Direct Fired Oxy-Fuel Combustor for sCO2 Power Cycles

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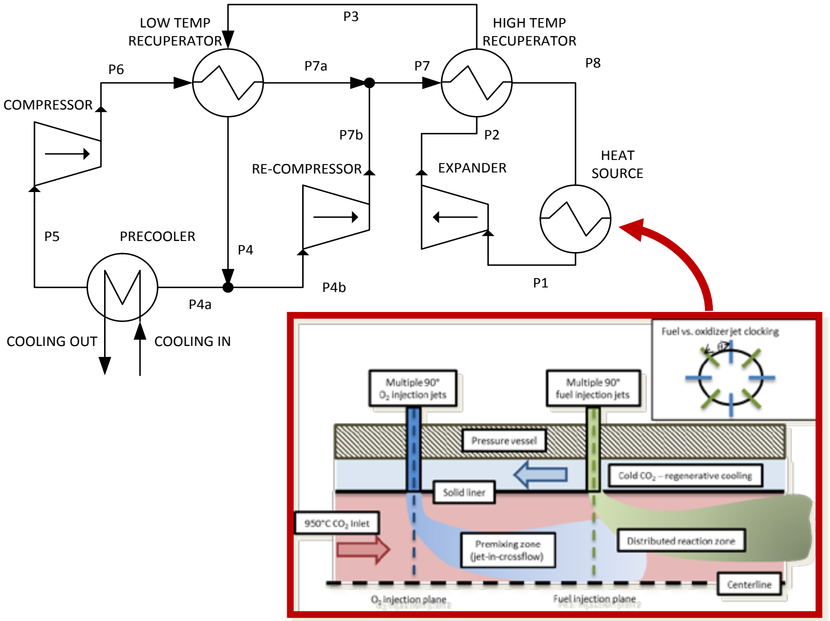
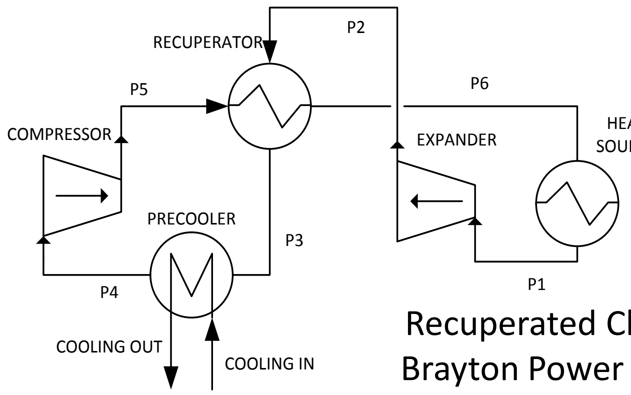


Outline

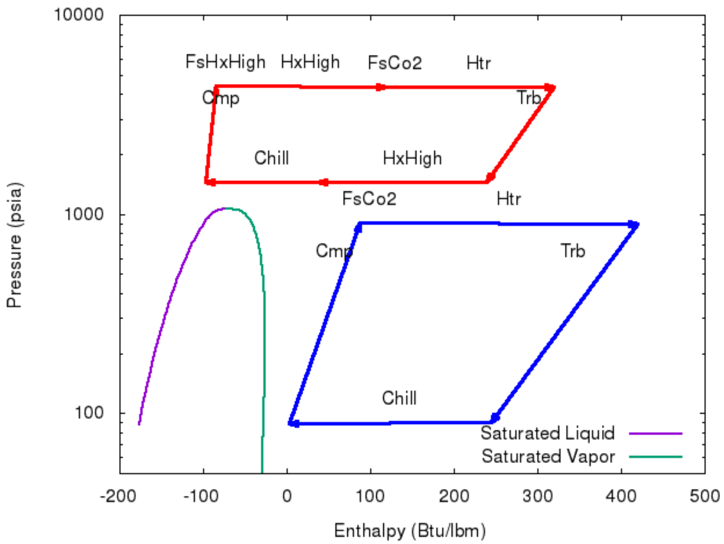
- Phase I Overview
  - Background
  - Project Objectives
  - Phase I Progress
    - Cycle Modeling
    - Chemical Kinetics
    - Preliminary Combustor Design
    - Bench-top Combustor Test
- Phase II Project Plan

What is a sCO2 cycle?

- Closed Cycle
  - Working fluid is CO2
- Cycle Type
  - Vapor phase
  - Transcritical
  - Supercritical
- Supercritical CO2 has:
  - High fluid density
  - High heat capacity
  - Low viscosity

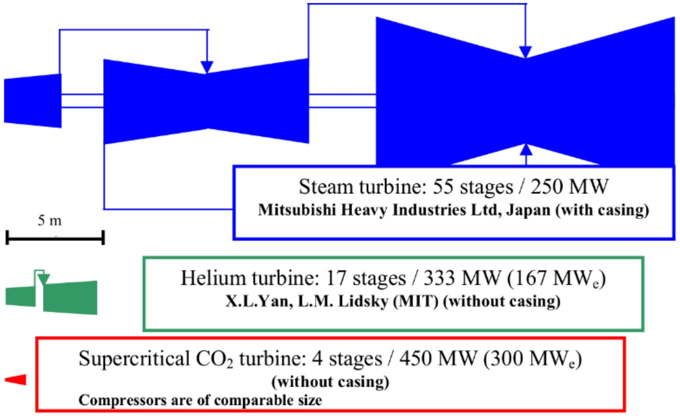


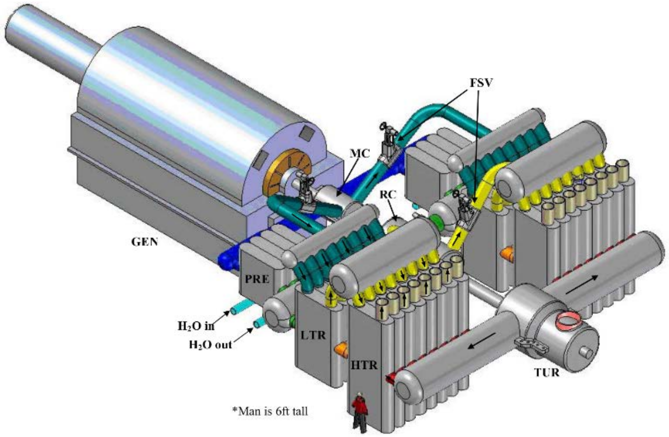
Recuperated Closed Brayton Power Cycle



Why sCO2 Power Cycles?

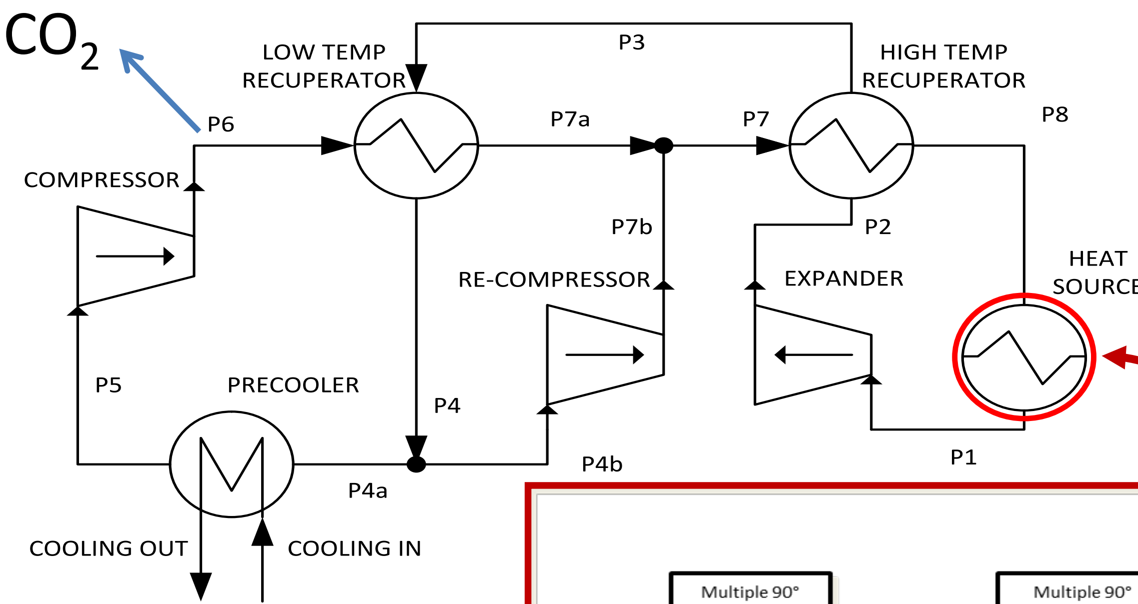
- Offer +3 to +5 percentage points over supercritical steam for indirect coal fired applications
- High fluid densities lead to compact turbomachinery
- Efficient cycles require significant recuperation

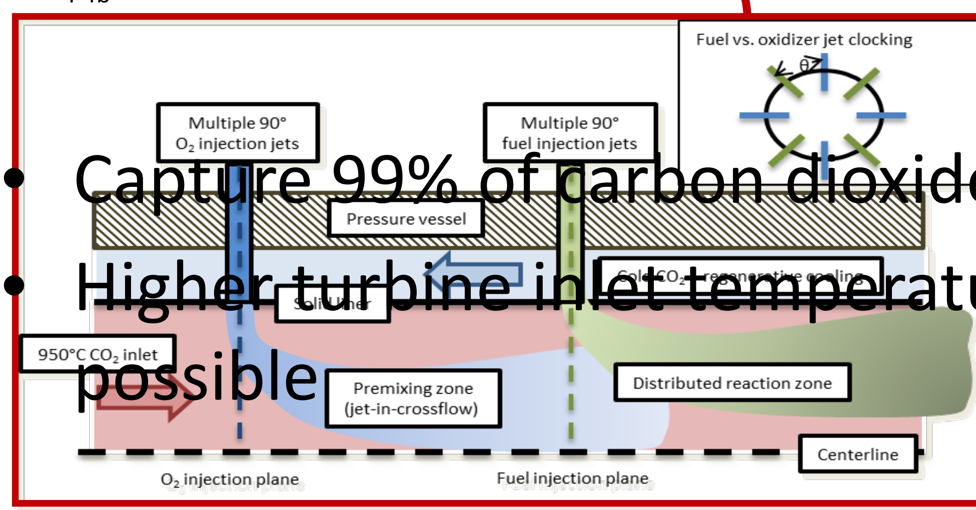




Third Generation 300 MWe S-CO2 Layout from Gibba, Hejzlar, and Driscoll, MIT-GFR-037, 2006

Why Oxy-Fuel Combustion?





