Direct Fired Oxy-Fuel Combustor for sCO2 Power Cycles

Jacob Delimont, Ph.D.
Nathan Andrews, Craig Nolen, Carolyn Day
Southwest Research Institute

Marc Portnoff
Lalit Chordia, Ph.D.
Thar Energy L.L.C.

Wenting Sun, Ph.D.
Georgia Tech

Subith Vasu, Ph.D.
UCF

Sarah Monahan, Ph.D.
Keith McManus, Ph.D.
GE-GRC

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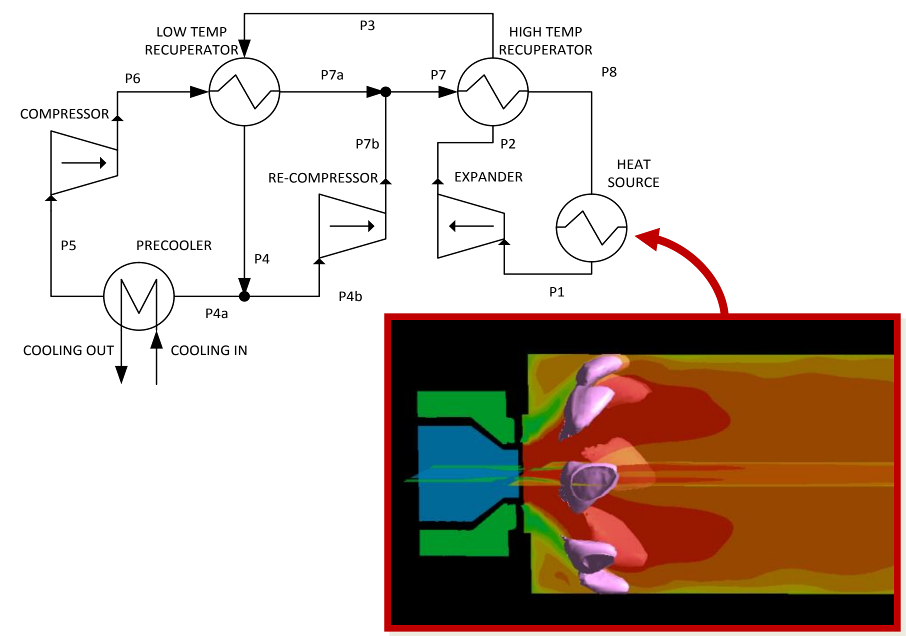
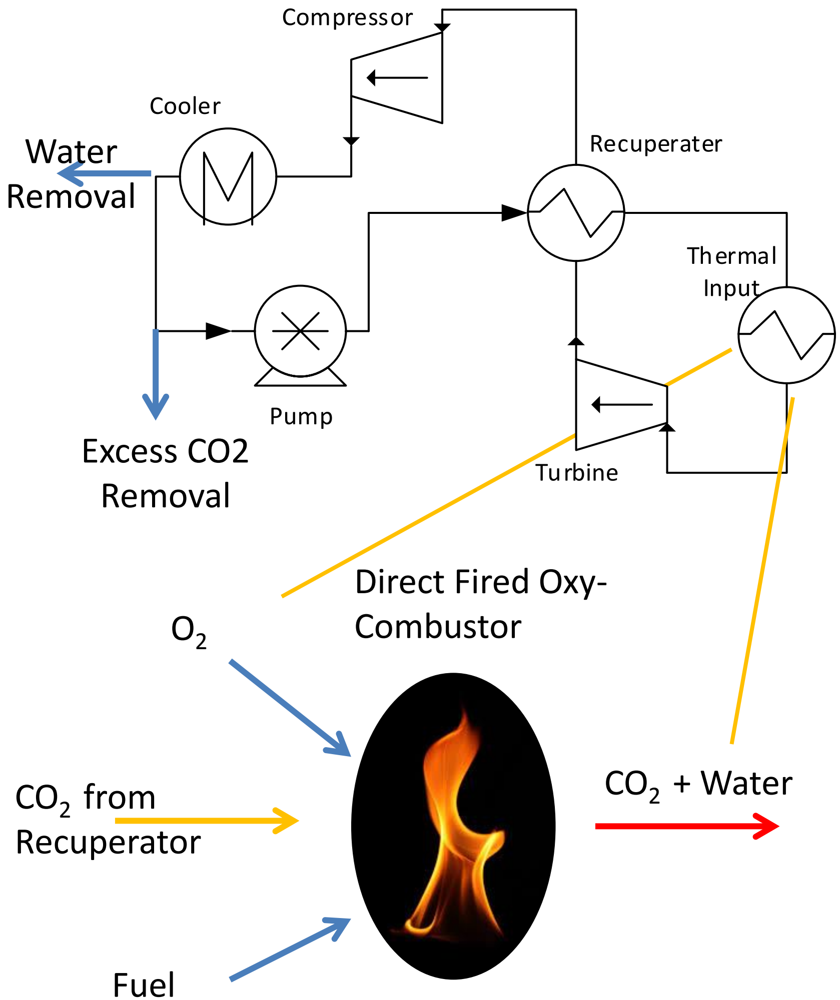


Outline

- Project Objectives
- Data From Bench Top Test
- Combustor Design
- Test Loop Design
- Future Work

Oxy-Combustion



- Oxygen + fuel
- Direct fired sCO2 combustors have a third inert stream
- Challenge:
  – Mix and combust fuel without damaging the combustor

Current Objectives

- Design a 1 MW thermal oxy-fuel combustor capable of generating 1200°C outlet temperature
- Manufacture and assemble a combustor and test loop, and commission oxy-fuel combustor
- Evaluate and characterize combustor performance
  - Optical access for advanced diagnostics

Project Schedule

- Design Phase: June 2018
  - Combustor design
  - Loop design
- Manufacturing construction and commissioning: June 2018 – Dec. 2019
- Test and data collection: Jan 2020 – March 2021

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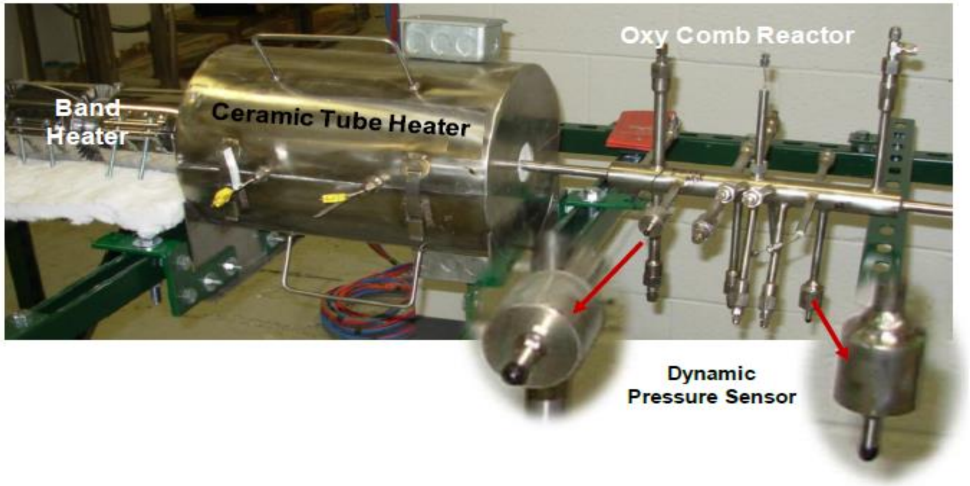
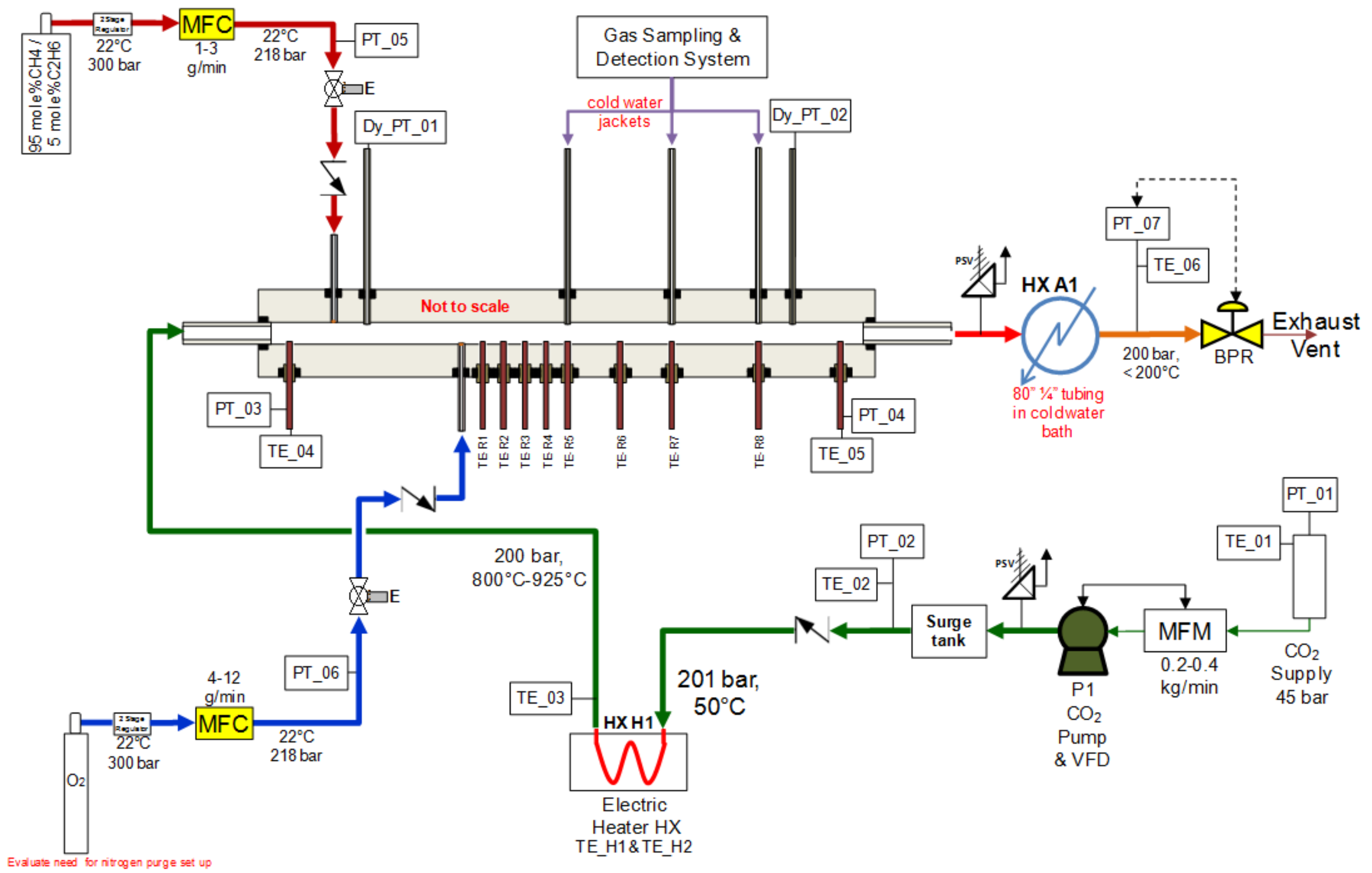
Bench Top Reactor

- 1/4in diameter
- Continuous flow auto-ignition reactor
- Inlet conditions ~900°C and 200bar

