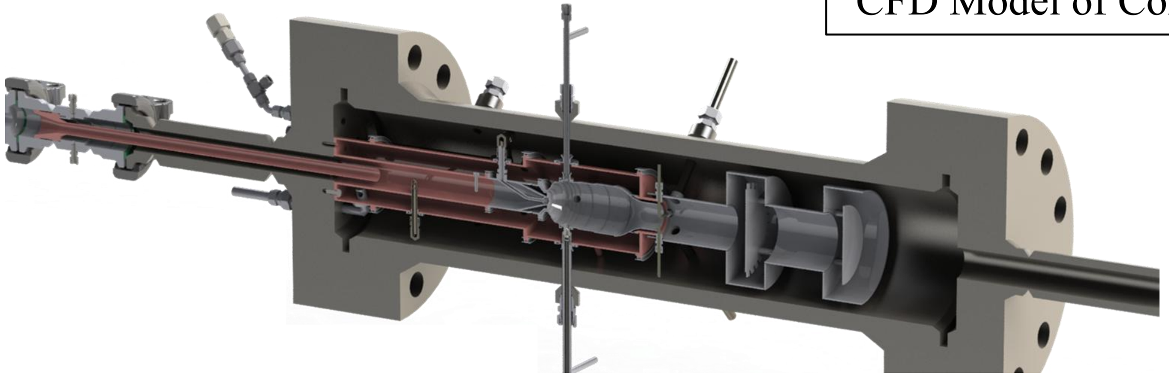
- Increase thermal power
- Collect more data to validate a numerical model
- Develop Raman spectroscopy system
- Design a more compact ignition laser setup



Raman Laser



CFD Model of Combustor



MW Oxy-Fuel Rig

Contact Information

Thank you!