- Capture 99% of carbon dioxide
- Higher turbine inlet temperatures possible

Project Objectives

- Optimize the supercritical CO2 power cycle for direct fired oxy-combustion
  - Target plant conversion efficiency is 52% (LHV)
- Technology gap assessment for direct fired plant configurations
- Develop a high inlet temperature oxy-combustor suitable for the optimized cycle
  - Target fuels are Natural Gas and Syngas

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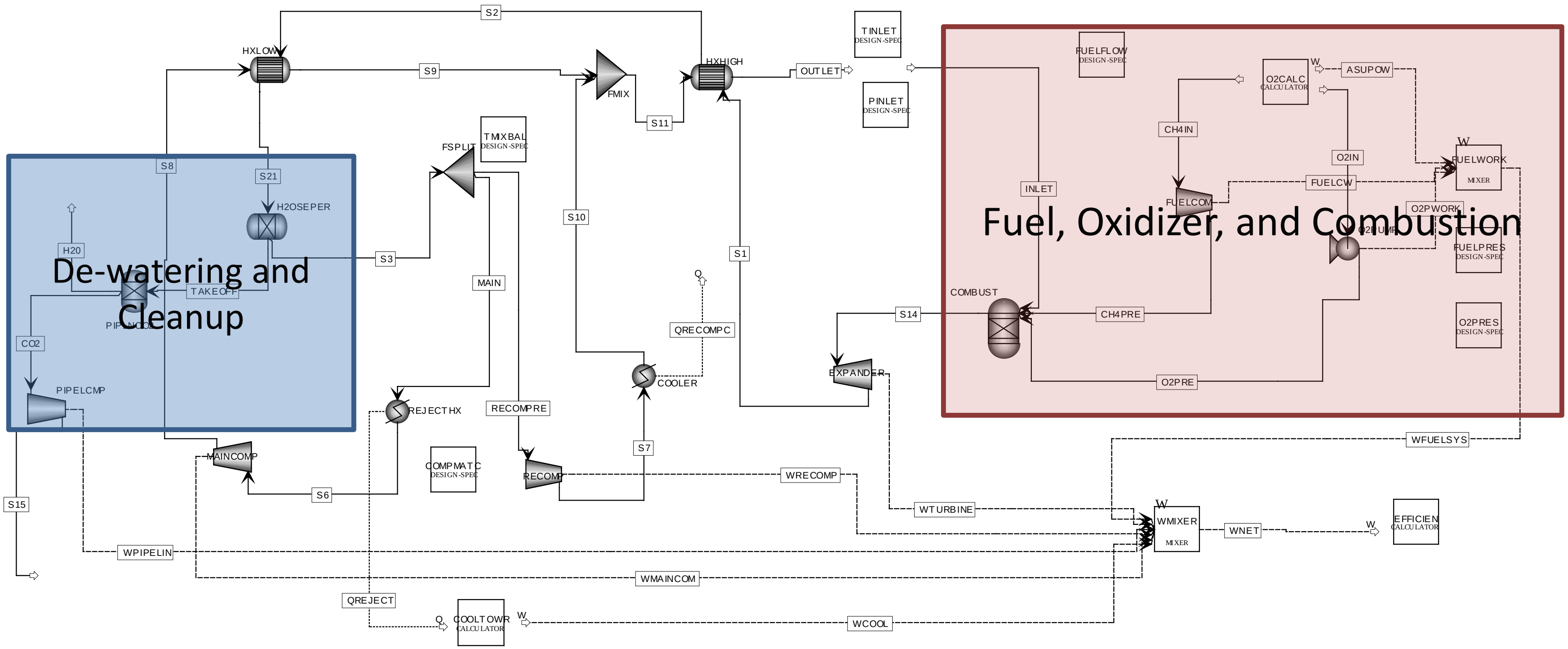
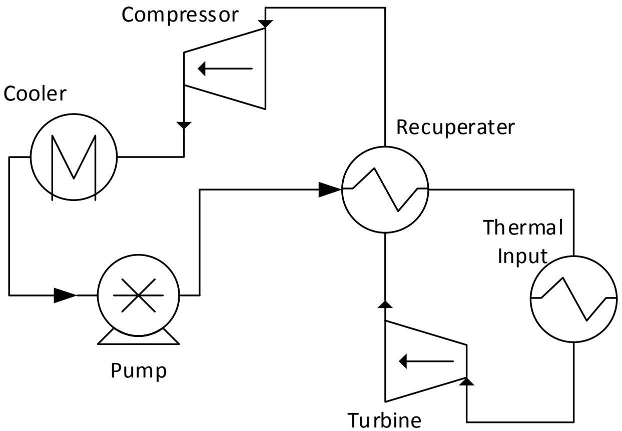
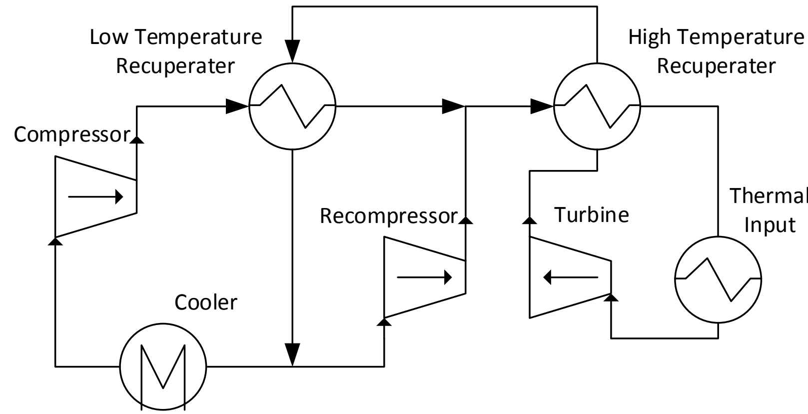
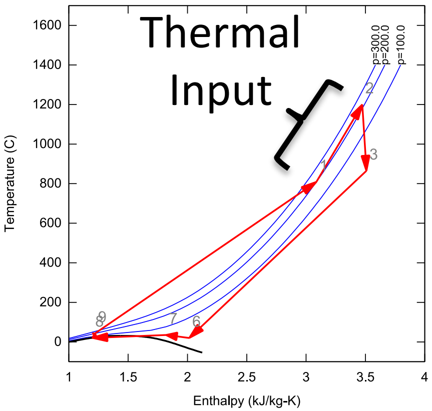
Oxy-Combustion Plant Model

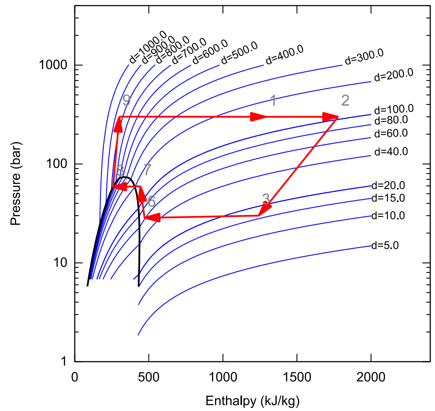


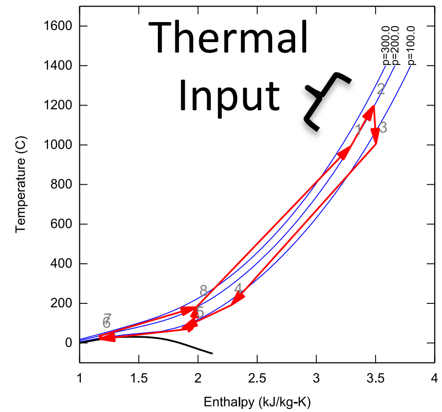
Condensation and Recompression Cycles

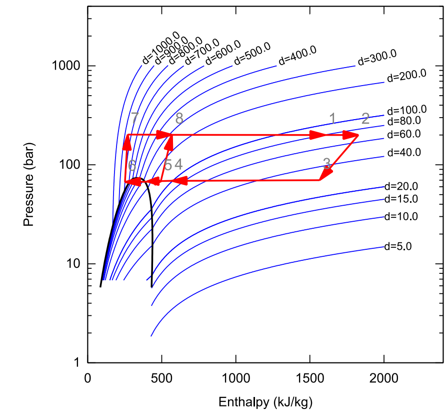












Cycle Analysis Results

- Recompression cycle has highest efficiency
  - 53.4% at 200 bar, 56.7% at 300 bar
- Condensation cycle
  - 51.6% at 200 bar, 54.0% at 300 bar
  - Superior in all other metrics
  - Reduced recuperation (~ 50%)
  - Lower combustor inlet temperature
  - Higher power density (power output / flow rate)
- Both cycle configurations are compatible with an *auto-ignition* style combustor for 1200 C Turbine inlet temperatures.