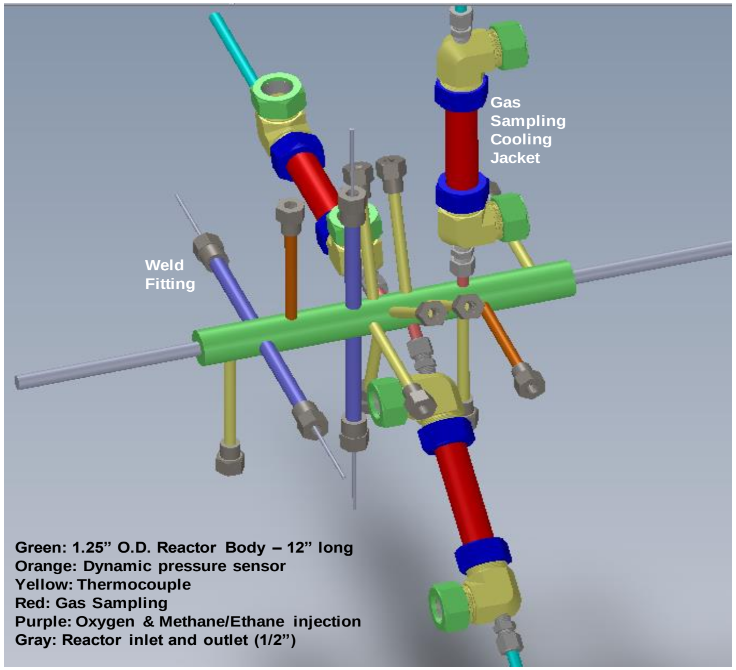


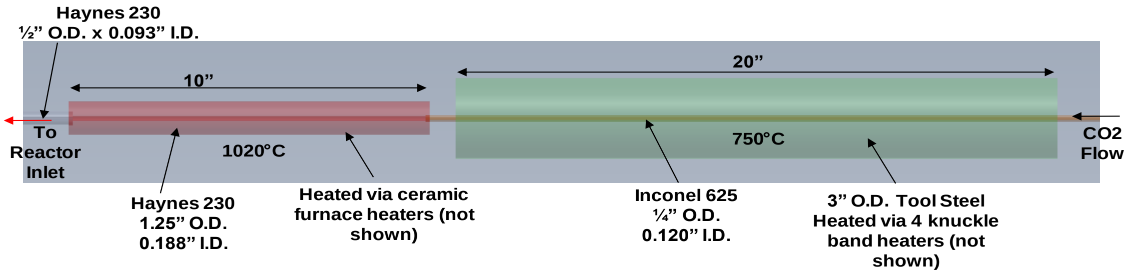
Test Stand Loop Design



Oxy-fuel Test Reactor

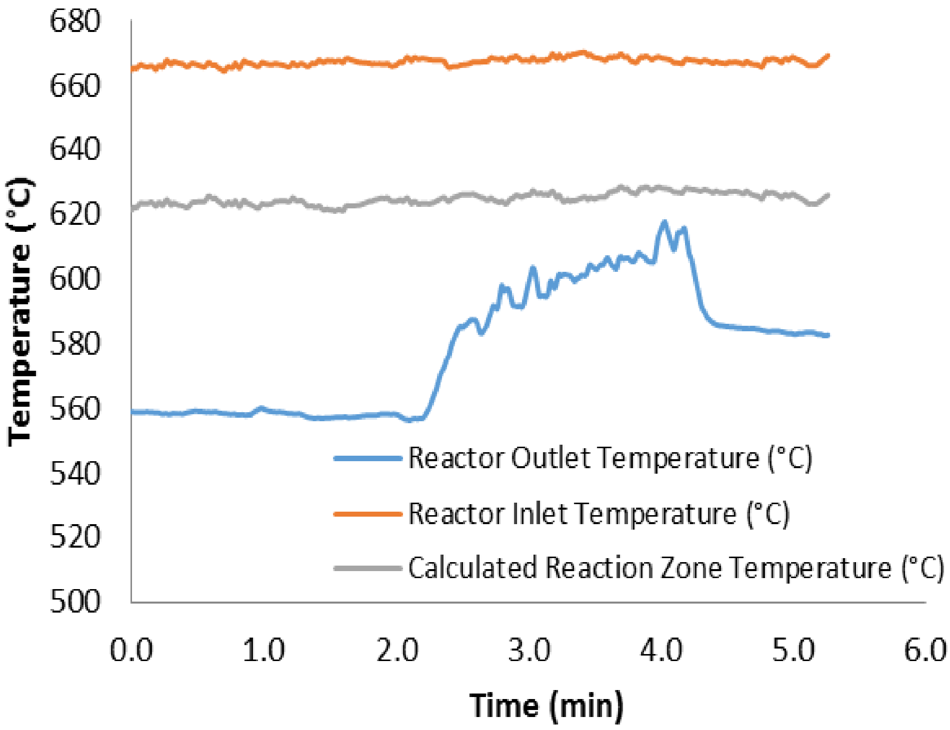
- Machined from Haynes 230 bar stock
- Instrumentation standoff tubes welded to main combustor
- Two stage pre-heater to achieve 925°C combustor inlet
- Water jacketed gas sampling





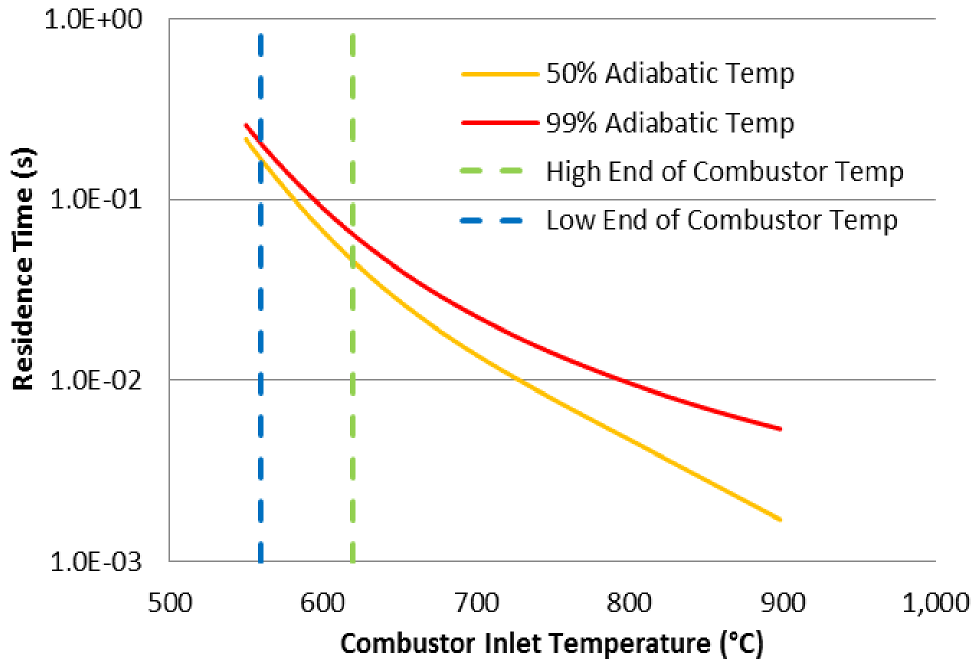
Bench Top Reactor Temperature Profile

- Significant heat transfer within the reactor
- Auto-ignition occurred at a significantly lower temperature than predicted
- Combustion zone temperature calculated based on a constant heat flux assumption
- Combustion zone temperature well below design temperature
  - Sufficient fuel and oxidizer for 1100°C



Reaction Time Scales

- Time scales for premixed combustion
- Combustion zone residence time was ~0.2s
- At these temperatures, combustion and residence time scales are similar



Results Discussion

- Fuel and oxidizer were sufficient to raise outlet temperature to ~1100°C
- Why didn't it?
  - Mixing time
  - Chemical kinetics
  - Heat transfer and wall effects
- Auto ignition occurred at high concentrations of CO_2 at ~620°C

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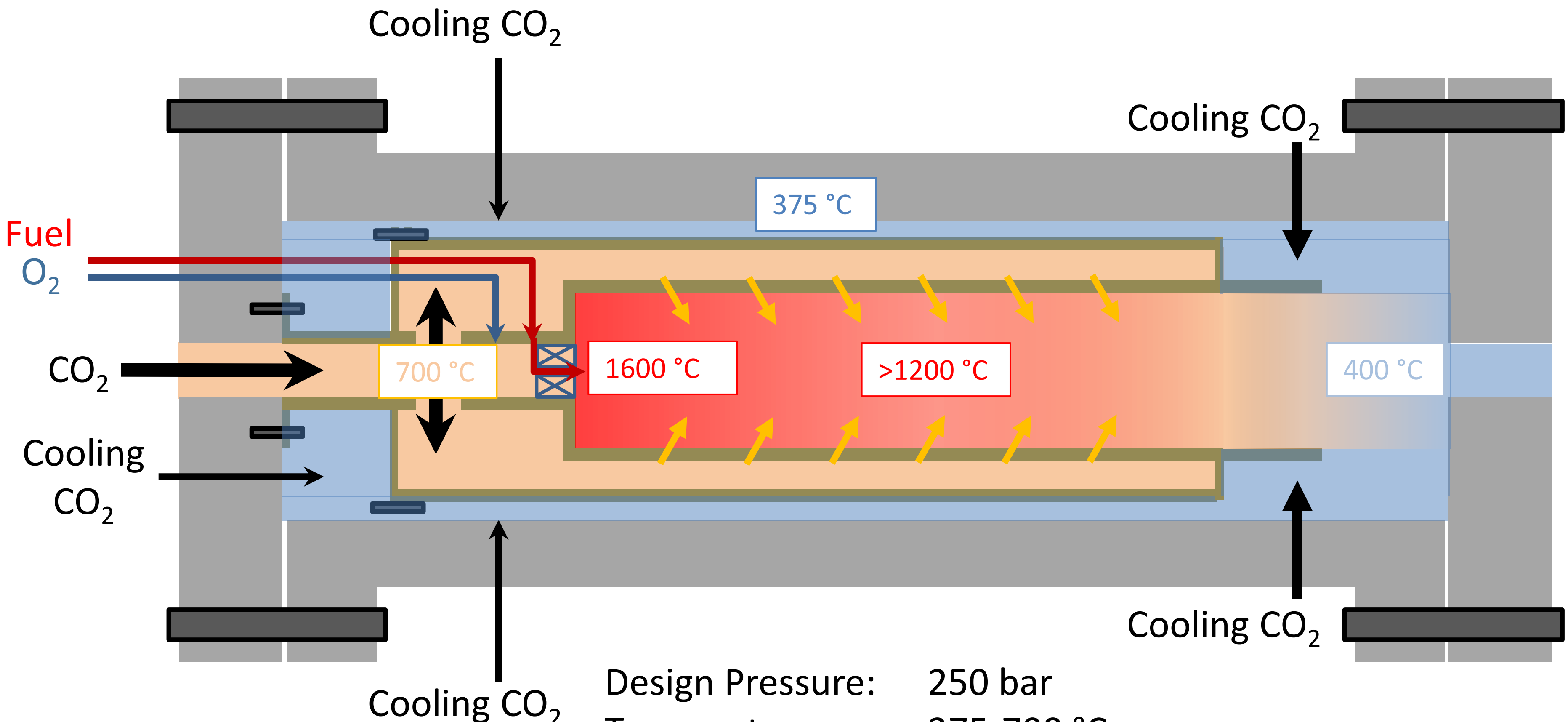
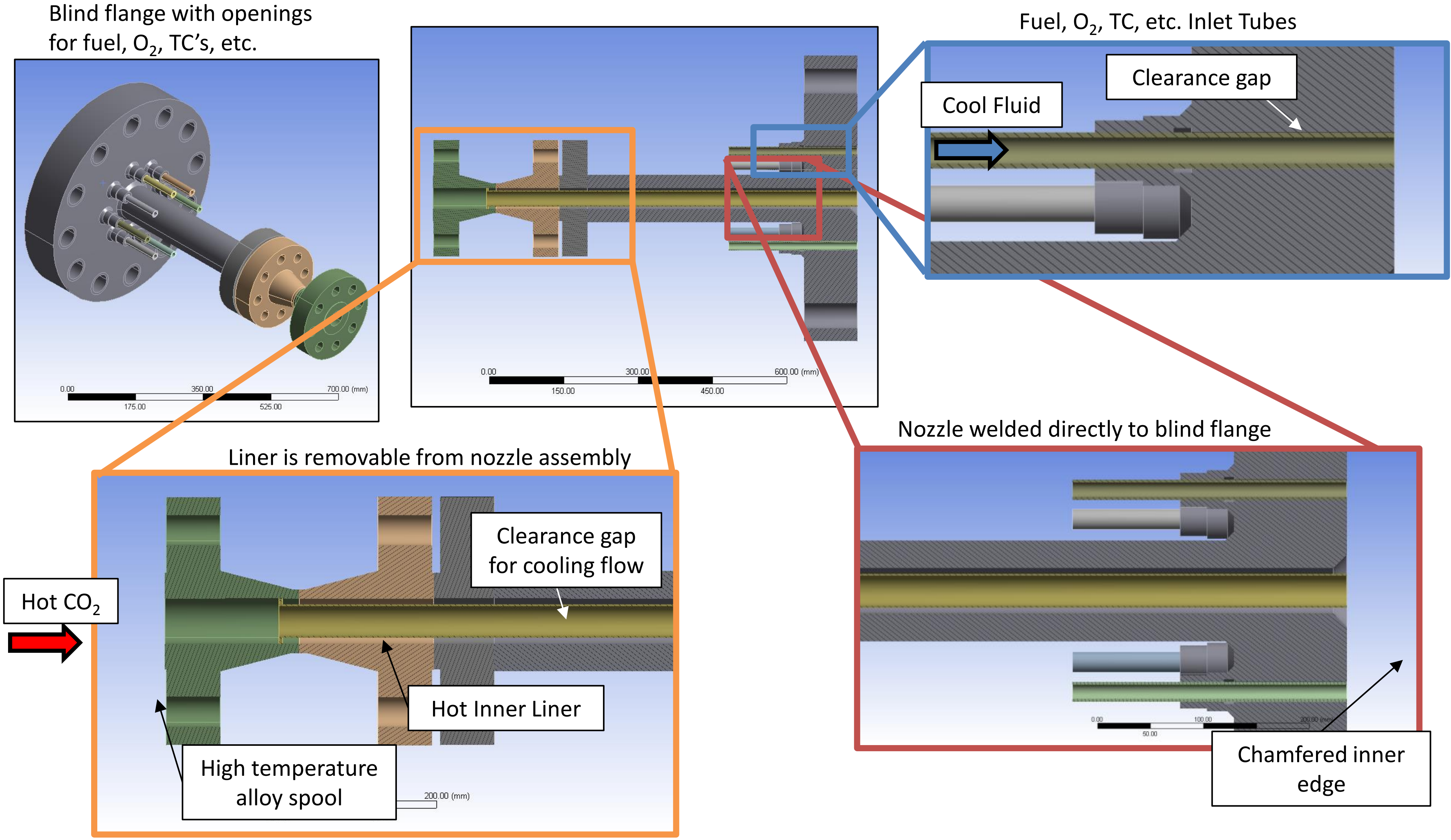
Cylindrical casing designed for 450 °C, 250 bar