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BACKUP SLIDES

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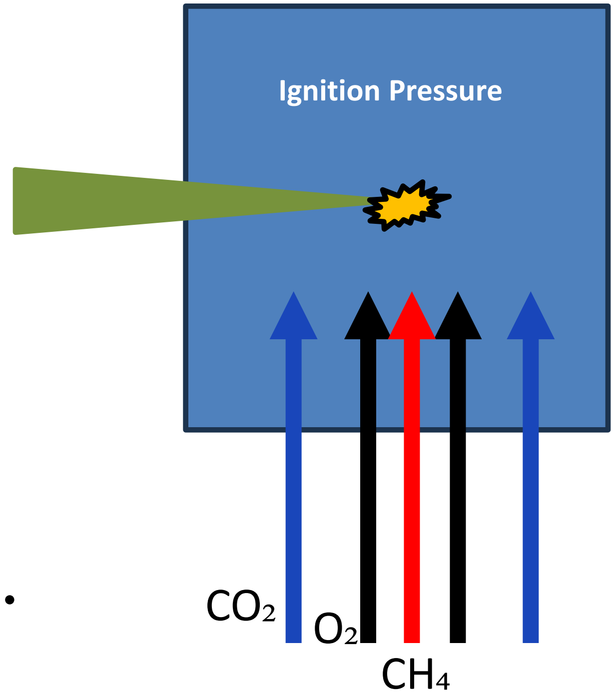
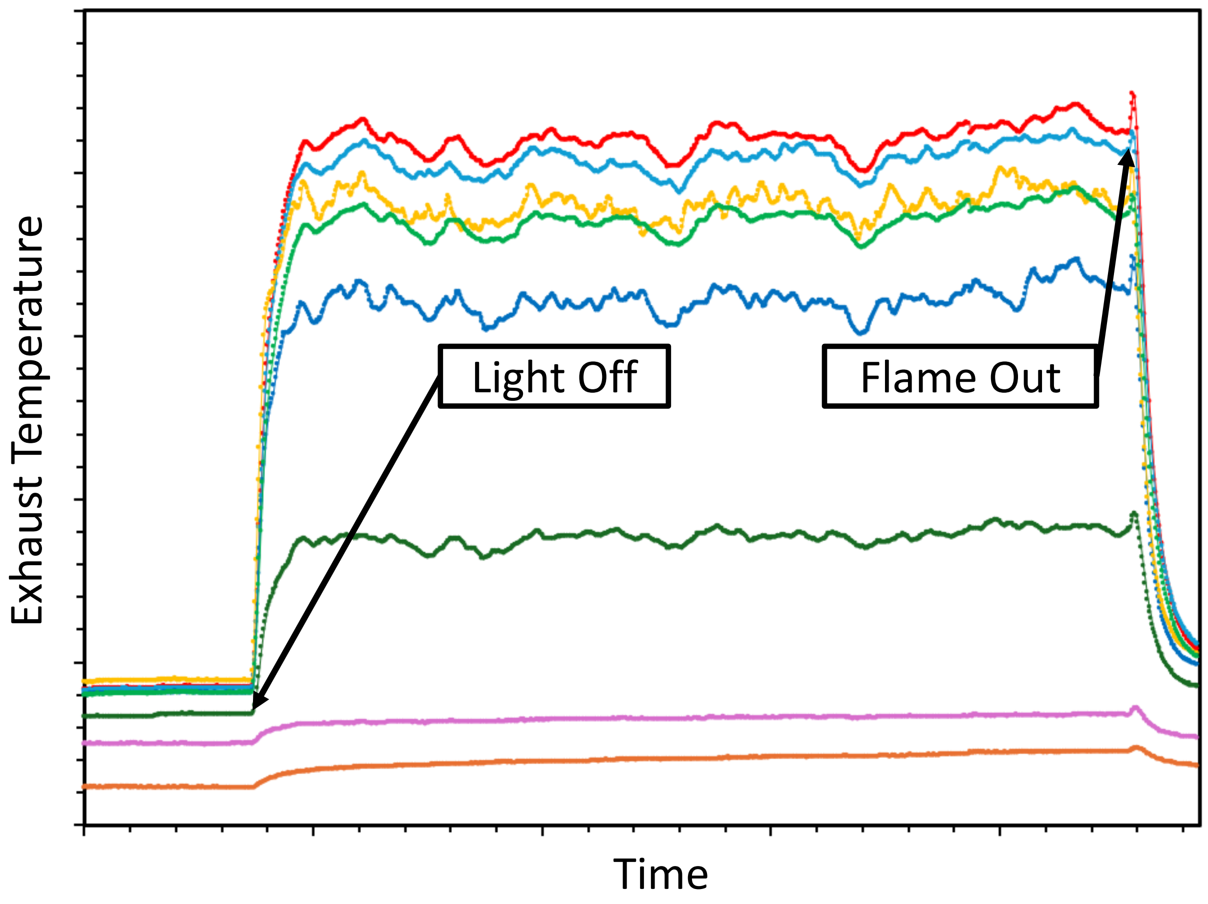
Test Methodology



1. Pressure in combustor dialed in
2. O_2 flow rate dialed
3. Introduce CH_4
4. 10s window for laser kernel to ignite mixture.
5. Laser off
6. Fuel, oxidizer, and CO_2 were scaled with pressure to maintain nozzle exit velocity