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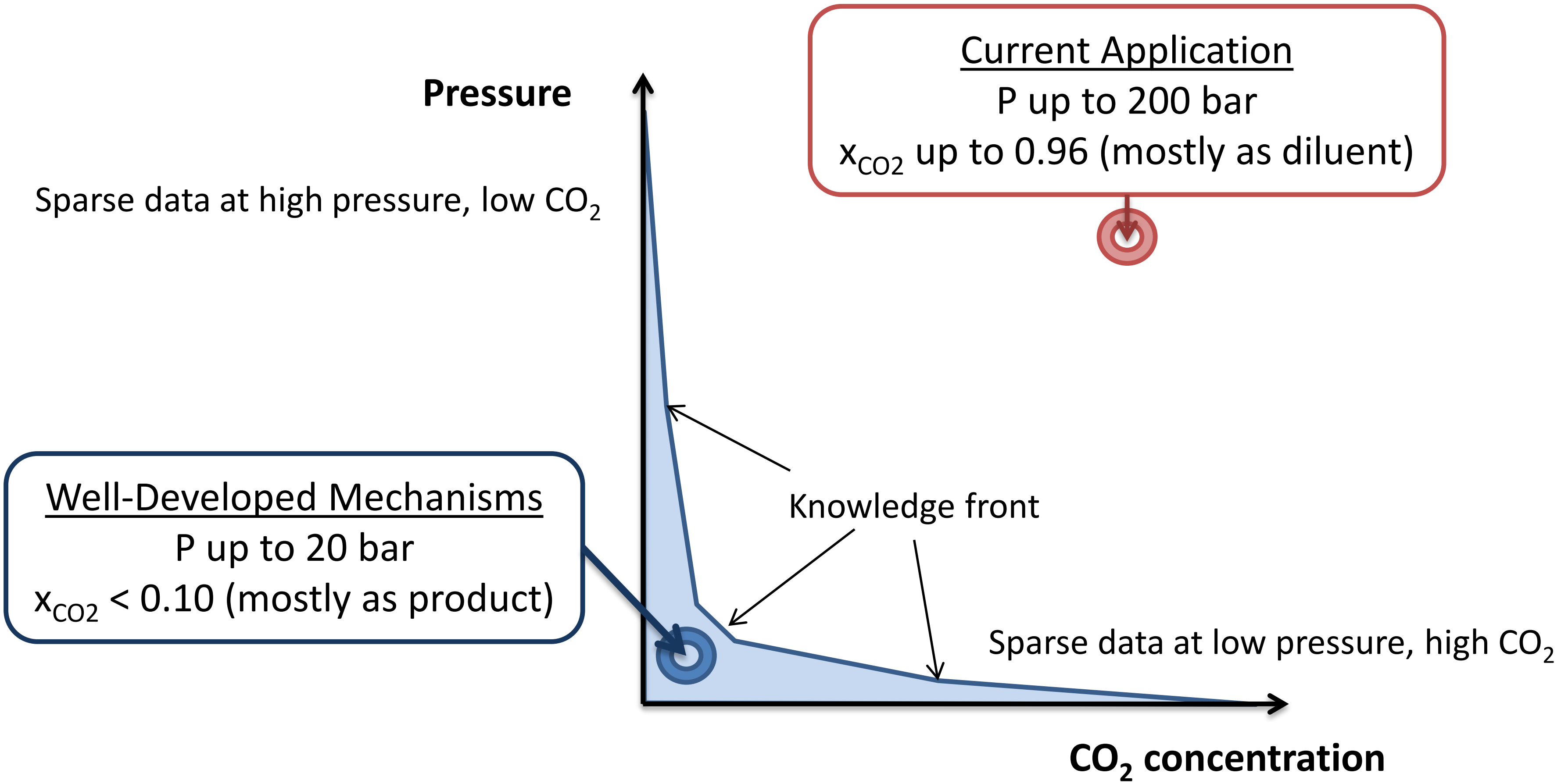
Kinetic Model: Motivation

- The fundamental size of the combustor is governed by the timescale of chemical reactions
- The chemical reaction kinetics determine how fast fuel oxidation occurs
  - A detailed chemical kinetic model is required to size the combustor
  - A reduced chemical kinetic model is required for detailed flow-field design in CFD

Kinetics Knowledge Base



No data available at conditions relevant to this application.

Mechanism Selection

- Primary selection criterion is accurate prediction of the overall reaction time scales
  - Drives the combustor design
  - More important than other details such as peak concentration values
- USC-II is the clear choice based on this criterion
  - Most accurate in highest pressure flamespeed and autoignition validation comparisons
- USC-II also had good to adequate performance in low pressure CO_2 studies
- USC-II predictions should carry +/- 50% uncertainty in this application

Reduced Order Model

- For incorporation into a CFD model a reduced order model was developed
- Equations based on Arrhenius rate equation were tuned to match USC-II model predictions
  - Match autoignition delay
  - Match residual CO levels
  - Overall time to complete reaction

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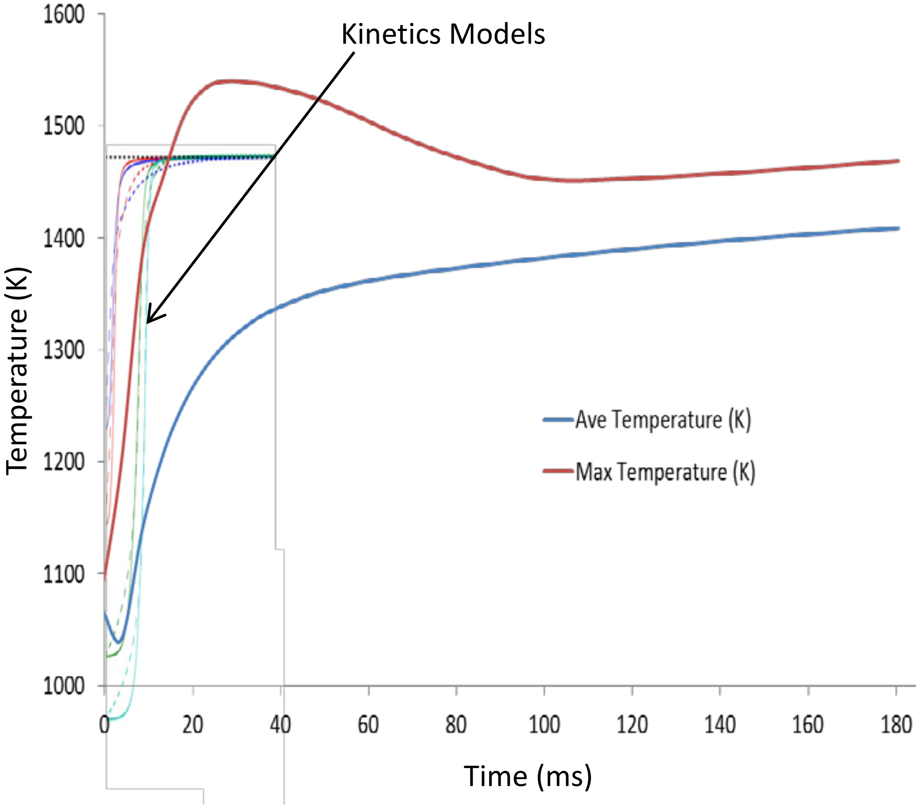
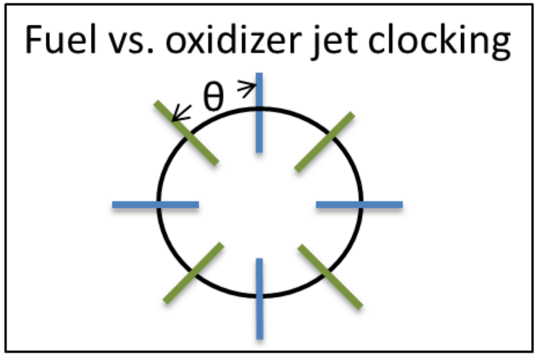
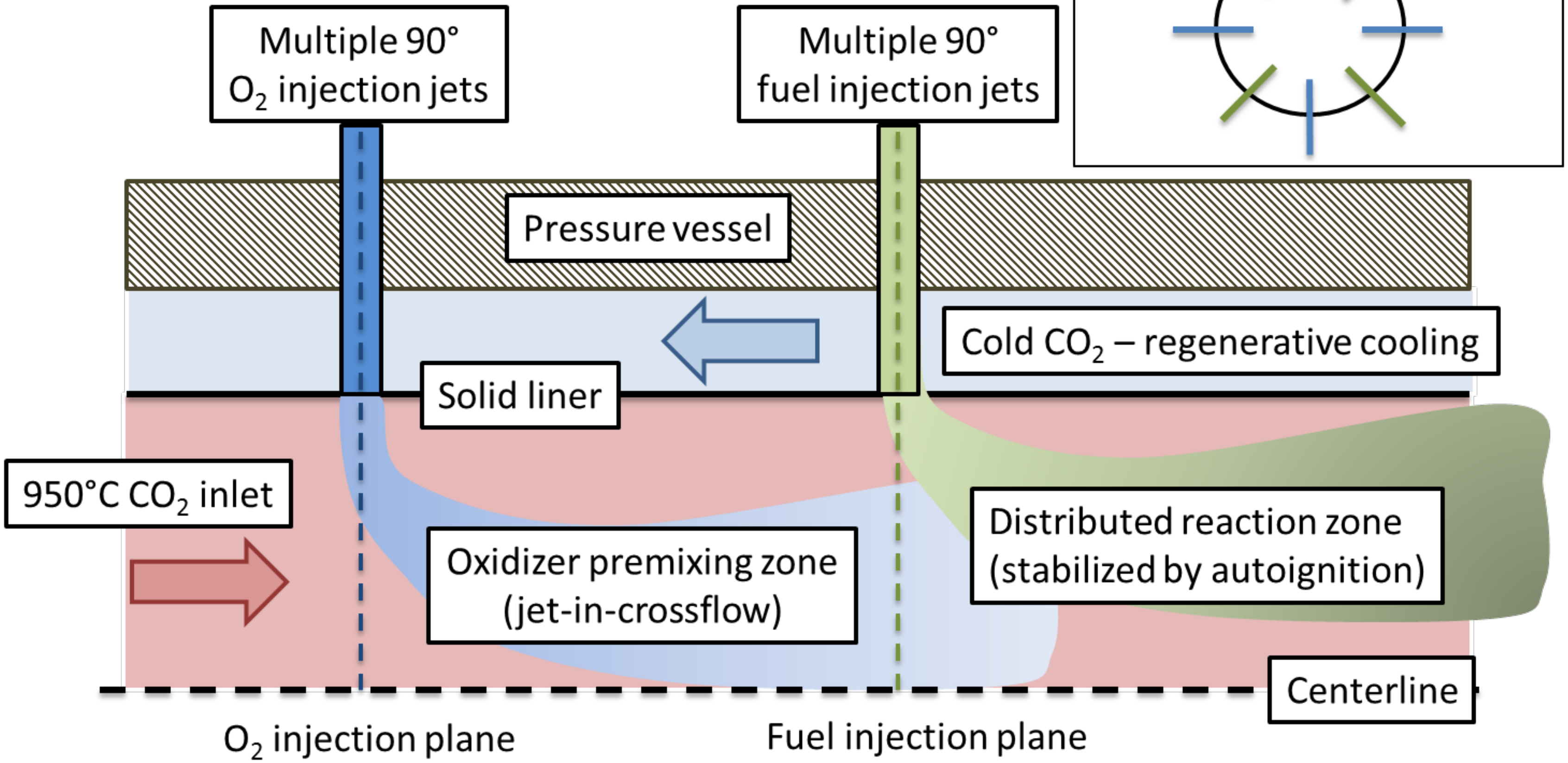
Mixing vs. Kinetics Time Scales