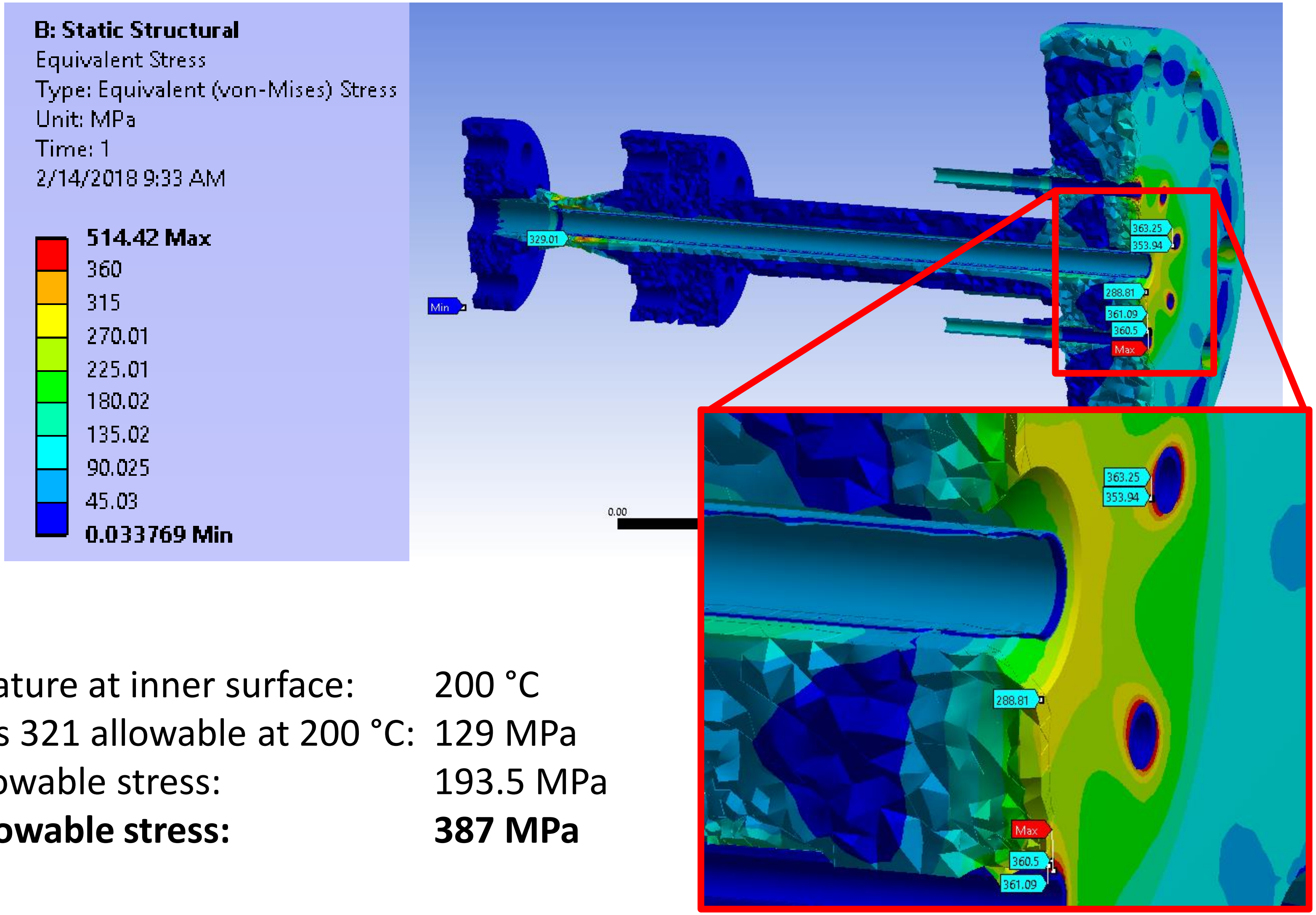


Design Pressure:	250 bar
Temperature:	375-700 °C
Material:	321 stainless steel
Casing ID:	10.13 in

Use of cooling flows reduces casing exposure temperatures for inlet blind flange

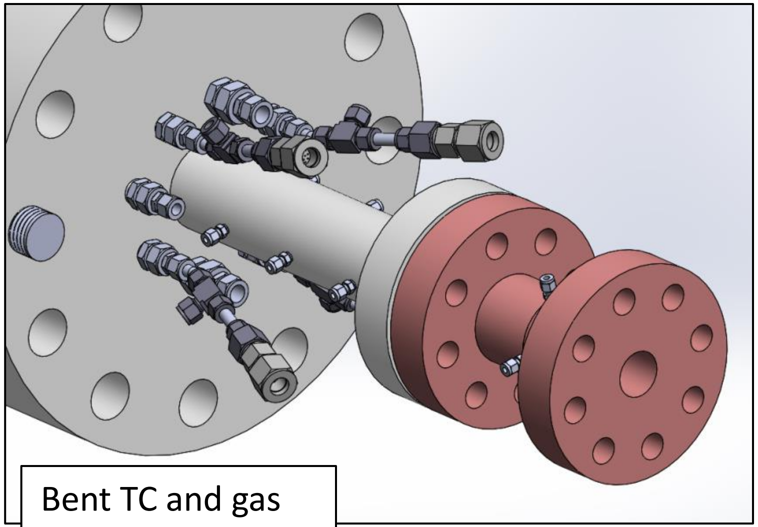


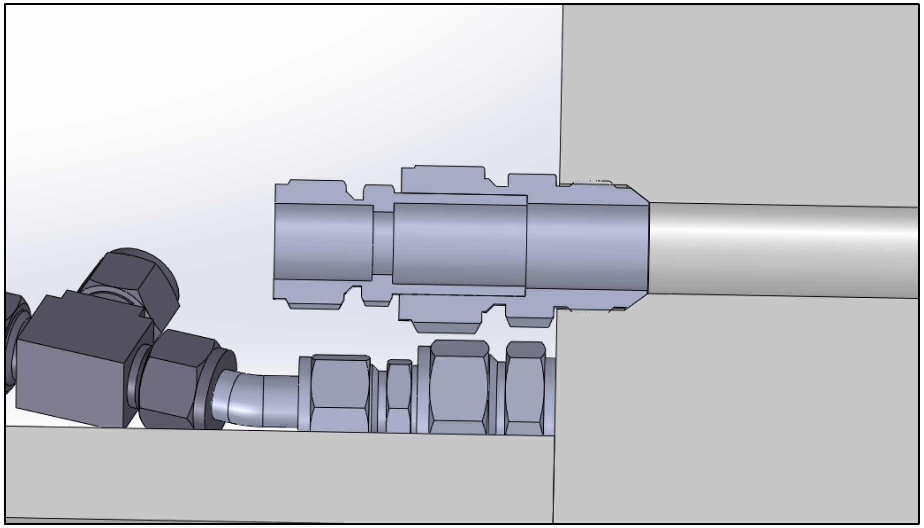
Stress highest near inlet connection to reinforcement collar, in blind flange, and near tube connections



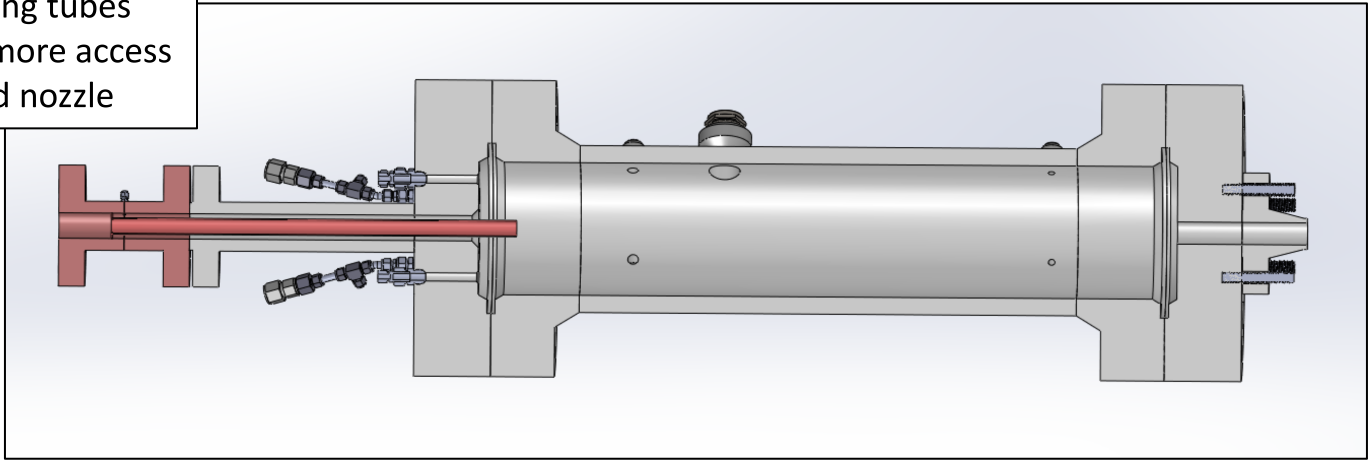
Temperature at inner surface: 200 °C
Stainless 321 allowable at 200 °C: 129 MPa
1.5x Allowable stress: 193.5 MPa
3.0x Allowable stress: 387 MPa

Use of AN fittings directly machined into combustor case eliminates potential leak paths