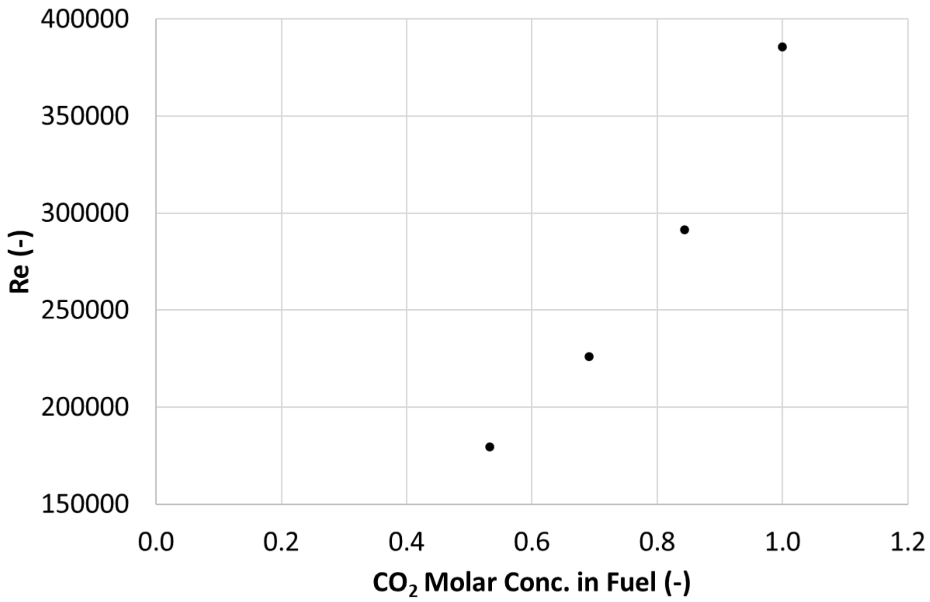
Example of Data Collection



Real-Time Temperature Data of Light Off Testing

Reynold's Number vs CO_2 Concentrations

- Reynolds number varied due to:
  1. Nozzle size
  2. **Nozzle exit velocity**
  3. **Nozzle exit density**
- CO_2 contributed to both (2) and (3)
- **Flame became more turbulent with increasing CO_2 in fuel**



Fluid	Density [kg/m³]	Dyn. Viscosity [μPa-s]
CO_2	132.49-241.45	20.148
CH_4	40.66-50.98	14.375
Ratio	~4	~1.4

* Between 160ºF (~310K) and 200ºF (~365K) at 73.8 bar from REFPROP

$$Re = \frac{\rho V D}{\mu}$$

SwRI CO_2 Capabilities

Supercritical Transformational Electric Power (STEP) Pilot Plant Test Facility

- **Objective**:
- Advance the state of the art for high temperature sCO2 systems
- Design, construct, and operate a *reconfigurable* 10 MWe sCO2 Pilot Plant Test Facility

- **Key Advances:**
- Turbomachinery for 715°C
- 740h Primary HX & Piping @ 250 bar, 715°C,
- Recuperator scale up at 600°C design temperatures
- Plant Controls and Operability

- **Project Team & Timeline**:
- $169 million Project and Building Budget with $134 million Federal
- System commissioned and generating electricity
- Project Team: U.S. Department of Energy (DOE NETL), Gas Technology Institute (GTI), Southwest Research Institute (SwRI), and General Electric Global Research (GE-GR)

- **Achievements**:
- Plant tested reaching 8.3 MW turbine power and 4 MWe to grid in simple recuperated cycle
- Plant reconfigured for Recompression Brayton Cycle (RCBC)

Design, Fabrication, Testing of 10 MWe-Scale Machinery

SunShot: Development of a High Efficiency 700°C sCO2 Hot Gas Turbo-Expander

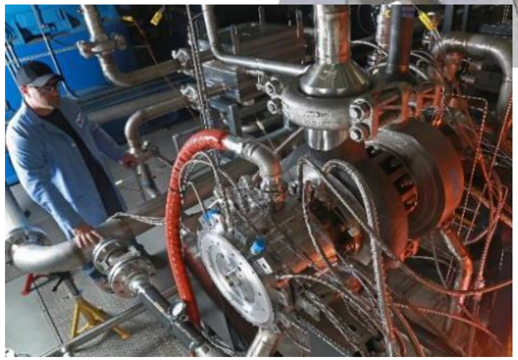
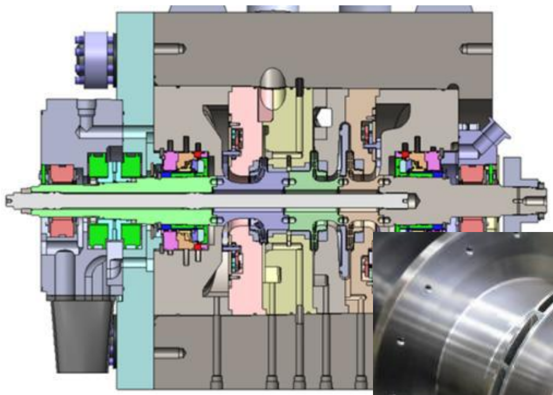
- 1MWe sCO2 flow at high temperatures and pressures for mechanical design validation
- Successful operation up to 715°C, 245 bar