- Time scale of reaction kinetics is much smaller than physical mixing time scales
- Combustion size and length governed by physical mixing
- Use of CFD with finite rate chemistry to model this



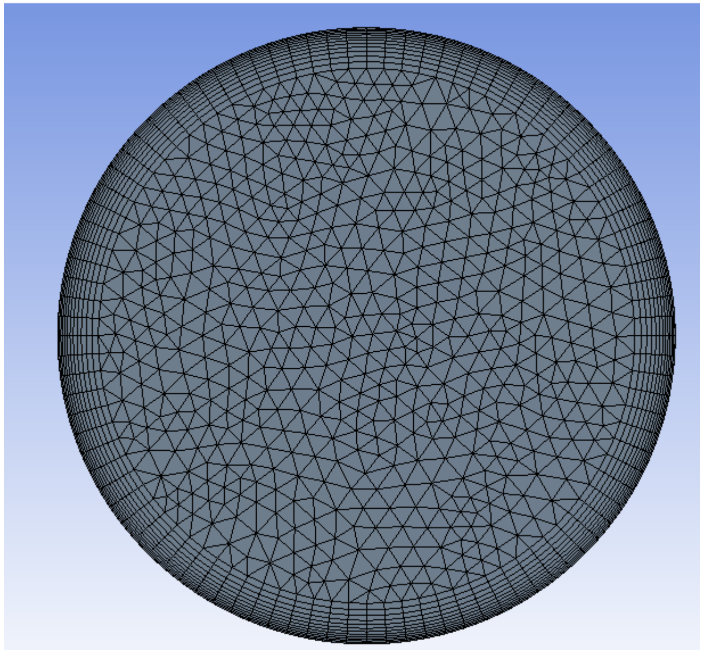
Initial Combustor Concept



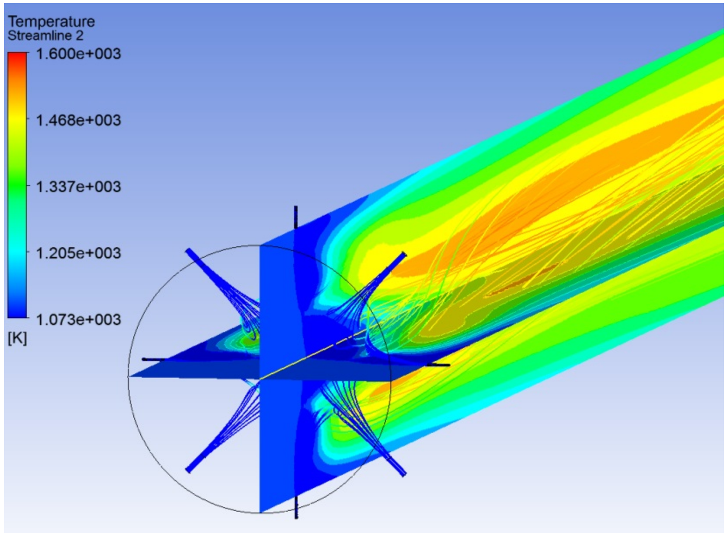


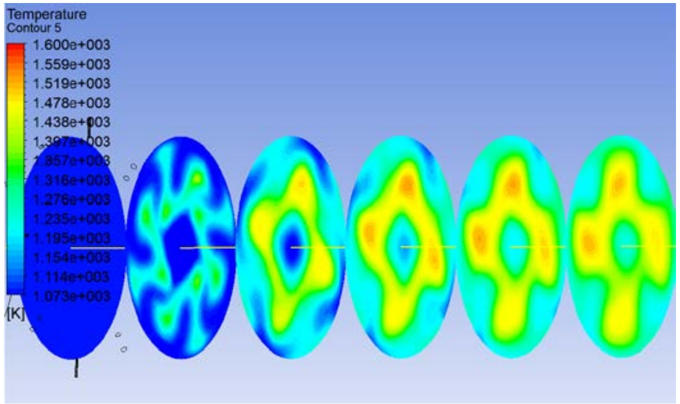
CFD Model Setup

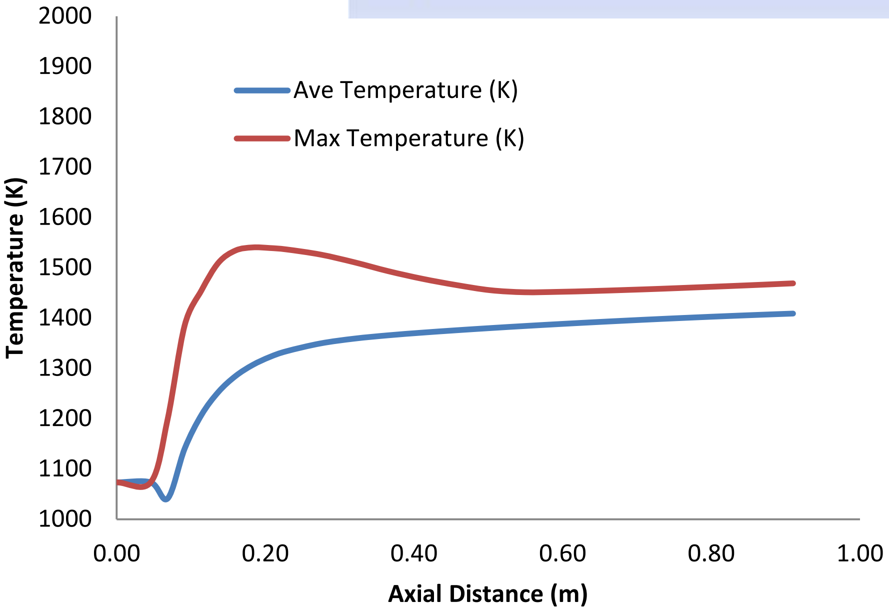
- ANSYS CFX 16.2
- Unstructured mesh
  - Boundary layer and injection region refinement
  - 4 million elements
  - Mesh sizes from 2 to 17 million elements for independence study
- Finite rate chemistry
  - Extrapolated reduced order equations