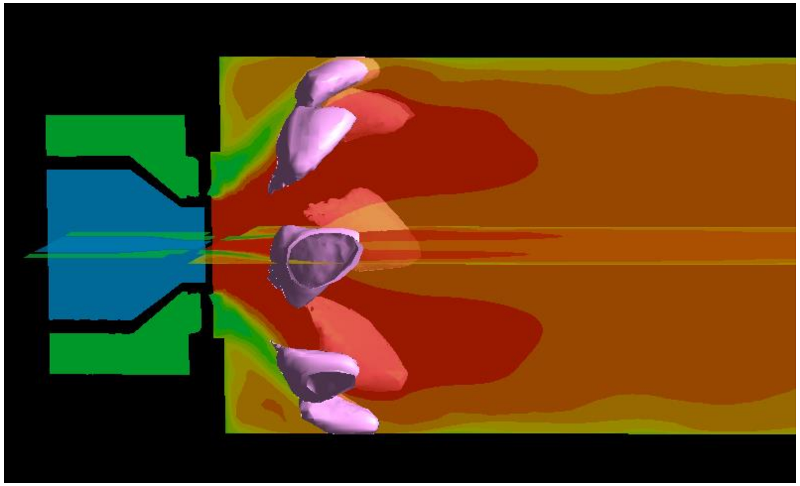




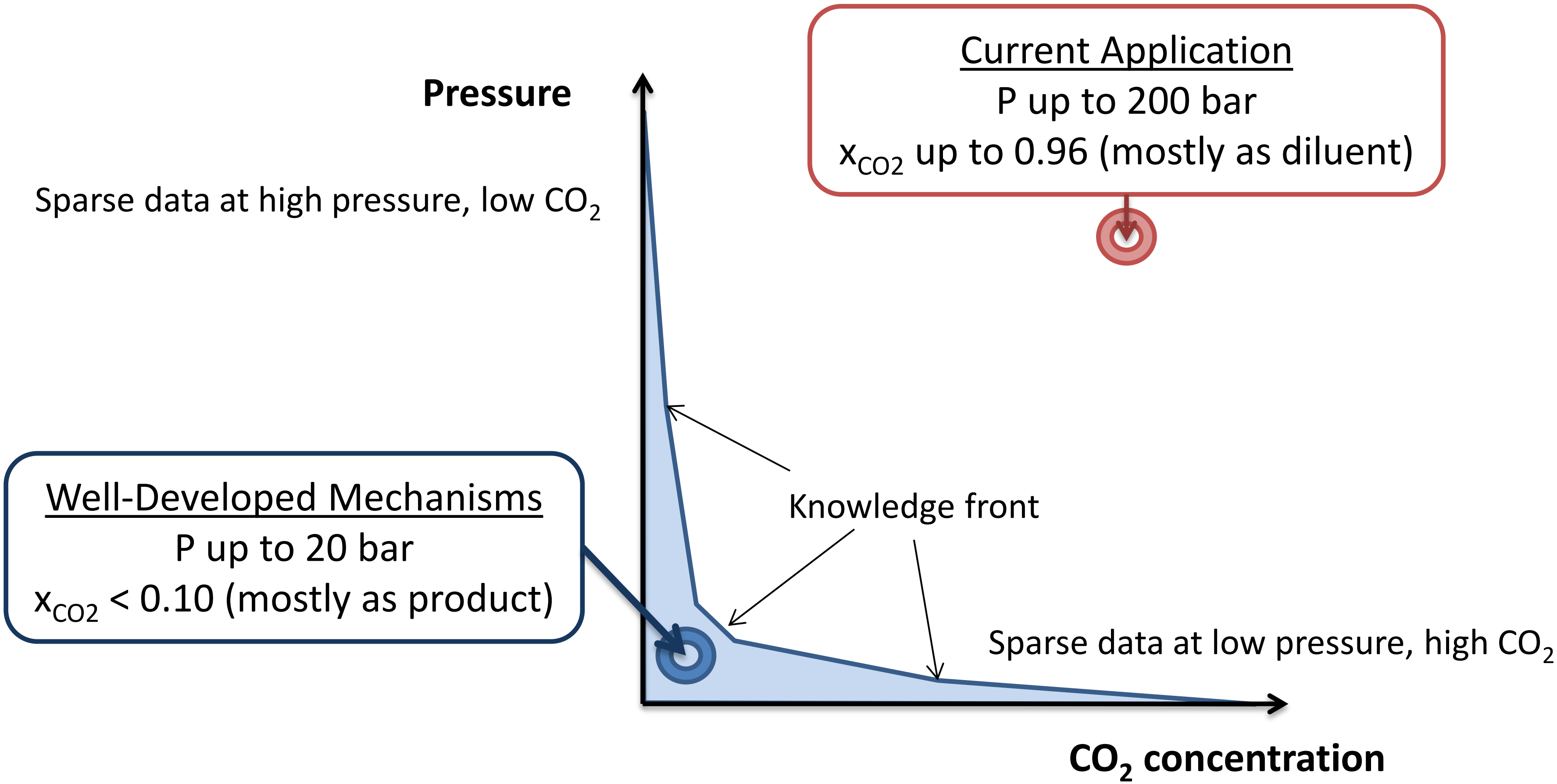
Bent TC and gas sampling tubes gives more access around nozzle



Combustor Aero-Thermal Design



Kinetics Knowledge Base

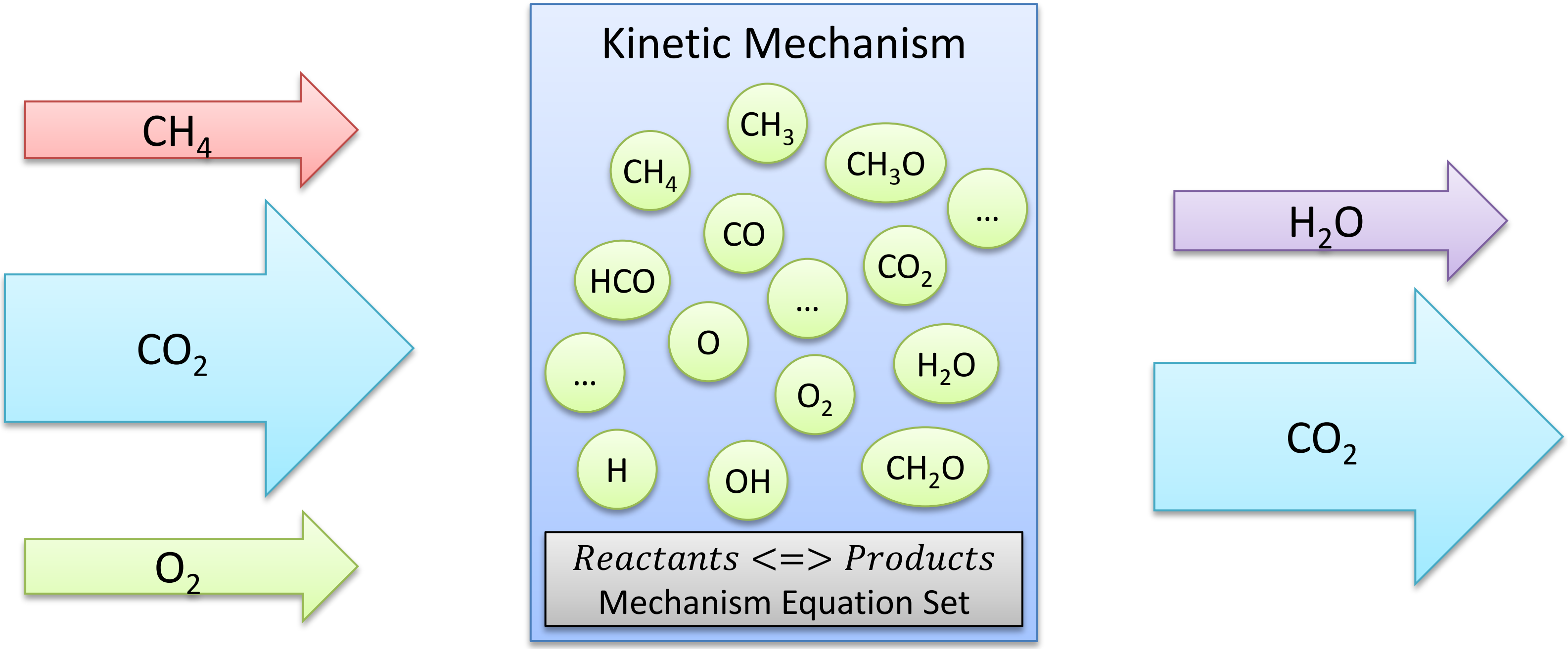


Limited data available – Current UCF and Georgia Tech projects

Chemical Reaction Kinetics

Overall Reaction: $CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$

Actual reaction is made of hundreds of intermediate chemical reactions with dozens of intermediate chemical species.

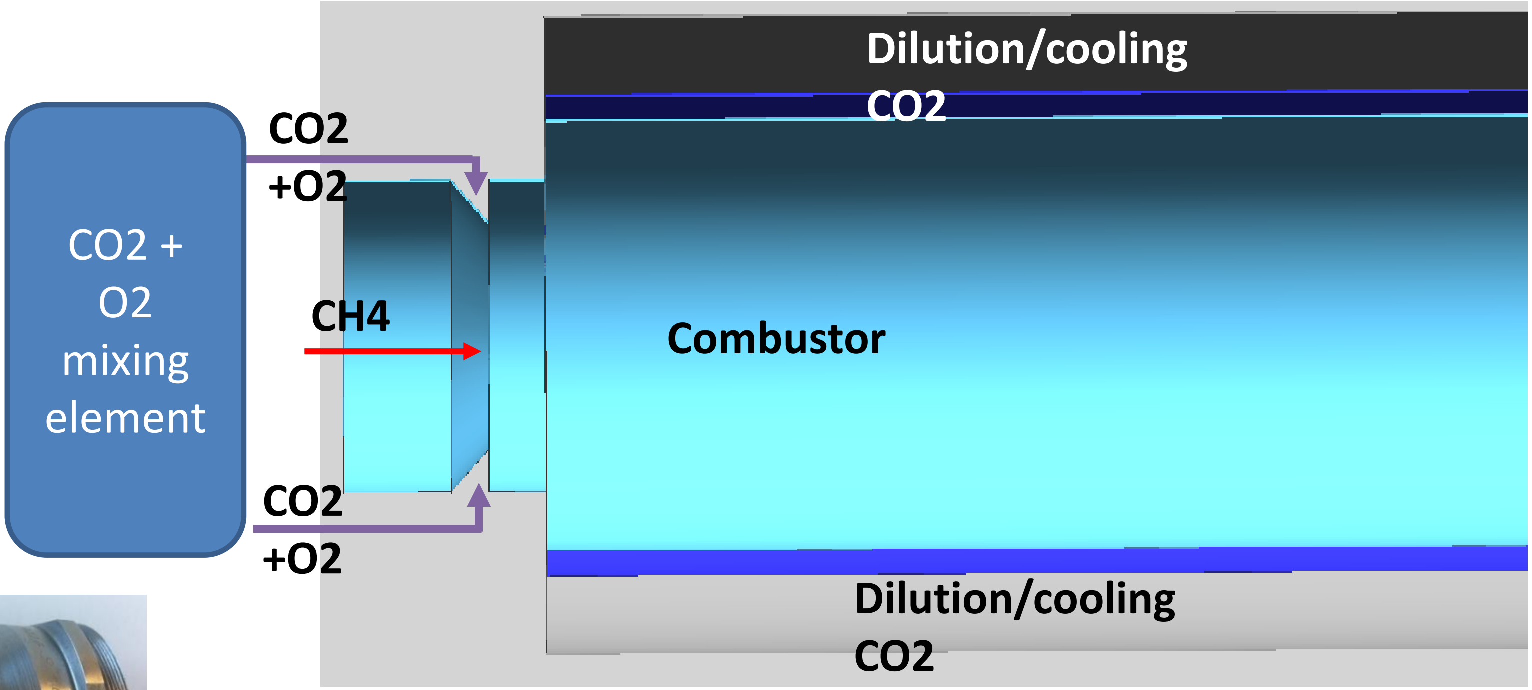


Current simulations employ mechanism created by Georgia Tech.
Leverages 12 chemical species and 25 reactions.

Computational Design

- Early design efforts constrained by high inlet temperatures needed to operate in a recompression cycle ~900°C combustor inlet
- Recuperator technology unlikely to be able to support those temperature in the near future
- Lower inlet temperature allow for easier design of submerged aerodynamic components
- Auto-ignition, sudden expansion, trapped vortex and swirl type injection explored

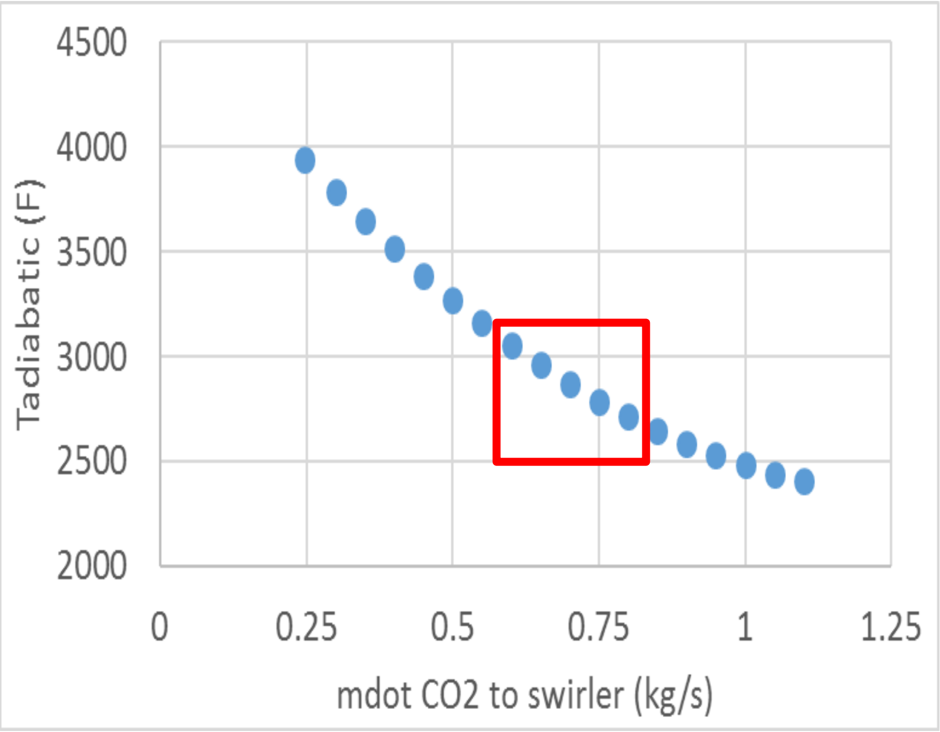
Schematic of Combustor Design Concept



- Basis: DLN-1 primary fuel nozzle
- Wide operability, stable flame, and extensive experience with this design