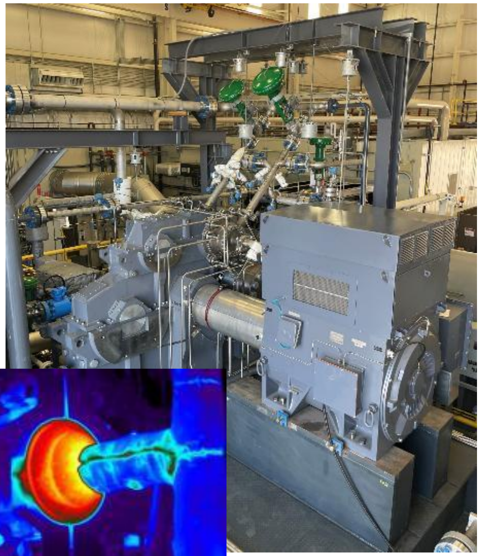
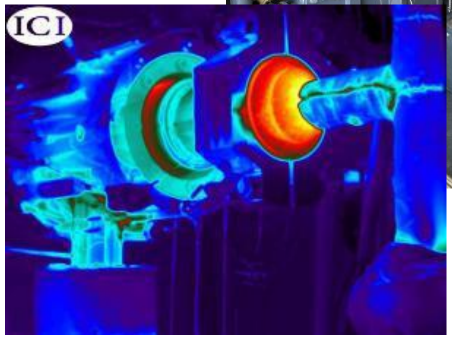
GE-Apollo High-Efficiency sCO2 Centrifugal Compressor Development

- Develop high-efficiency sCO2 compressor Efficiency of 80%
- >2:1 flow range at constant speed
- 10 MWe sCO2 compressor mechanical and aero performance

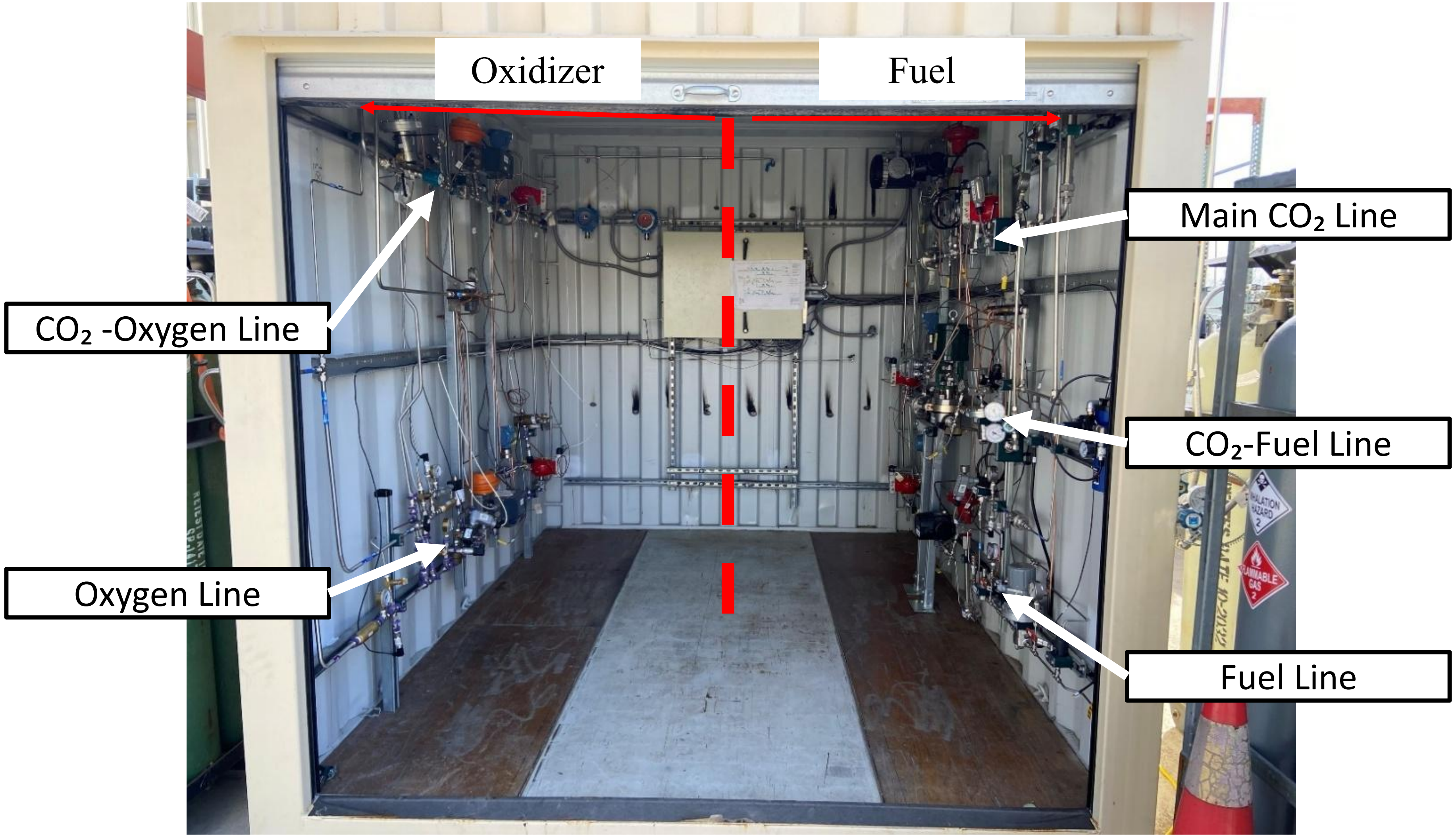
Ultra High Efficiency **Integrally-Geared sCO2 Compander**