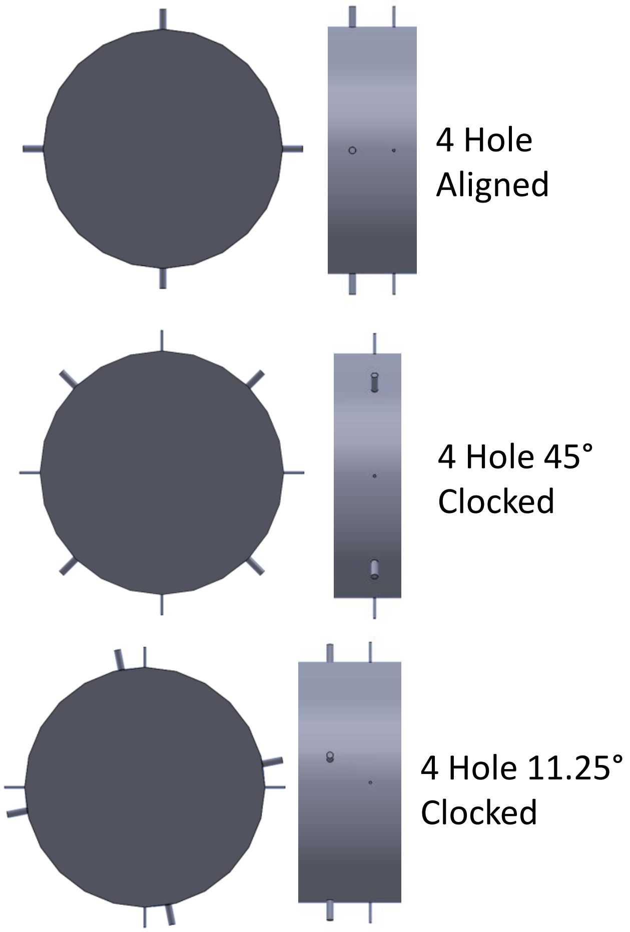
Temperature in 45° Clocked Case



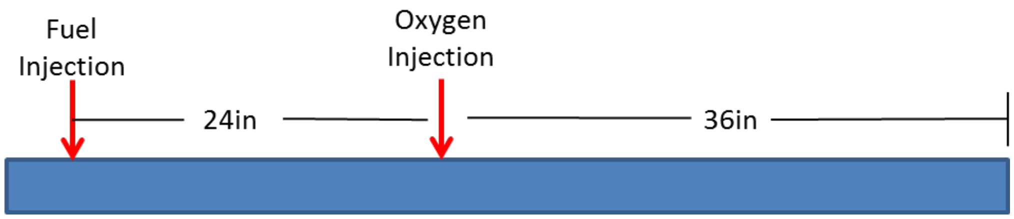




Change Injection Spacing

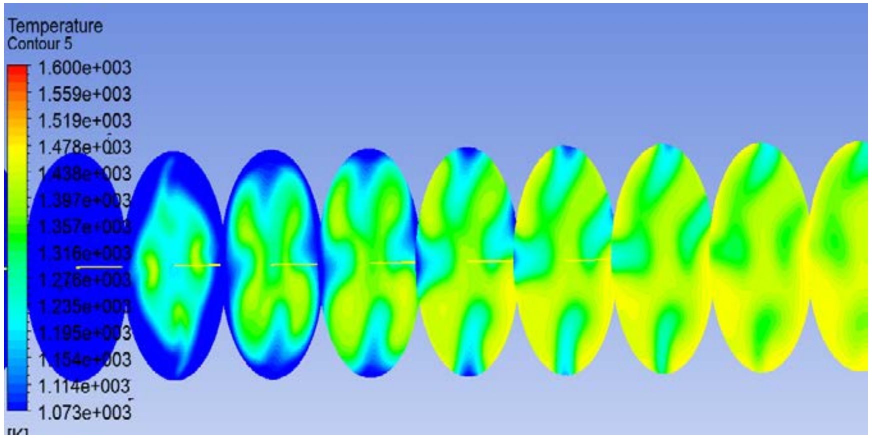


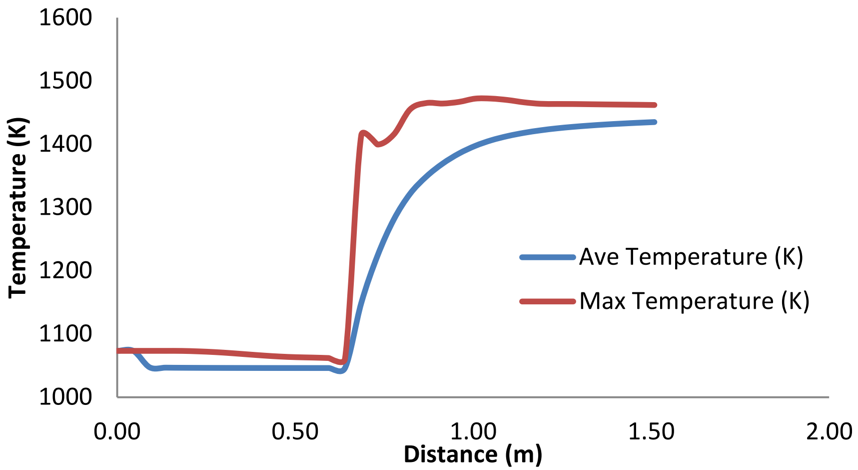
- Injection oxygen and fuel need not be at same location
- Auto-ignition allows even small concentrations of fuel+oxidizer to react



Final Design: Fuel Injection 24in Upstream

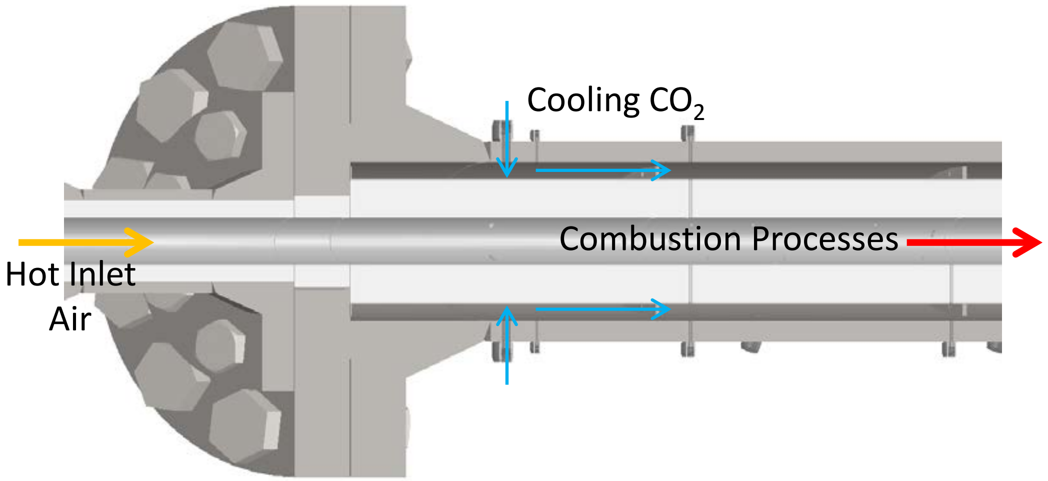
- Fuel well mixed throughout combustor before oxygen
- Allows hydrocarbon “cracking” before oxygen injection
- Cooler max temperatures
- Very good mixing at outlet
- Very low unburnt fuel percentage





Preliminary Mechanical Design

- Thermal design
  - Thermal containment using refractory insulating layer
  - Cooling CO_2
- Mechanical design
  - Utilizes stainless steel ANSI pipe and flanges



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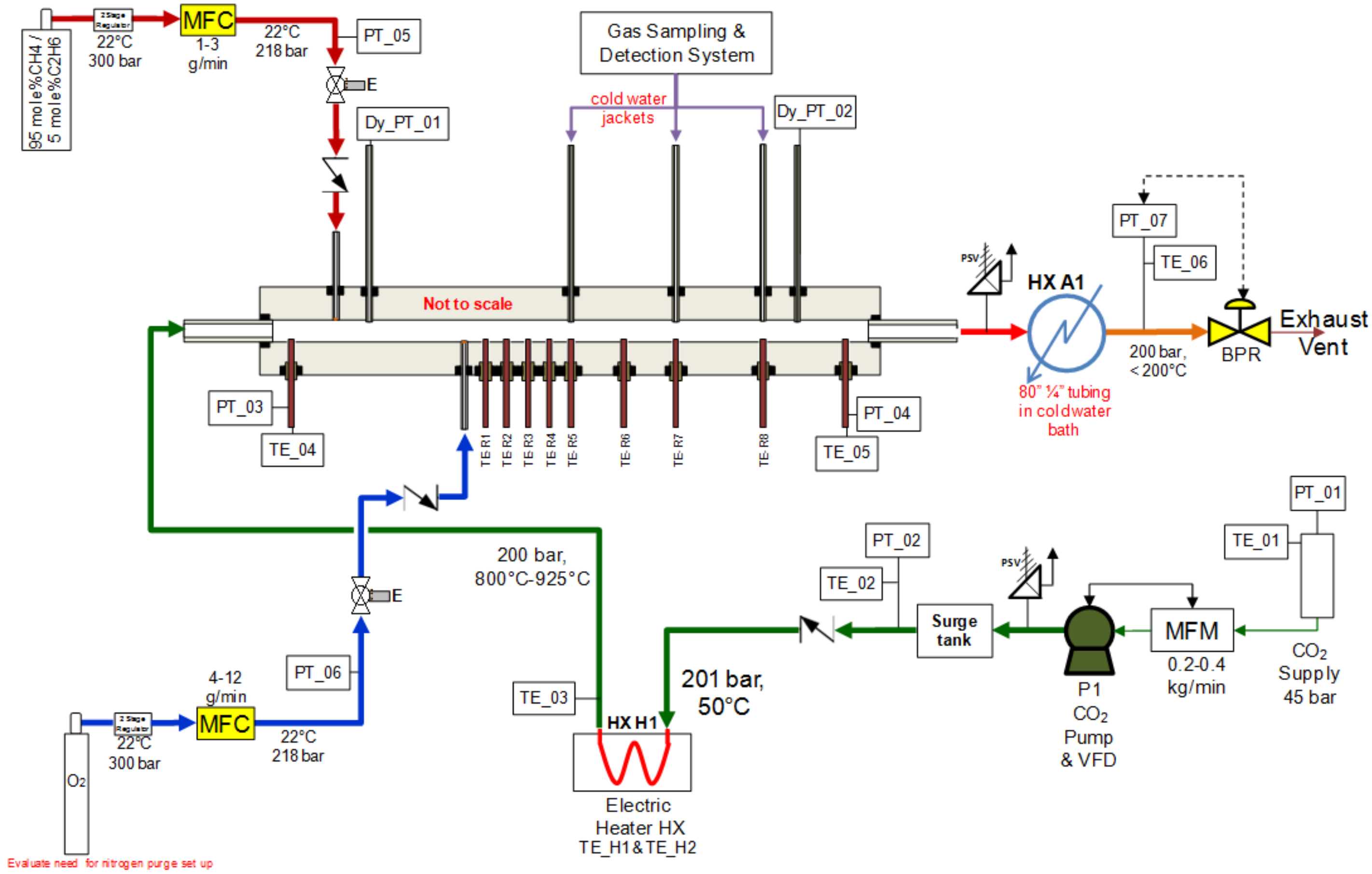
Bench-top Combustor Test