Range of CO_2 Flow Splits to Primary Combustor & Bypass Cooling

Component	Mass Flow (kg/s)
CH_4	0.02
O_2	0.08
CO_2 to combustor	0.6 - 0.8
CO_2 to bypass	0.925 – 0.725
Total mass flow	1.625



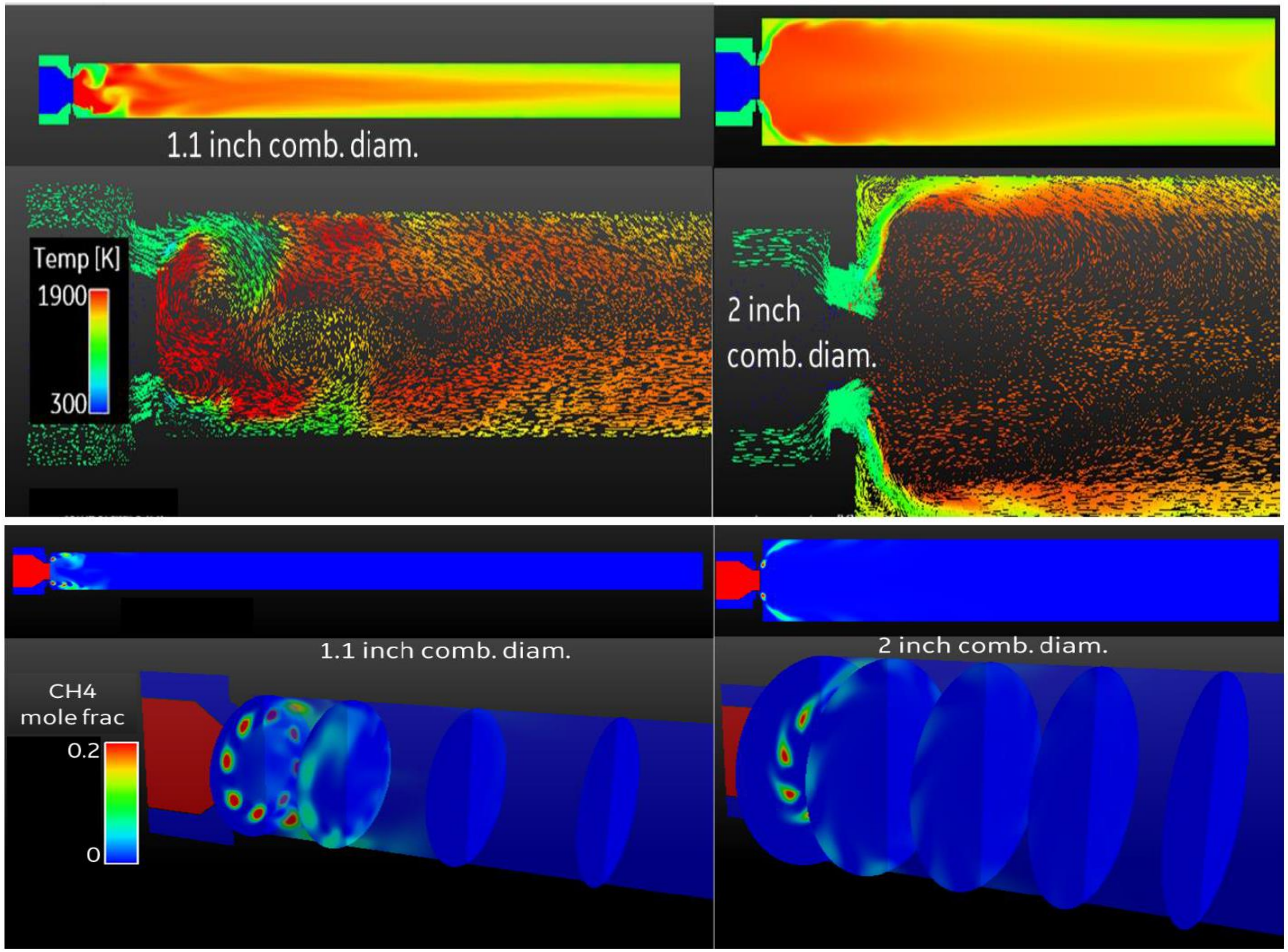
Aiming for $T_{adiabatic}$ = 2700-3000 F for flame stability

Combustor Design Point

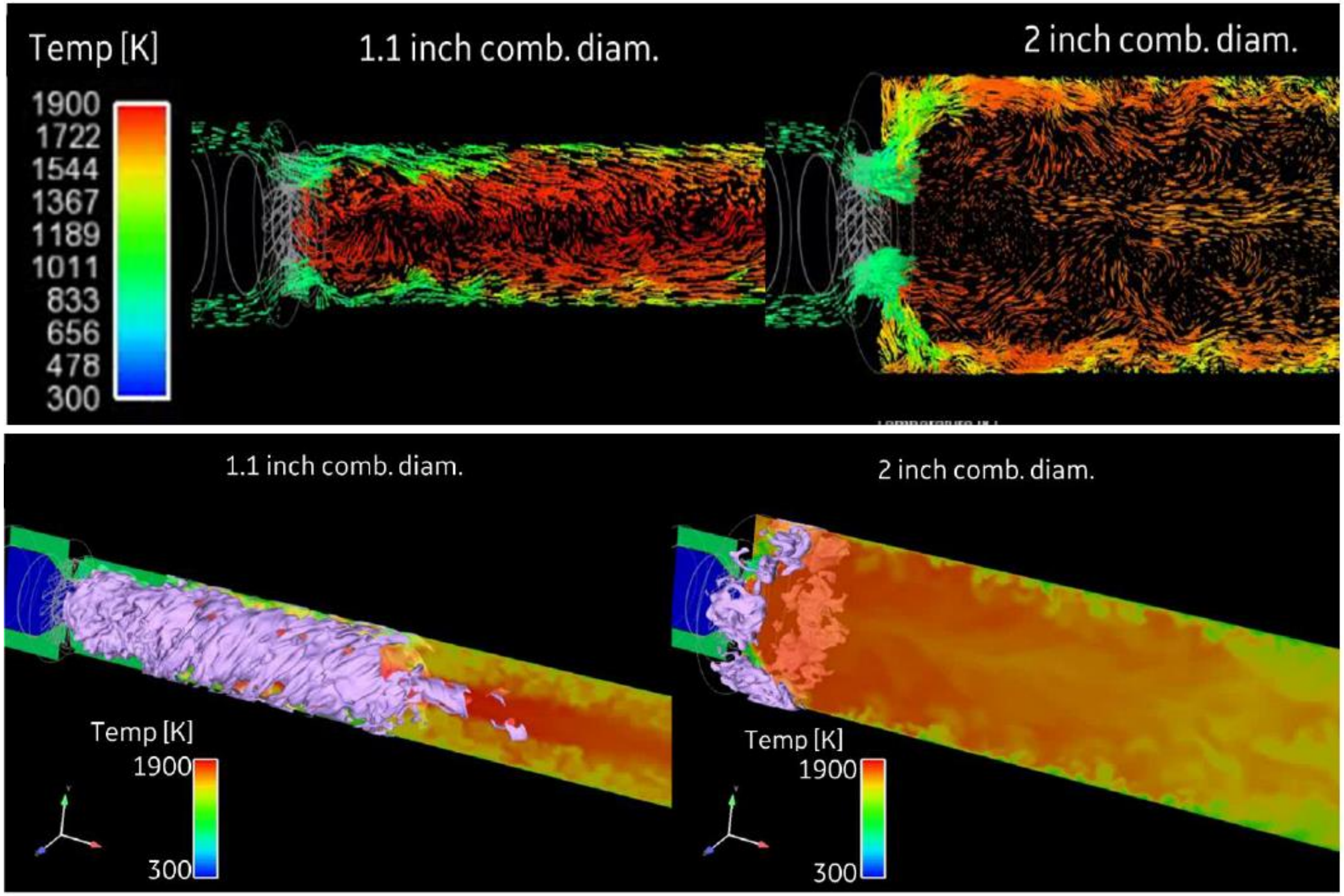
Component	Mass Flow (kg/s)
CH4	0.02
O2	0.08
CO2 to combustor	0.626
CO2 to bypass	0.899
Total mass flow	1.625

- Design point for adiabatic flame temperature of 3000 F
- CO2 flow distributed as diluent or as bypass as shown above
- GE in-house spreadsheet tools used to determine effective area and combustor size