- Combine compression and expansion stages into a single integrally geared housing connected to a low-speed motor/generator

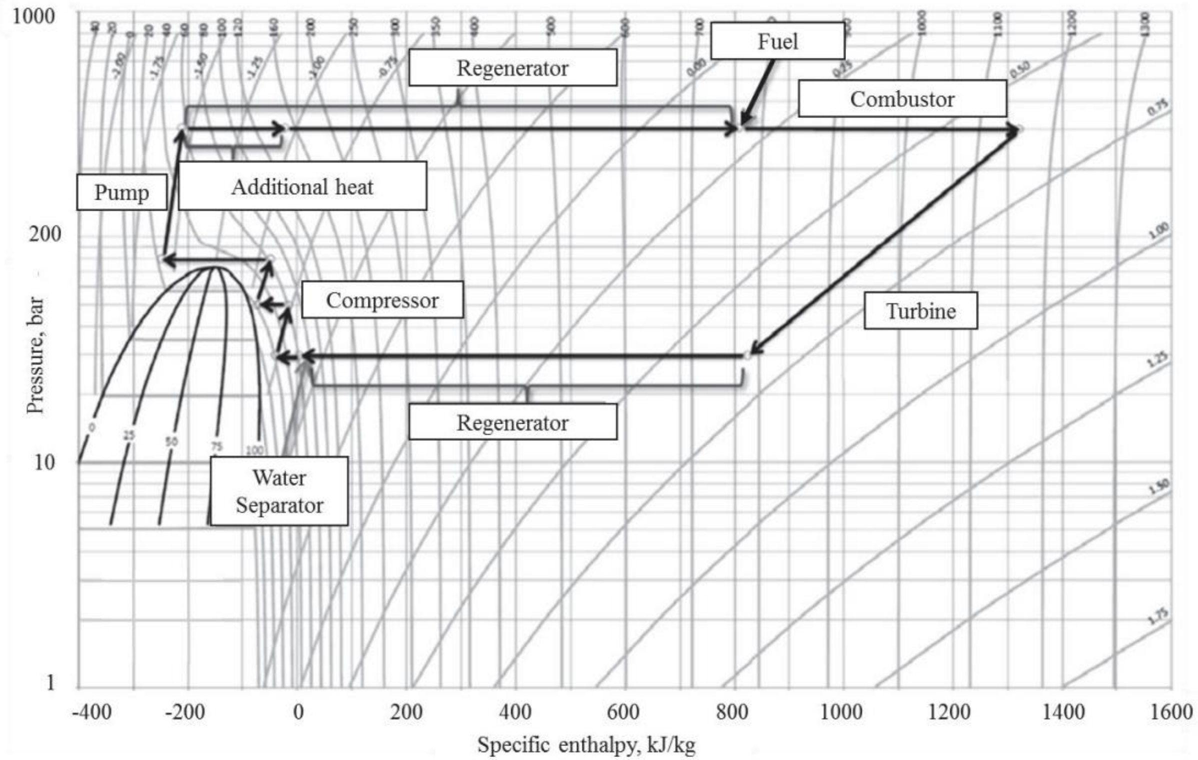