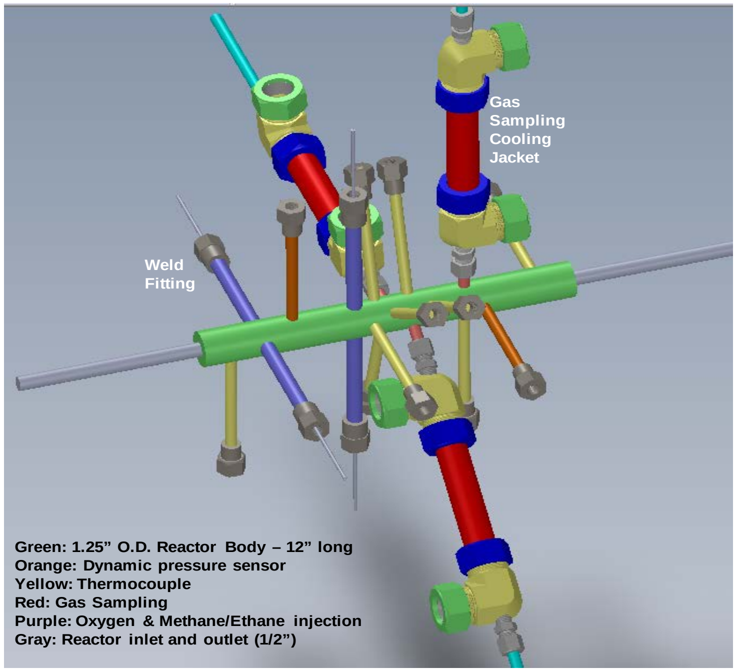
- Small bench top test to study proof of concept, autoignition delay, and chemical kinetics
- Once through type system
  - 200 bar pressure
- Electric heaters used to set inlet temperature
- Jet in cross flow type fuel and oxidizer injection

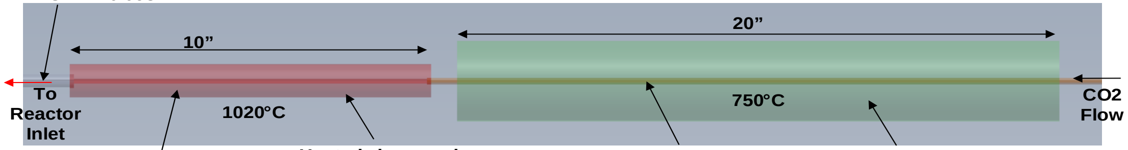
Test Stand Loop Design



Oxy-fuel Test Reactor

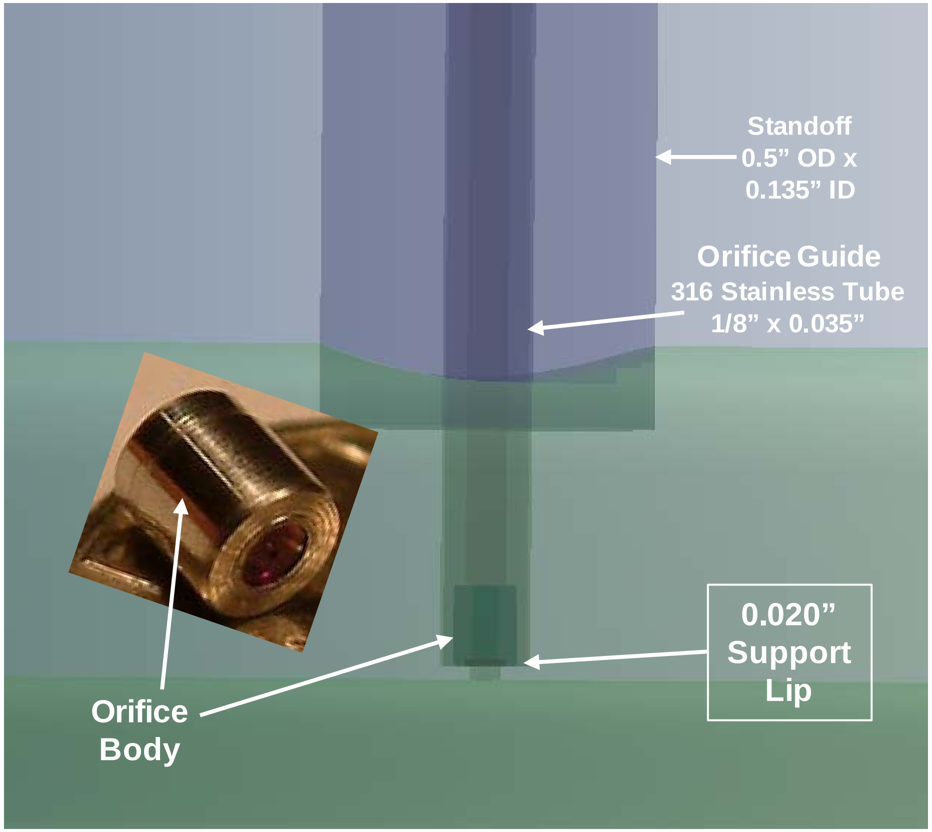
- Machined from Haynes 230 bar stock
- Instrumentation standoff tubes welded to main combustor
- Two stage pre-heater to achieve 925°C combustor inlet
- Water jacketed gas sampling



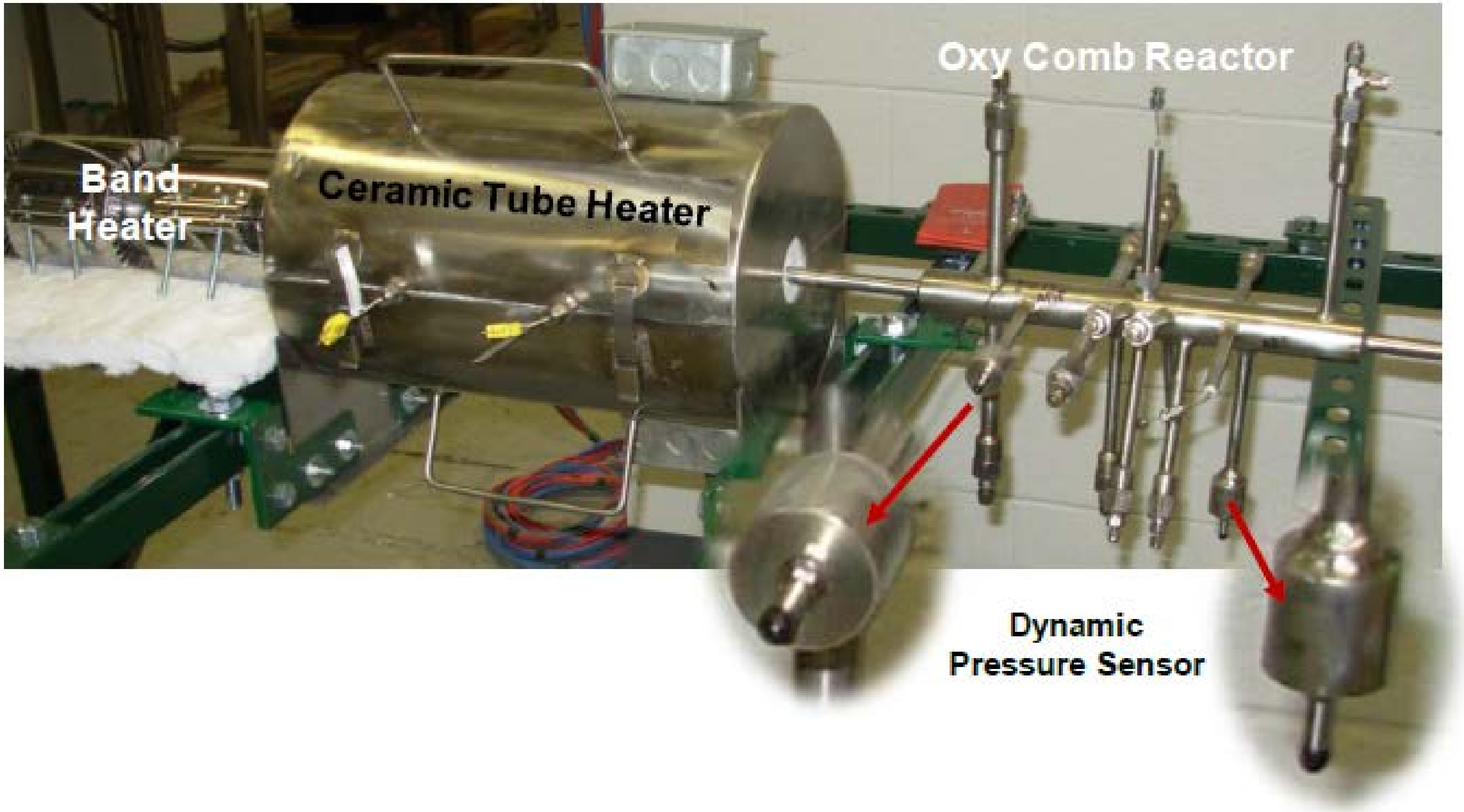


Fuel and Oxygen Injector Design

- Precise sapphire orifice set into stainless steel mount
- Orifice constriction placed close to the combustor
- Mounted inside welded in place standoff