GE RANS Simulations

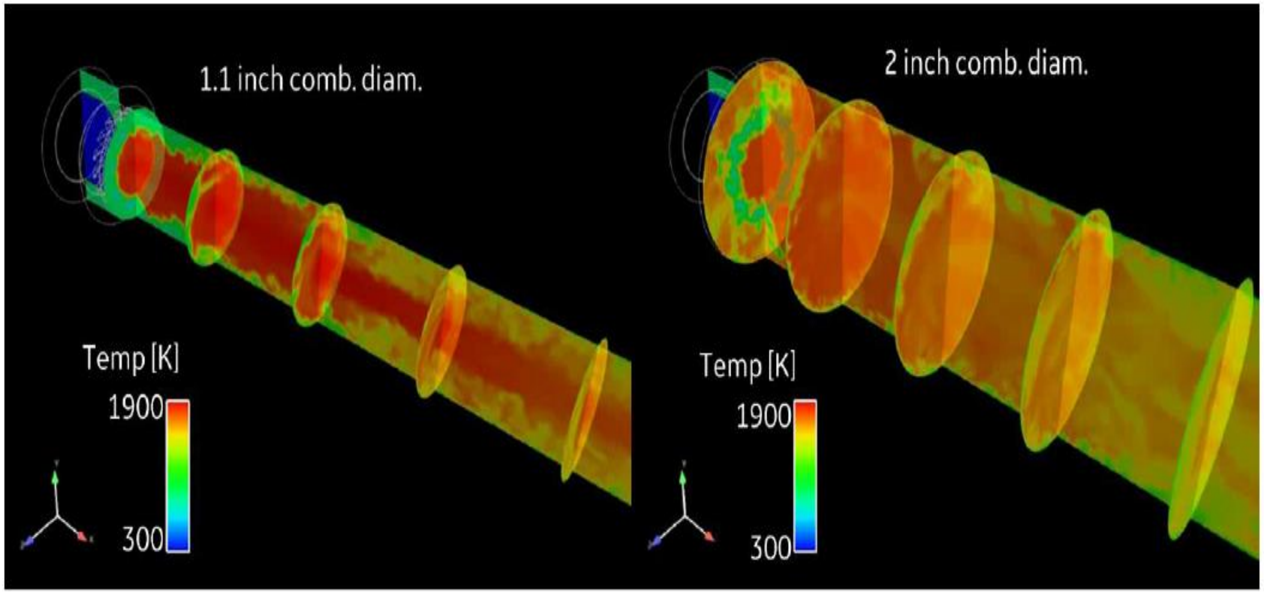


GE LES Simulations



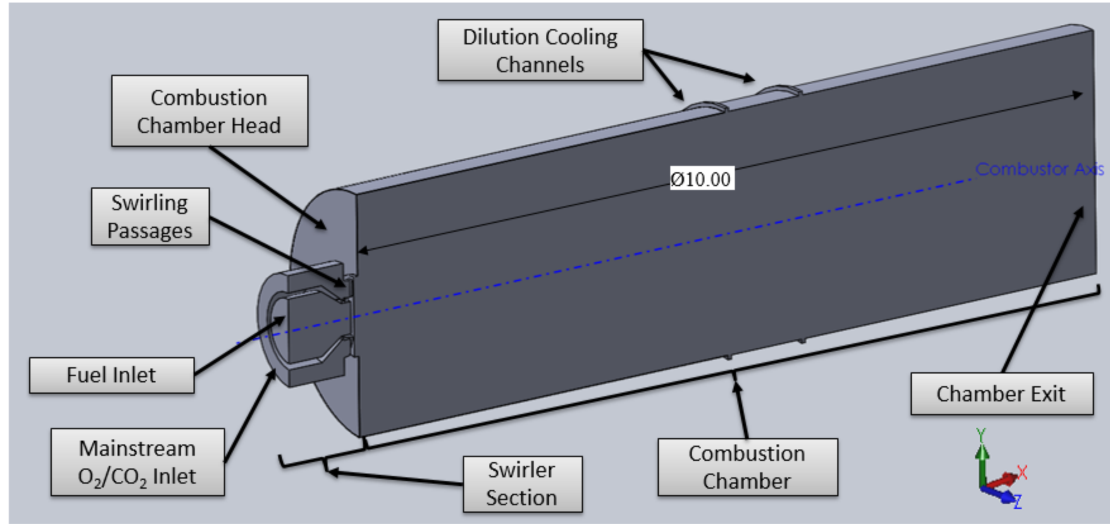
GE Results

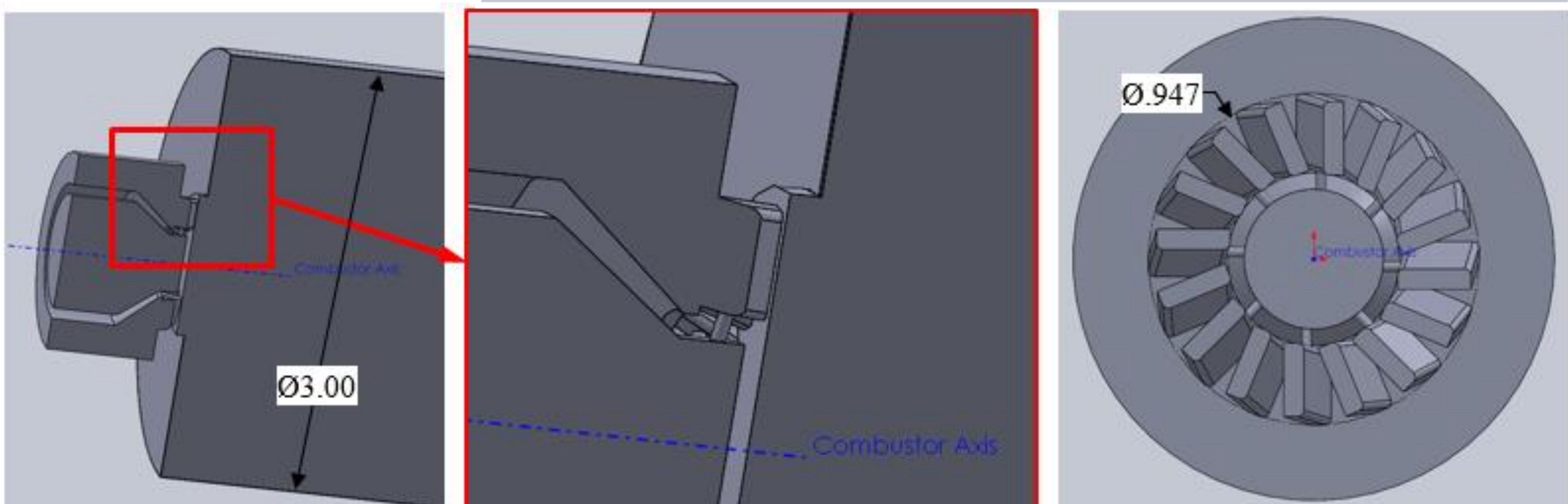
- 2in diameter combustor performed significantly better than 1.1in diameter
- Further variations in combustor sizing/residence time to be considered



Combustor Geometry

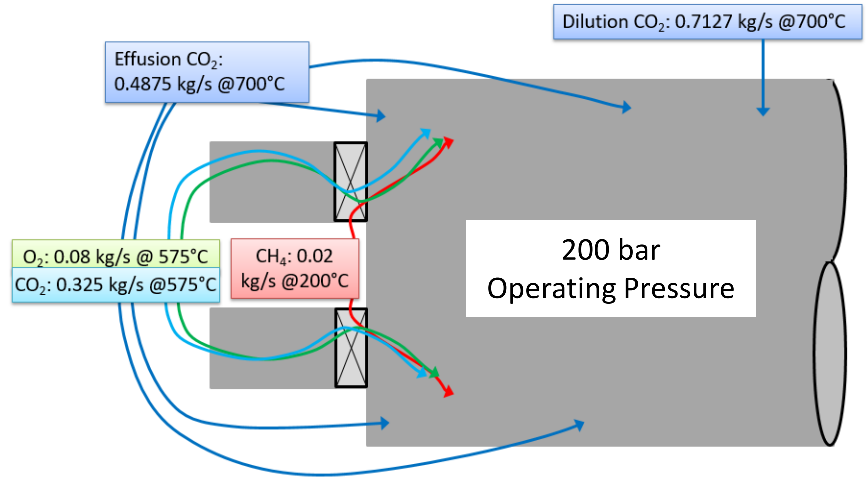
- 0.05” wide dilution cooling slots, 1” apart
- 16 swirling channels, 0.506”(h) x 0.207”(w), 40° radial swirl w/ 10°down angle
- 8 fuel injectors

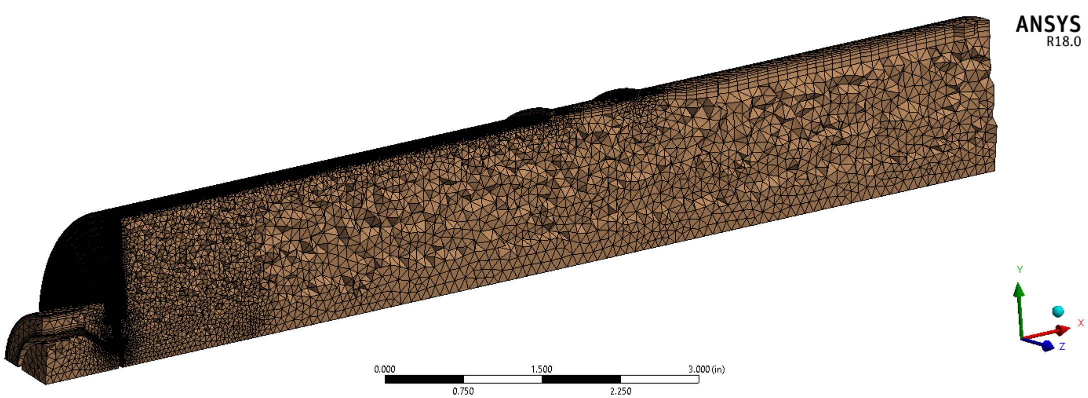


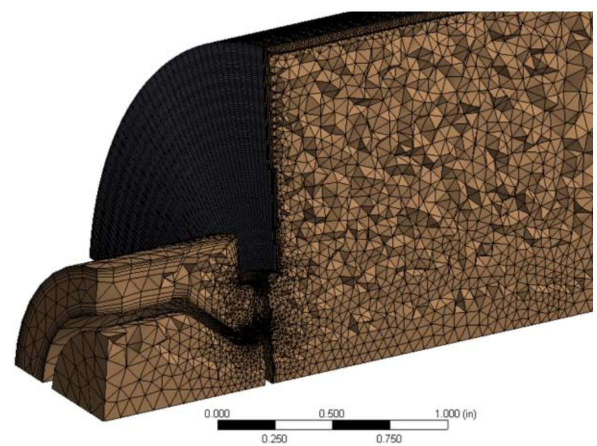


CFD Domain and Setup

- Computational domain:
  - ¼ Domain w/ periodic boundaries
  - 1.125 MM elements
  - 5-6 Wall inflation layers
- CFD Modeling Setup:
  - Pseudo Steady State RANS, Realizable k-ϵ model, Standard wall function
  - Compressibility, Ideal Gas EOS, C_p polynomials, gas mixture rules
  - Pressure outlet @ 2% total pressure loss
  - Mass flow inlets





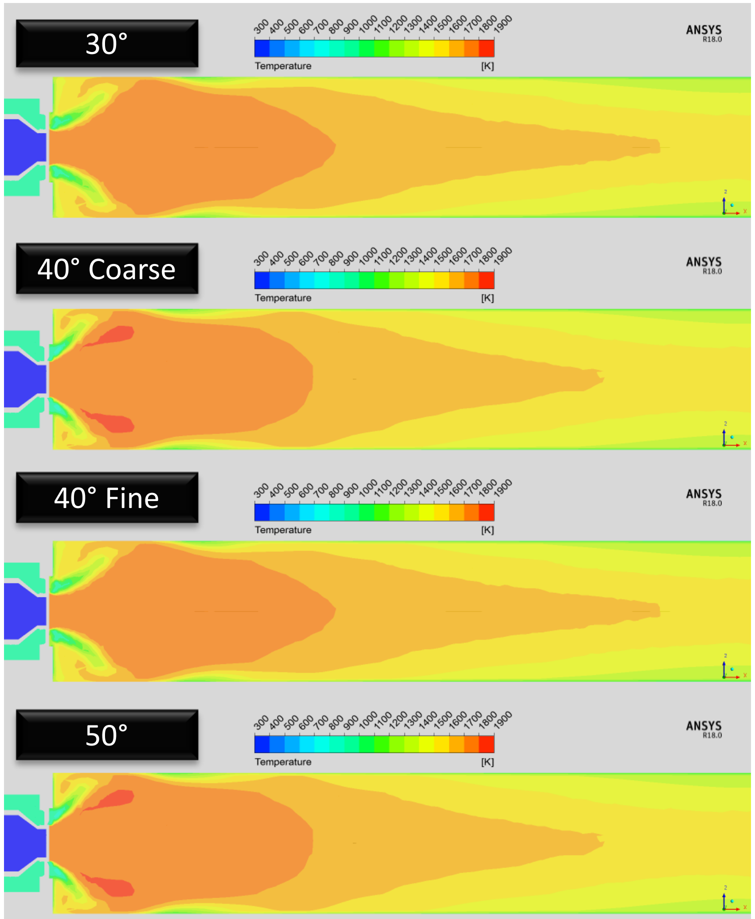


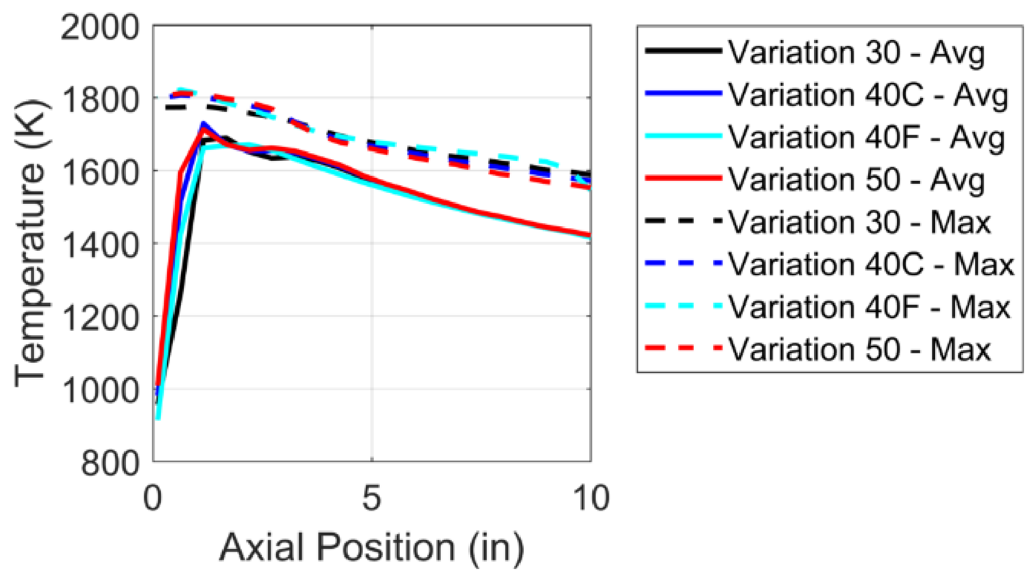
Design and Off-design CFD Boundary Conditions

- Design point simulations
- Off-Design: Unique problem of sCO2 oxy-fuel combustion is the cold startup case
  - Roughly order magnitude change in density

	Design Point	Cold Start	Fast Start
CO_2 Mass Flow (kg/s)	1.53	1.02	1.02
Pressure (bar)	200.00	133.33	133.33
CO_2 Inlet Temp (°C)	700	50	150
CO_2 Density (kg/m^3)	104.2	649.4	203.5
O_2 Mass Flow (kg/s)	0.0806	0.0806	0.1360
CH_4 Mass Flow (kg/s)	0.0200	0.0200	0.0338