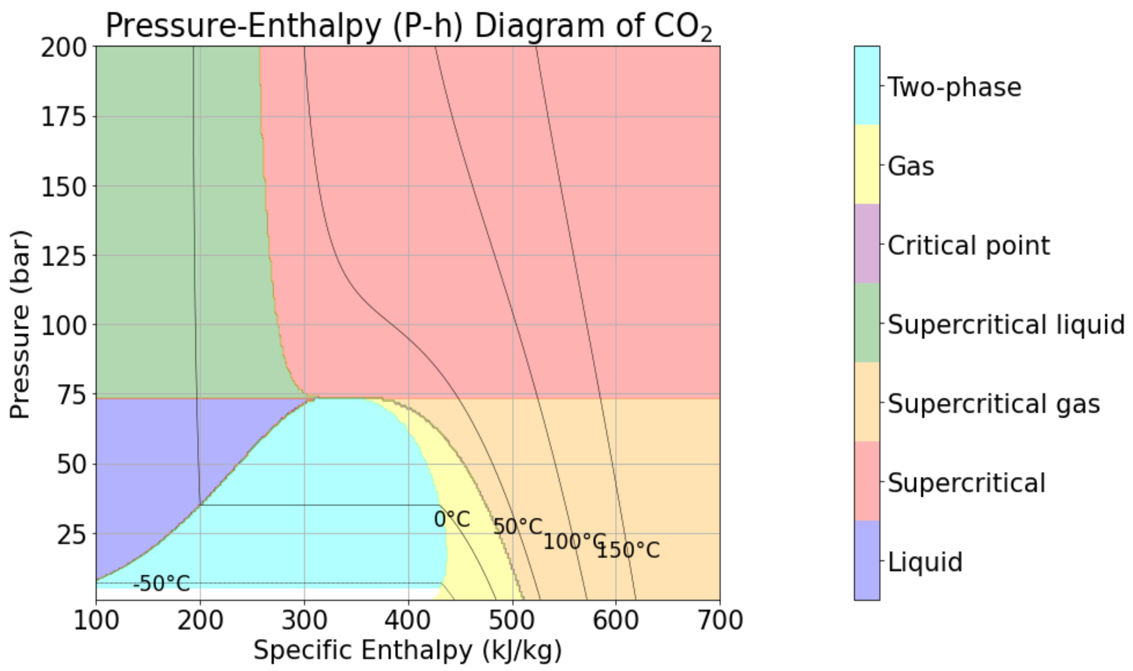
Fuel Supply System Layout



Allam cycle P-h diagram

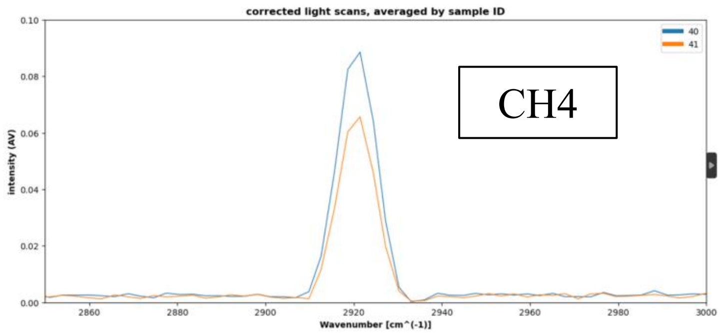
Critical point of CO_2, 31 ^oC and 73.8 bar