Combustor Test Stand

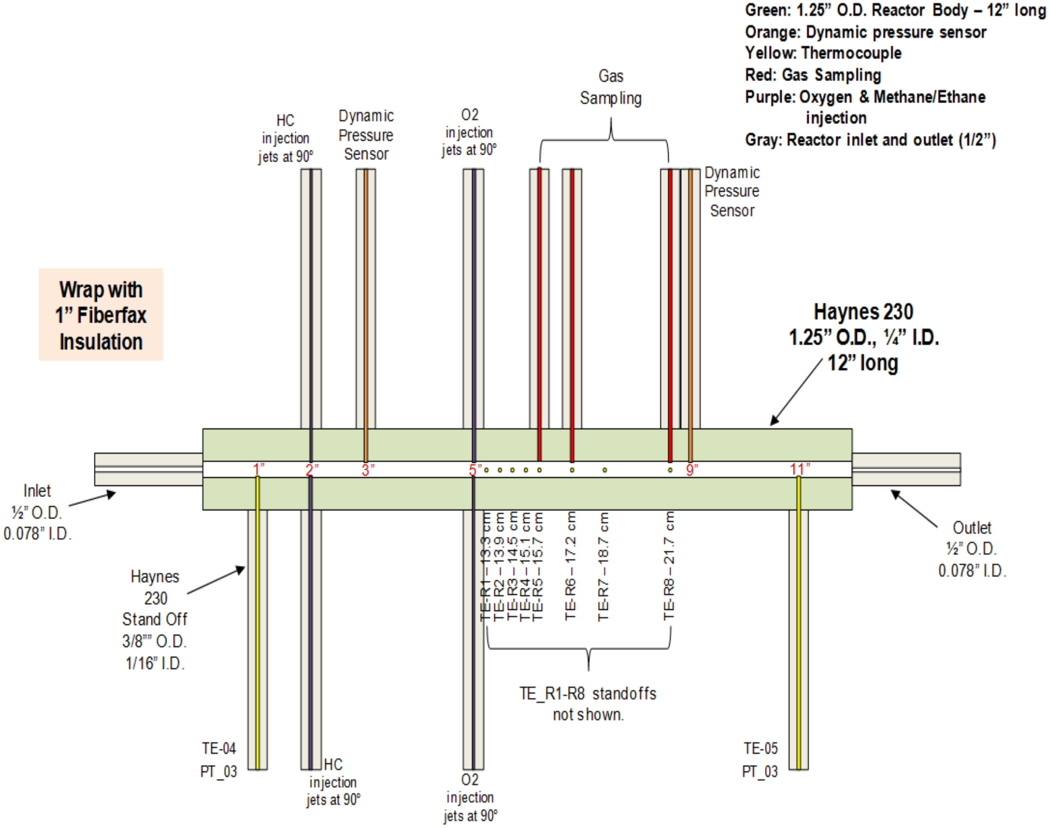


Test Stand Assembly

- Testing at Thar's facility in Pittsburg, PA
- Outdoors with remote operation

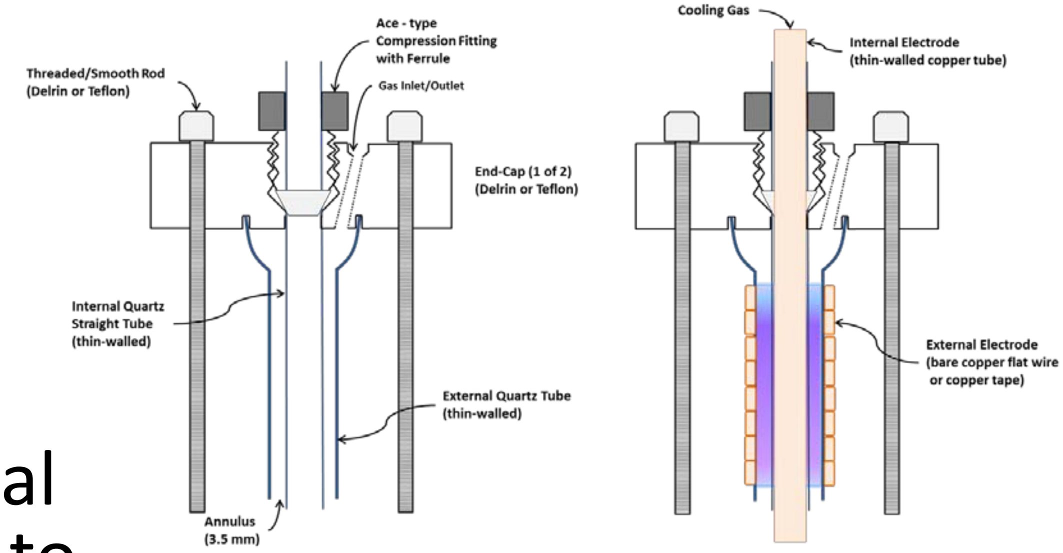
Instrumentation

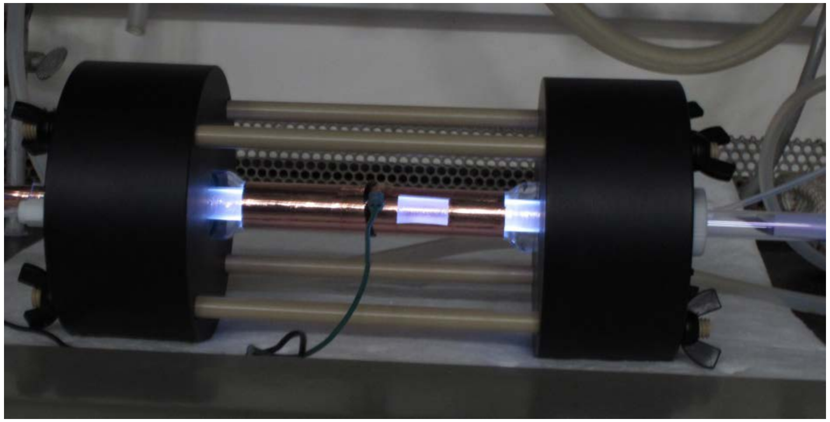
- Thermocouples in combustion zone
- Dynamic pressure transducers
- Three gas sampling ports
  - Optical emission spectroscopy (OES) to analysis chemical makeup



OES

- Optical emission spectroscopy (OES)
- Utilizes a plasma generator to identify chemical species
- Requires rapid thermal quenching of sample to halt chemical reactions
- SwRI has experience using OES for gas species analysis





Test Stand Operation

- Shake down tests
  - Observed auto-ignition combustion during shakedowns at full pressure and 80% temperature
- Component failures
  - Backpressure control valve
  - Mass flow controllers
    - Viton rubber does not mix with sCO2

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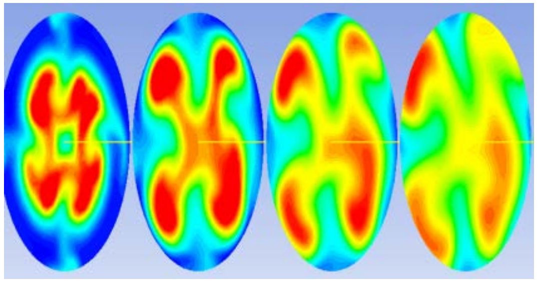
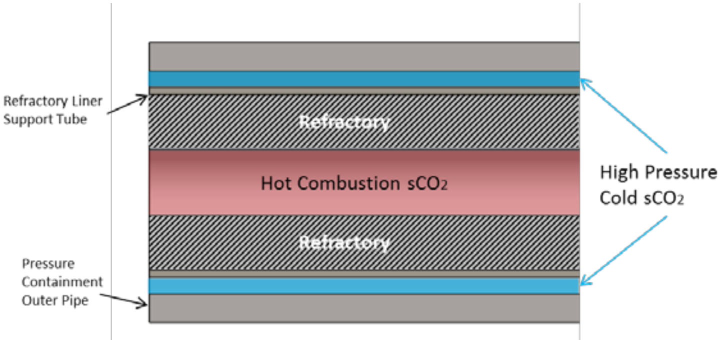
Phase II

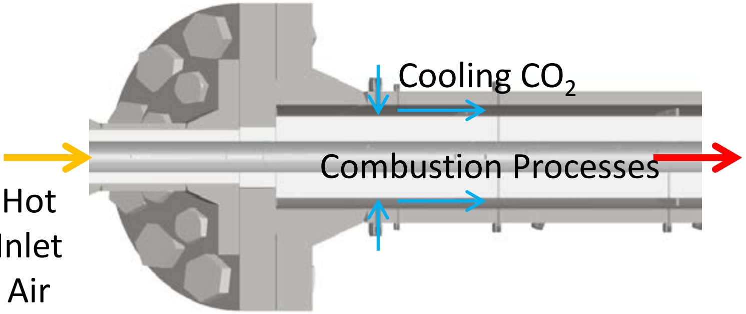
- Complete detailed design
- Fabricate combustor and test loop
- Shake down and commission
- Test combustor
- Phase II duration: 3.5 years
- Partnered with Thar Energy, Georgia Tech, UCF and GE Global Research