Temperature Predictions





CO Concentrations

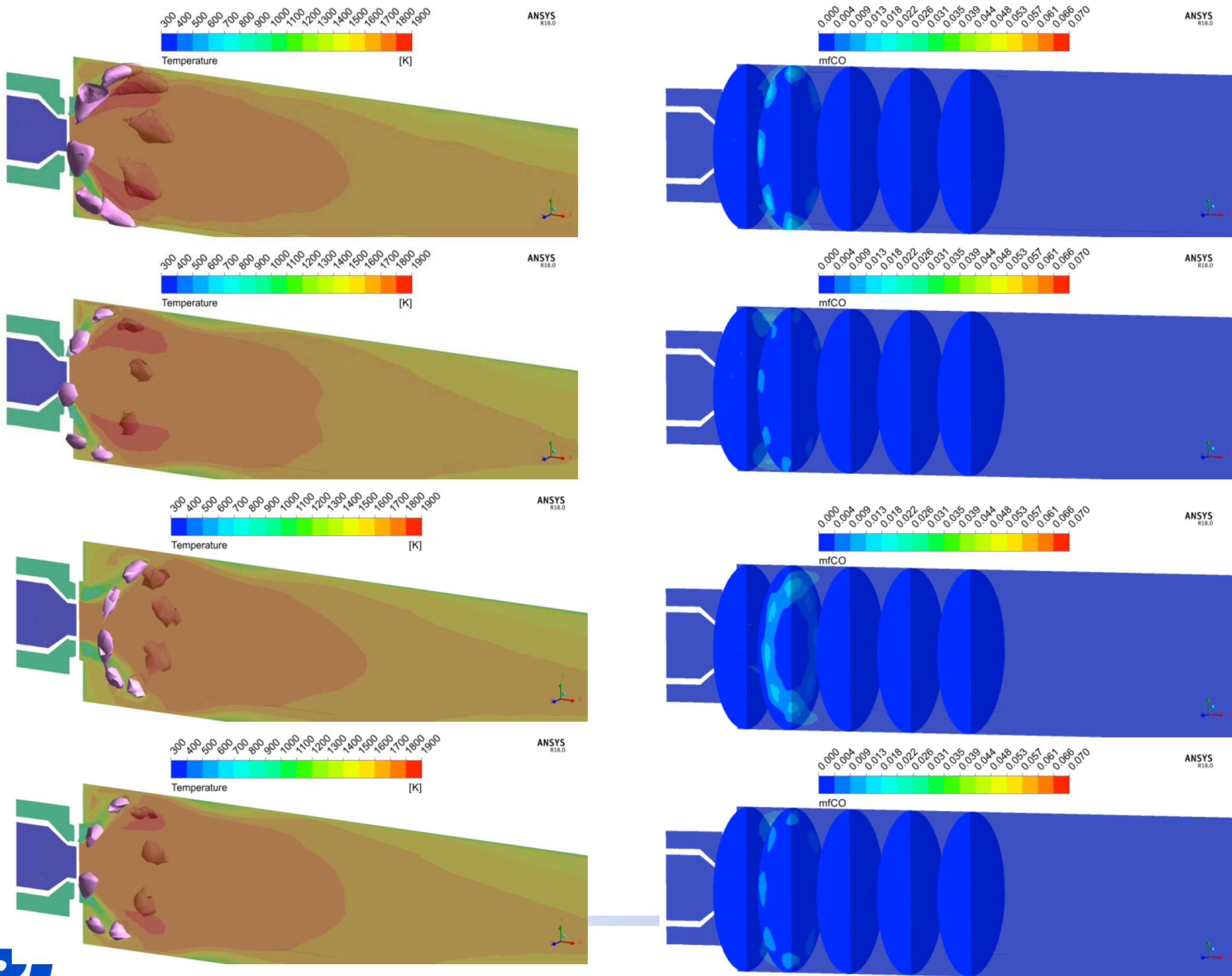
30°

40° Coarse

Light Purple zones are for mole fraction CO=0.008

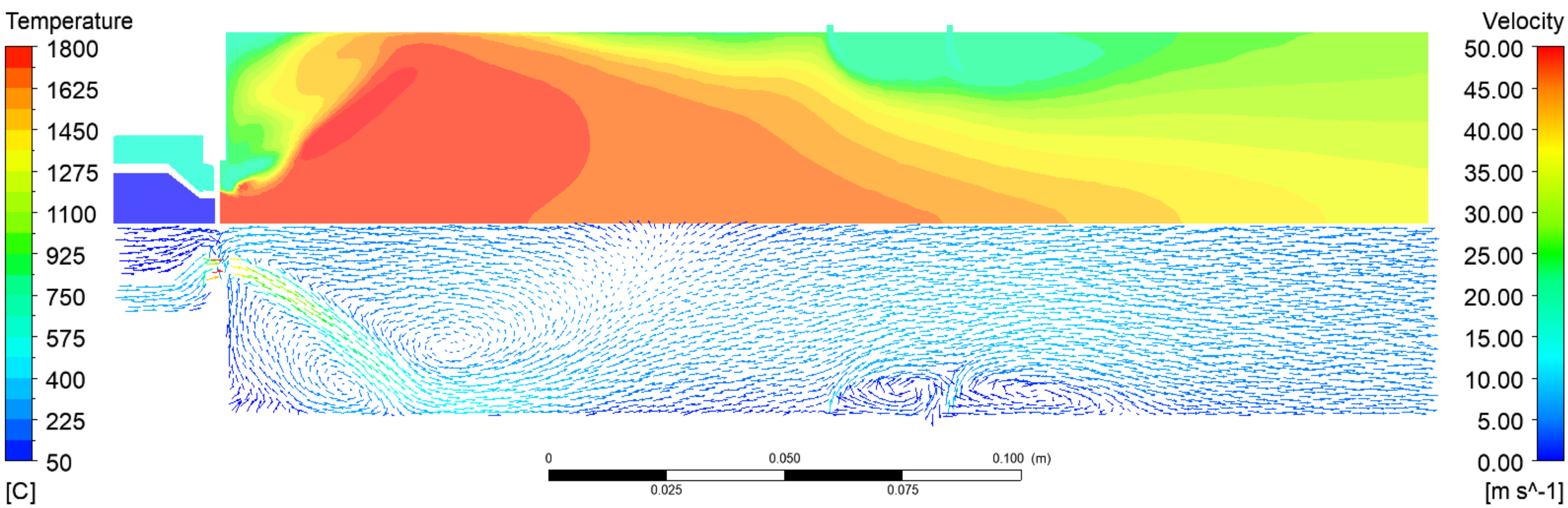
40° Fine

50°



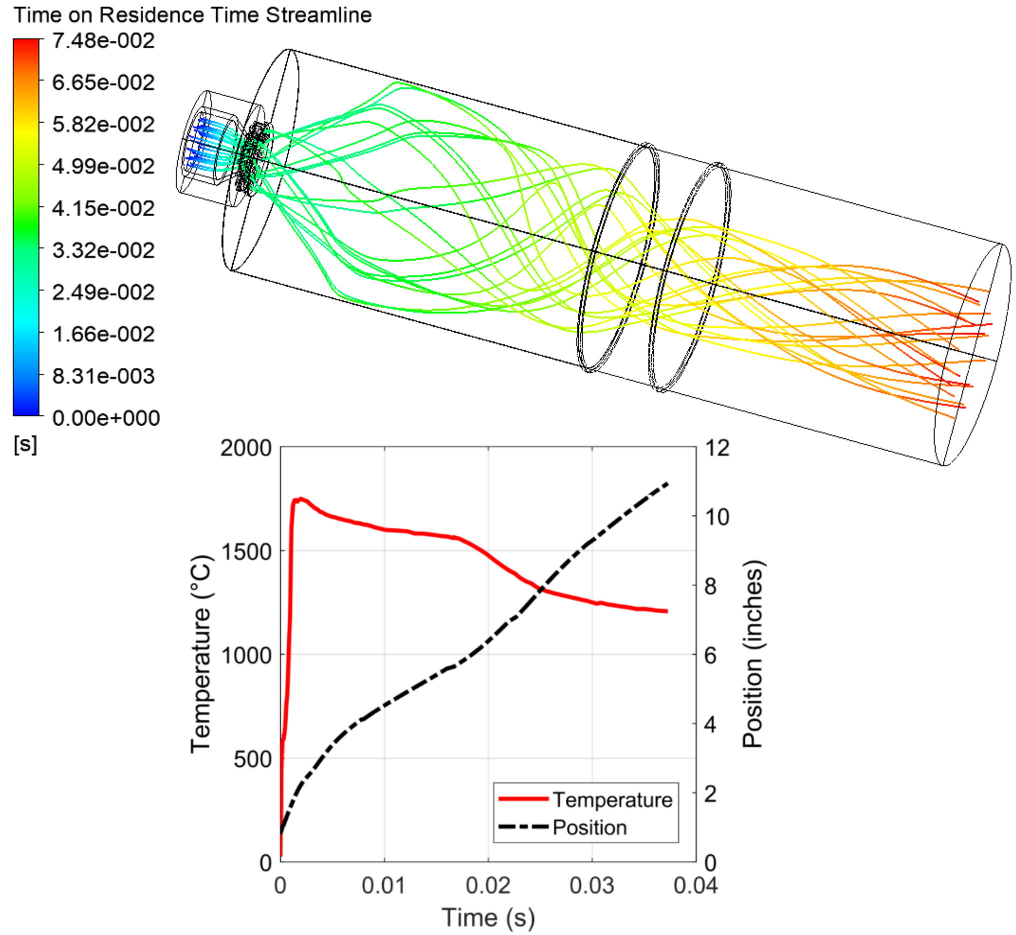
Selected Results with Dilution

- Fairly strong recirculation zone
- High temperature near walls
  - Adiabatic wall boundary conditions
  - Additional cooling



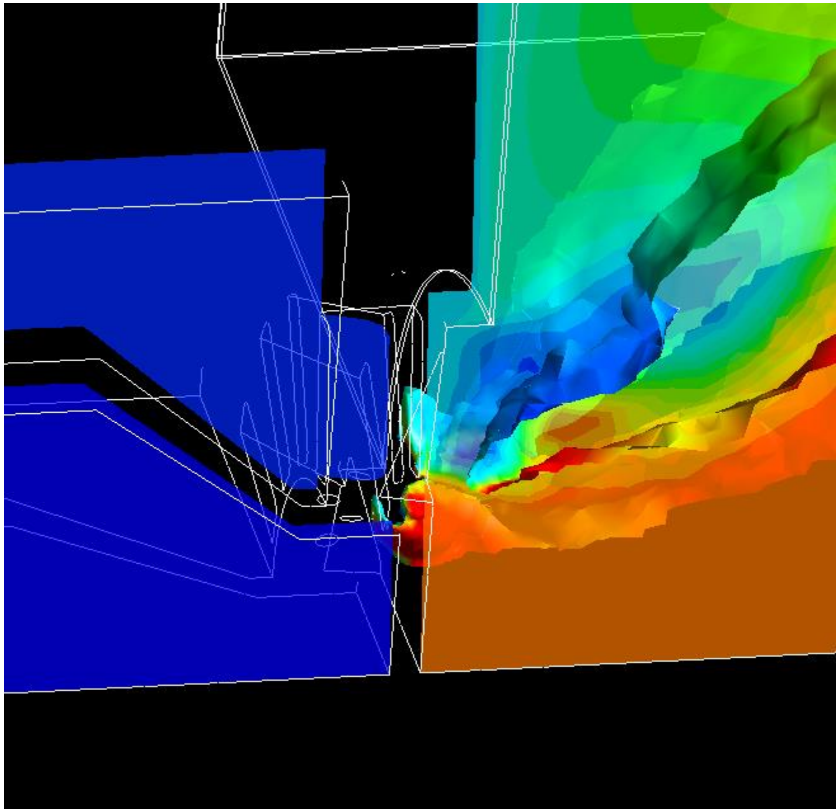
Residence Time

- Combustor is designed to allow for a fairly long residence time
- For fluid not trapped in recirculation – ~0.02s in primary zone



Possible Flame Hold Concerns

- Partially premixed injector
- Kinetics as faster than anticipated
- Startup case where velocity is much lower than design point



Simulations

- Rapid iteration on geometry variations
  - RANS
  - Relatively course Tet meshes
  - Reduced mechanism
- Design and off-design cases considered
- Effort to develop a functional 1MWth scale oxy-fuel combustor