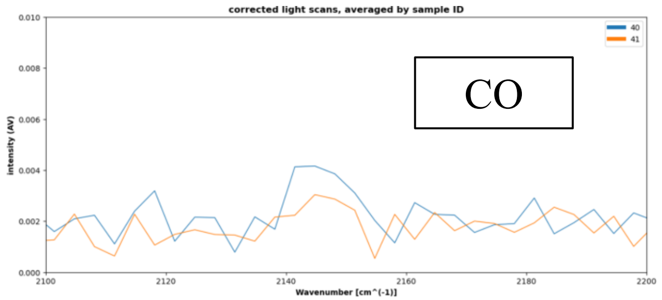


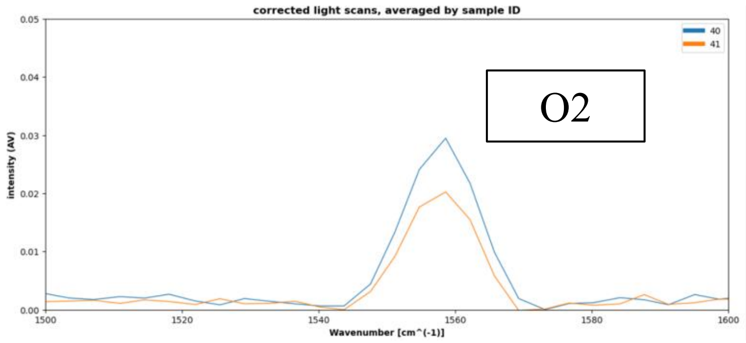


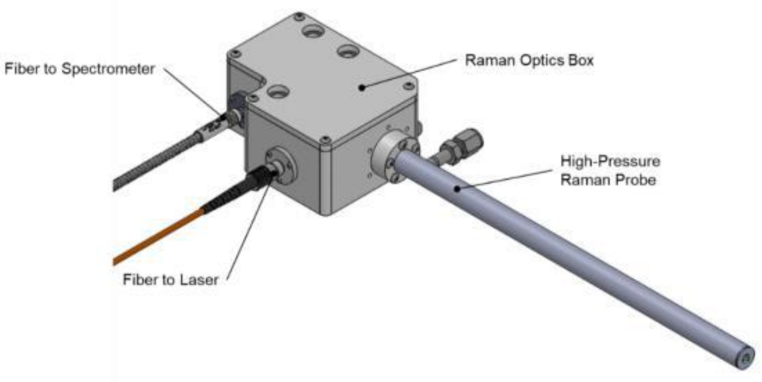
Source: Allam et al., Energy Procedia, 2013
Source: Zaryankin et al., APS, 2018