Detailed Combustor Design

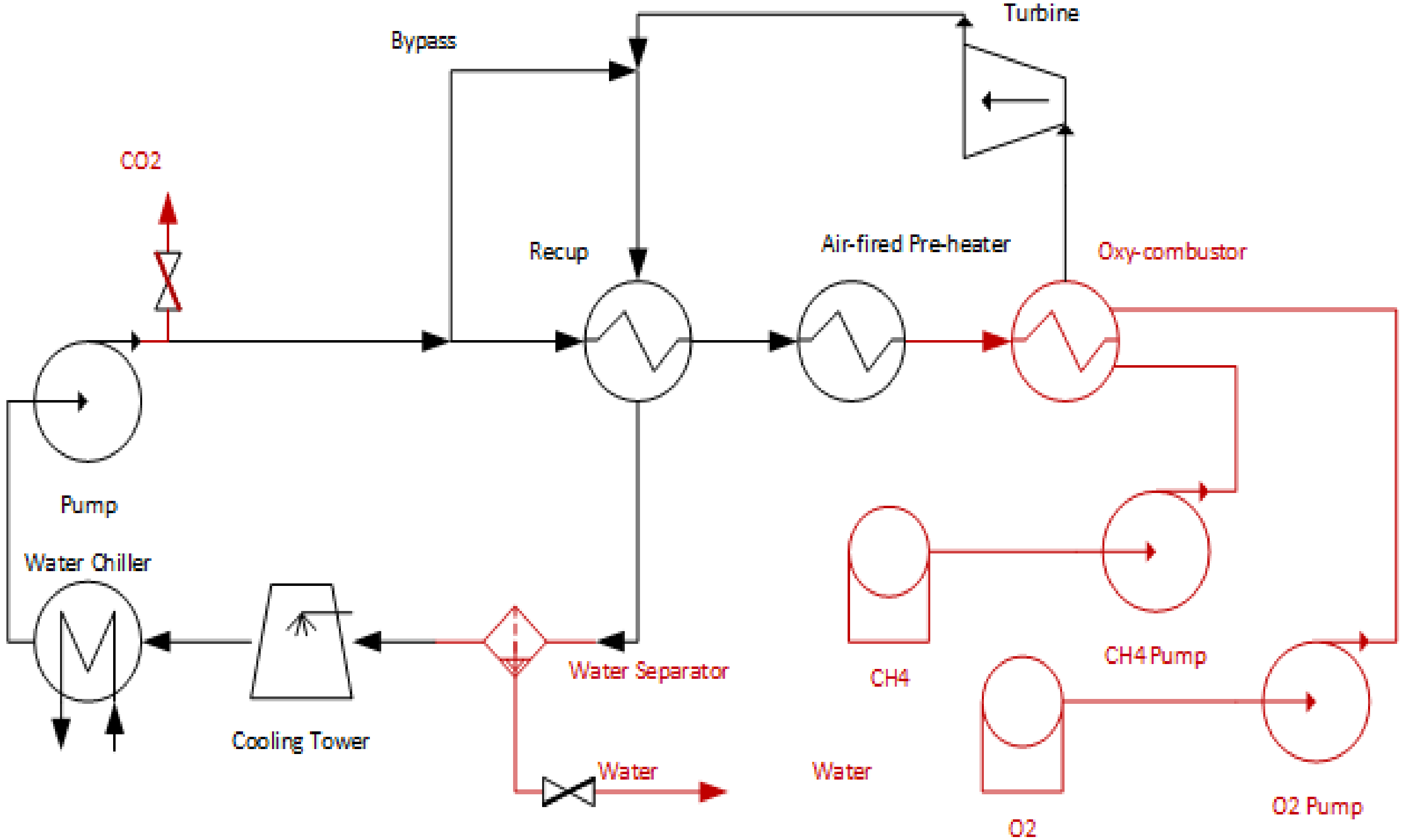
- Develop more detailed and accurate combustion kinetic mechanisms
- Utilize CFD to study combustion flow field
- Detailed thermal and mechanical design
- Final design for manufacturing







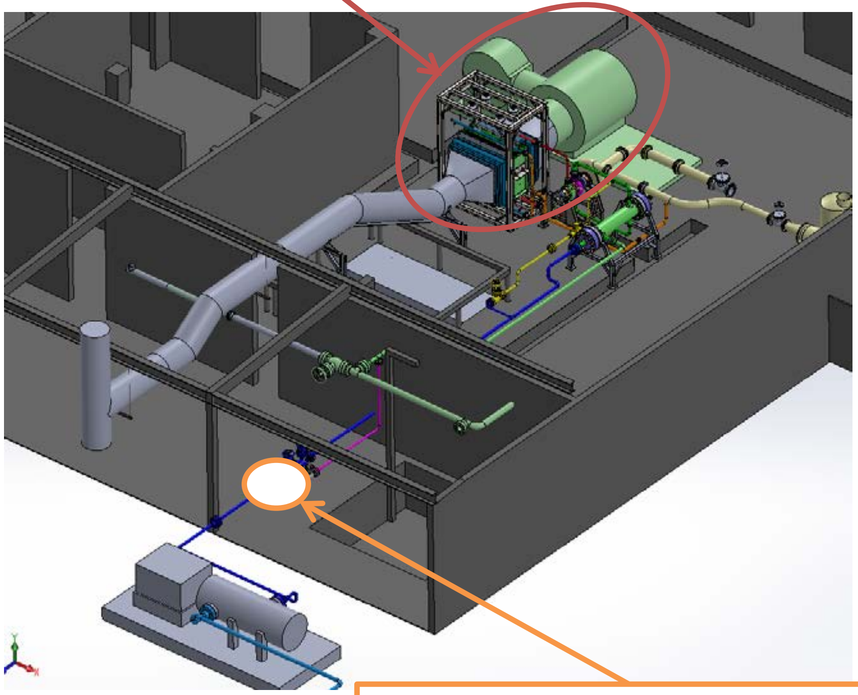
Combustor Integration with Sunshot Test Hardware



Combustor Integration

- Utilize existing Sunshot hardware
- Install oxy-fuel combustor
  - Demonstrate a direct fired oxy-combustor in a closed Brayton cycle
  - Evaluate combustor performance
  - Evaluate flue gas cleanup
  - Indirect heater allows for various combustor inlet conditions to be studied

Oxy-Combustor added downstream of indirect heater

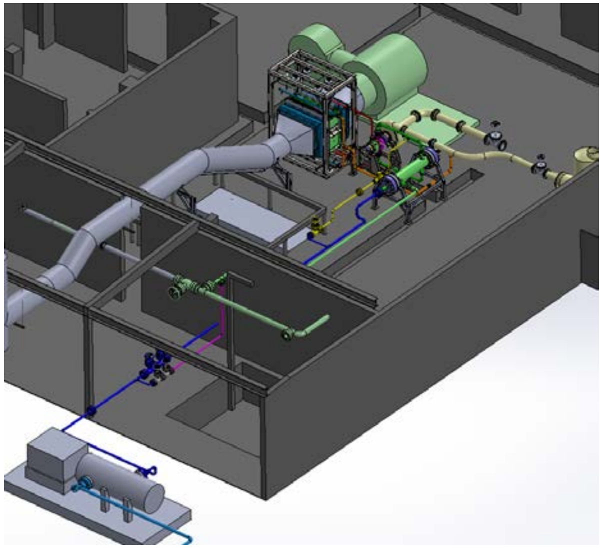


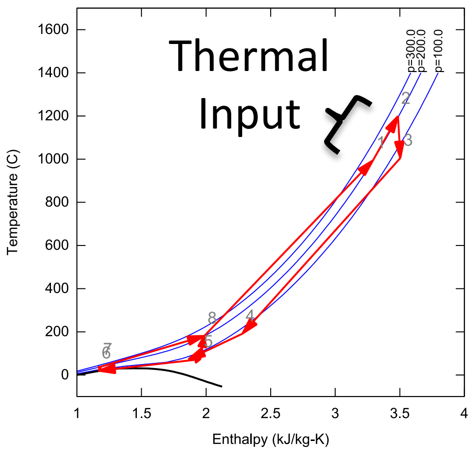
Add flue gas cleanup and water separation

Planned Test Measurements

- Multiple OES sample locations
- Temperature measurements
- High speed pressure measurement for acoustic phenomena
- Study water dropout and separation
- Possible measurements
  - Optical access for advanced diagnostics
  - Materials sample testing

QUESTIONS?





Thermal
Input
Temperature (C)
Enthalpy (kJ/kg-K)
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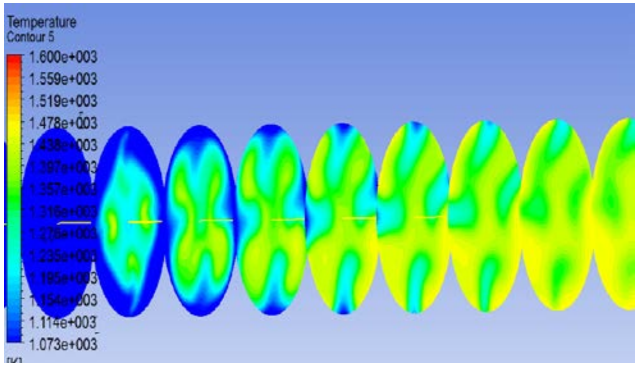
p=200.0
p=100.0



Temperature
Contour 5
1.600e+003
1.559e+003
1.519e+003
1.073e+003