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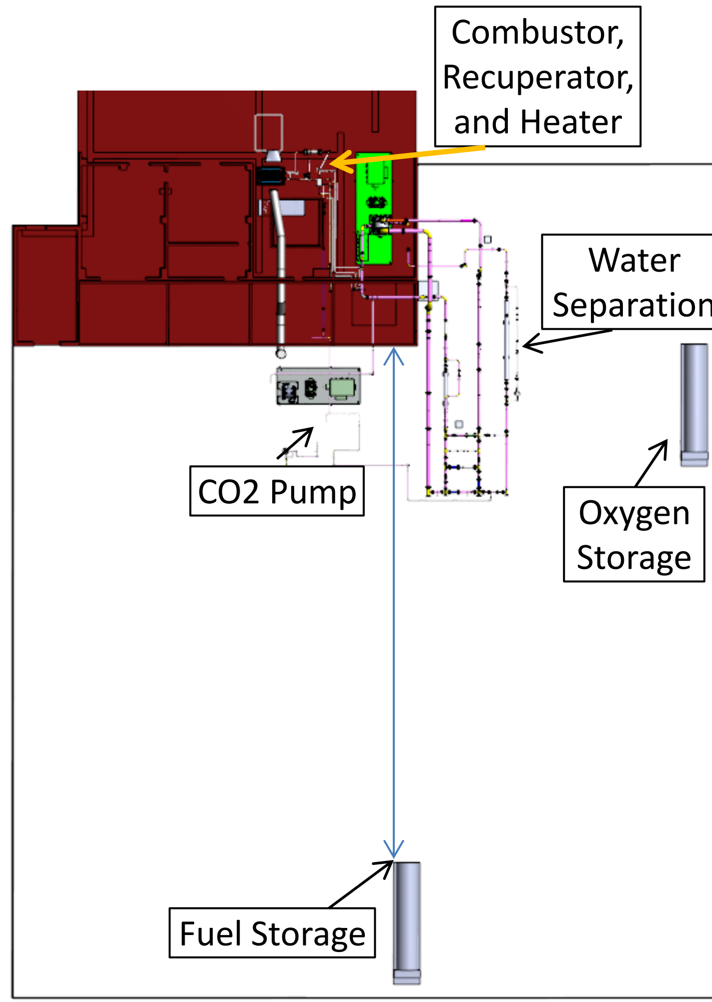
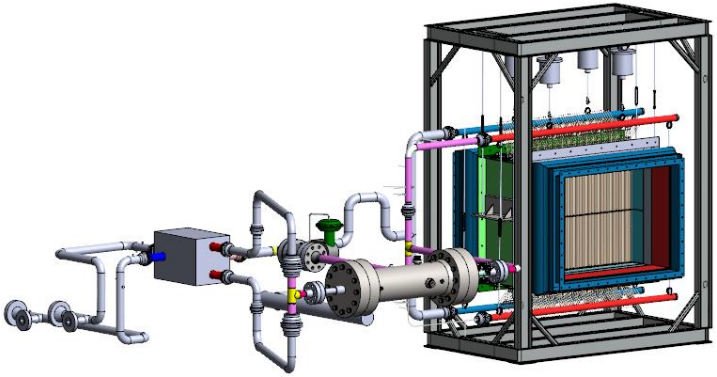
SwRI sCO2 Facility

- Turbo Machinery Research Facility, located in San Antonio, TX



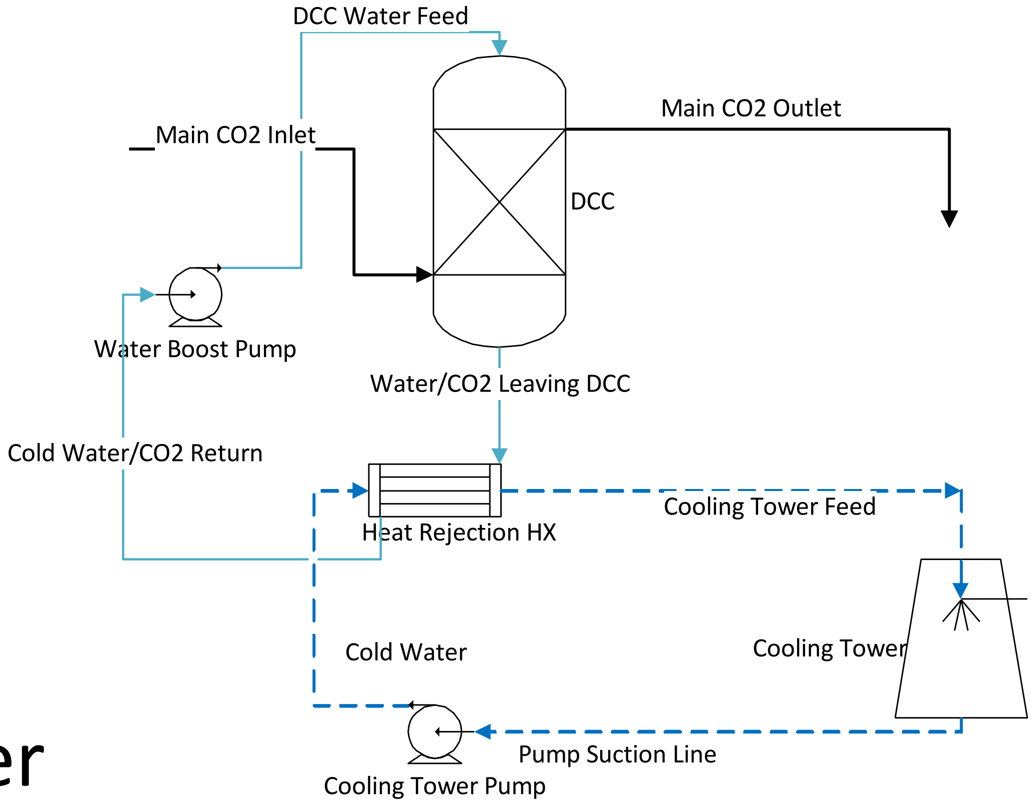
Sunshot Test Loop

- The project will make use of a an existing sCO2 loop at SwRI
- Sunshot turbine will be replaced with letdown valve
- Addition of water separation
- Various other systems to support combustion testing



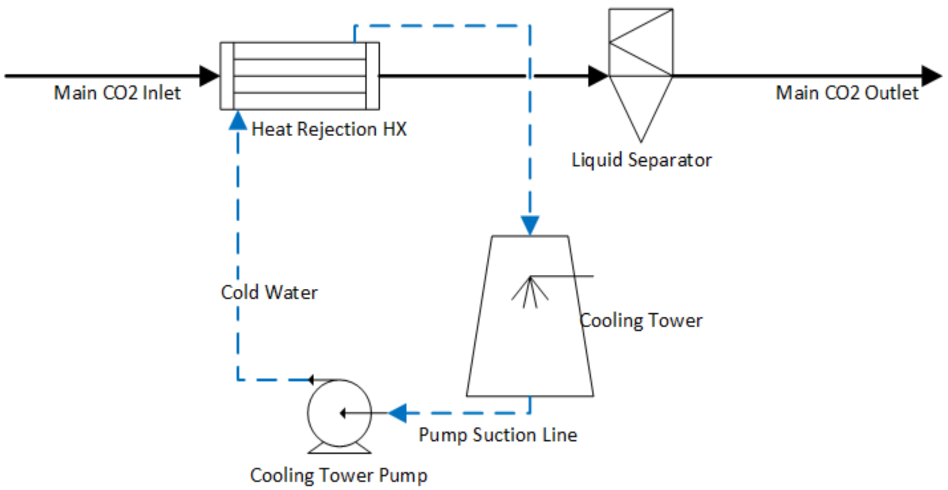
Water Separation (DCC)

- Water is not particularly soluble in CO_2 below 100°C
- Cascaded water system prevents excess CO_2 loss from cooling water



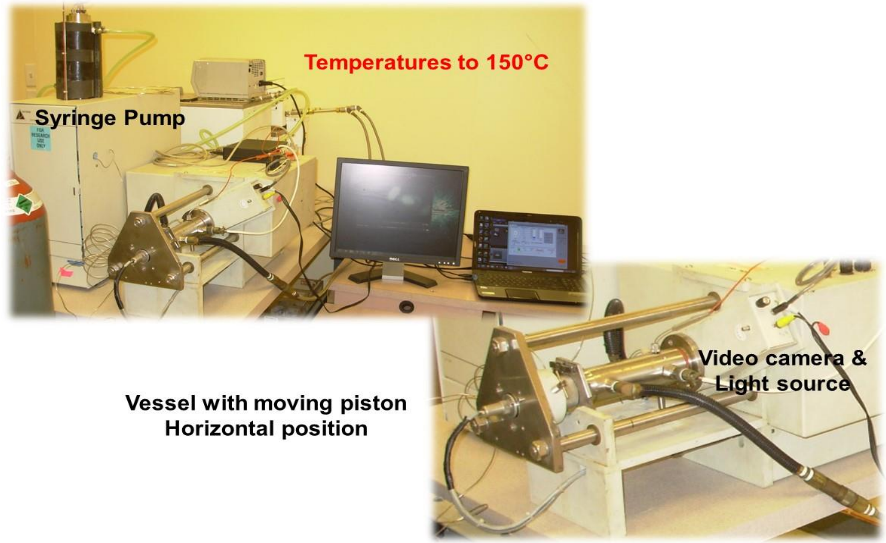
Water Separation (Inertial Separator)

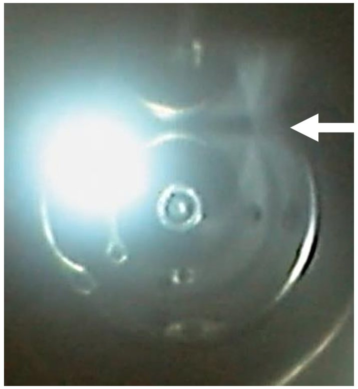
- Heat exchanger to bring temperature down
- Multistage separator system to remove liquid water
- After reviewing both option, a separator has been selected

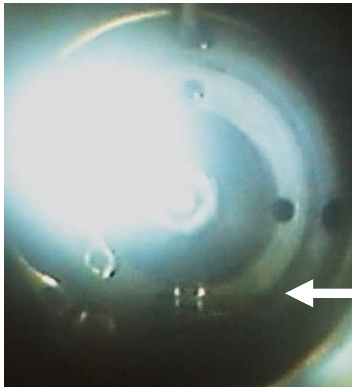


Water/CO_2 Equilibrium Testing

- Phase equilibrium test ongoing at Thar Energy
- Testing to confirm solubility limits of water in CO_2
- Needed for modeling of water separation
- Results confirm water fully condenses from CO_2







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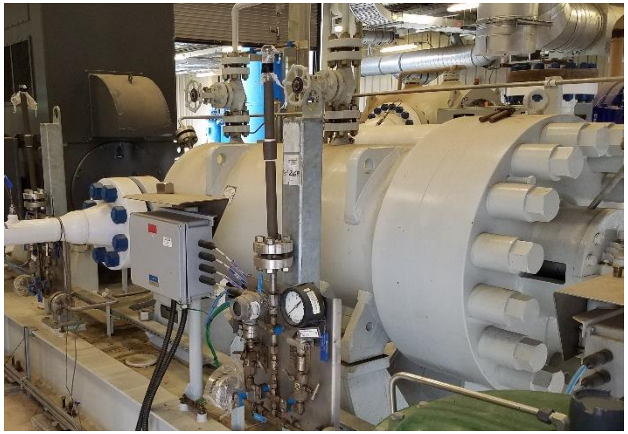
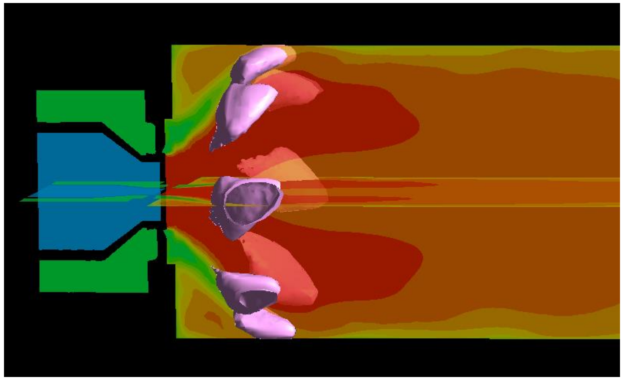
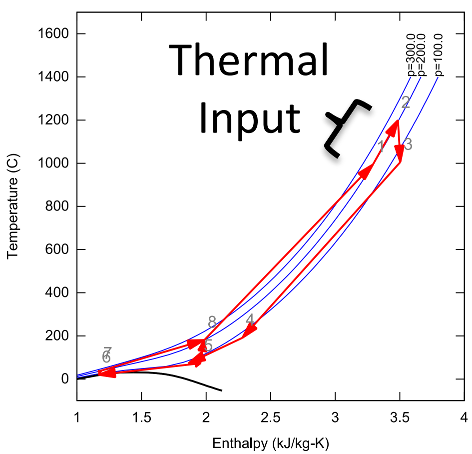
Next Steps

- Finalize combustor design
  - Instrumentation details
- Finalize combustor manufacturing plan
- Long lead items purchases
- Begin manufacturing

QUESTIONS?






Thermal
Input
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p=200.0
p=100.0
1600
1400
1200
1000
800
600
400
200
0
1
1.5
2
2.5
3
3.5
4
Temperature (C)
Enthalpy (kJ/kg-K)