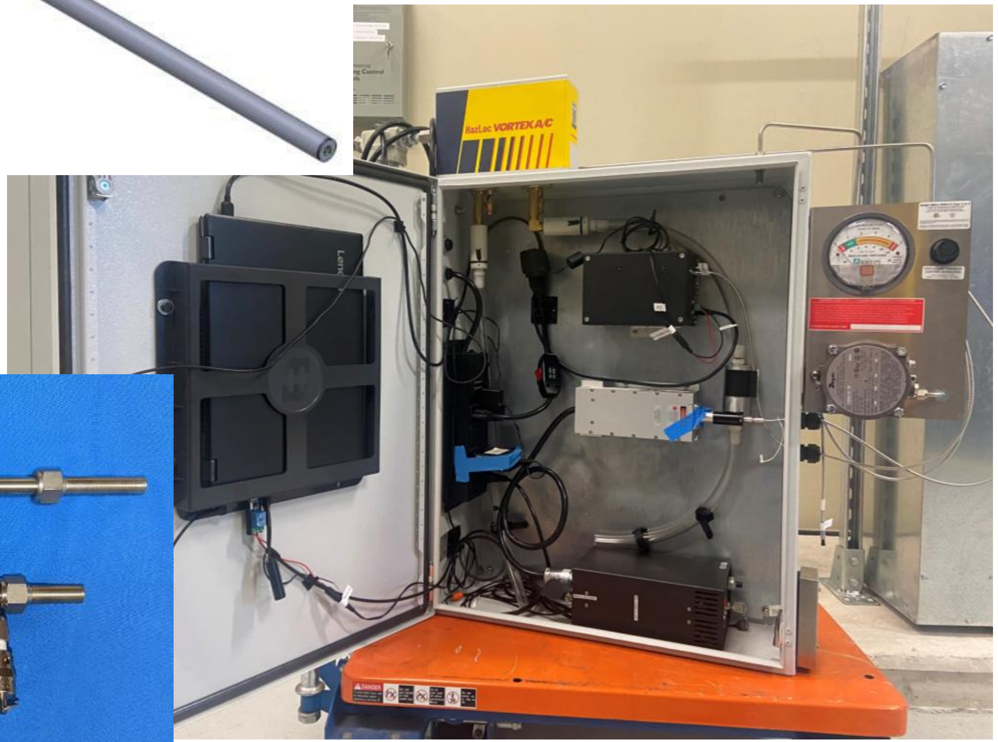
Raman Spectroscopy Setup

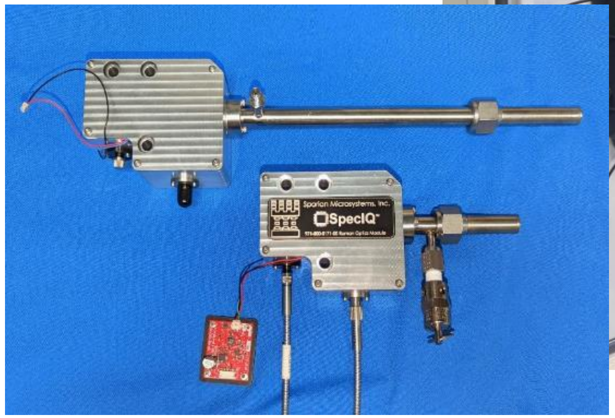






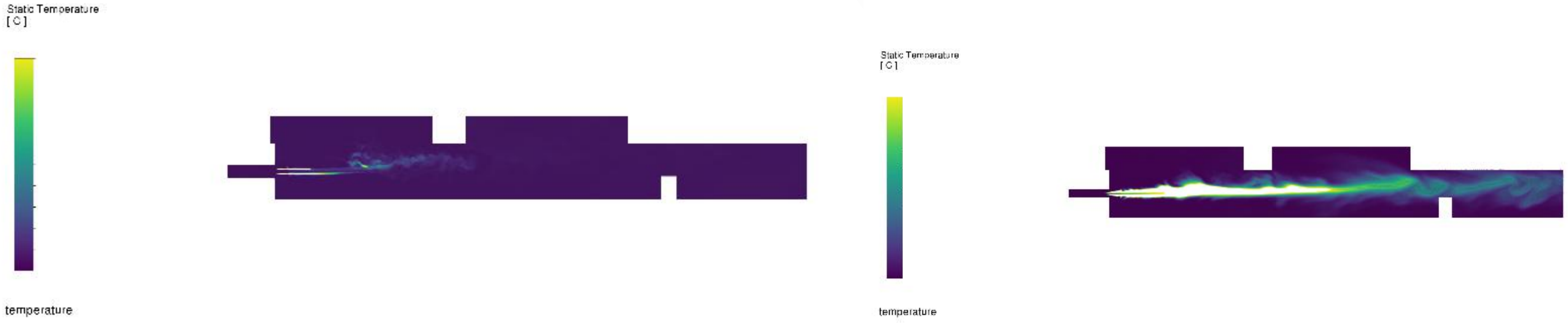






DDES CFD Results

CFD Results Showing Center Plane and Span Planes 1-4



Center Plane Temperature Contours for High Pressure and Atmospheric