

March 2, 2026
sCO2 Symposium, Pittsburgh, PA

Tutorial: sCO₂ Combustion

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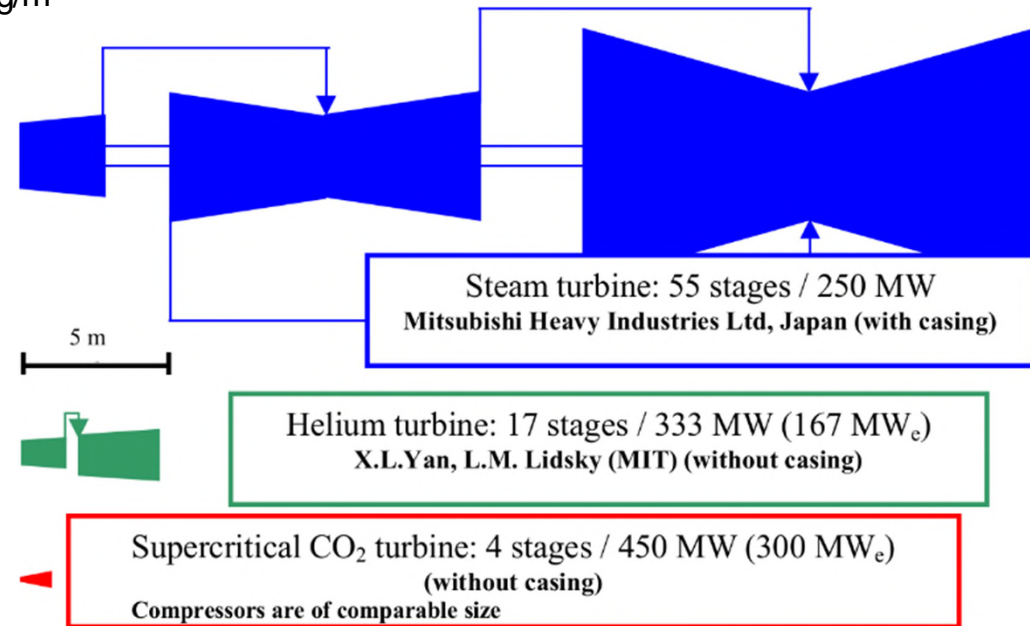
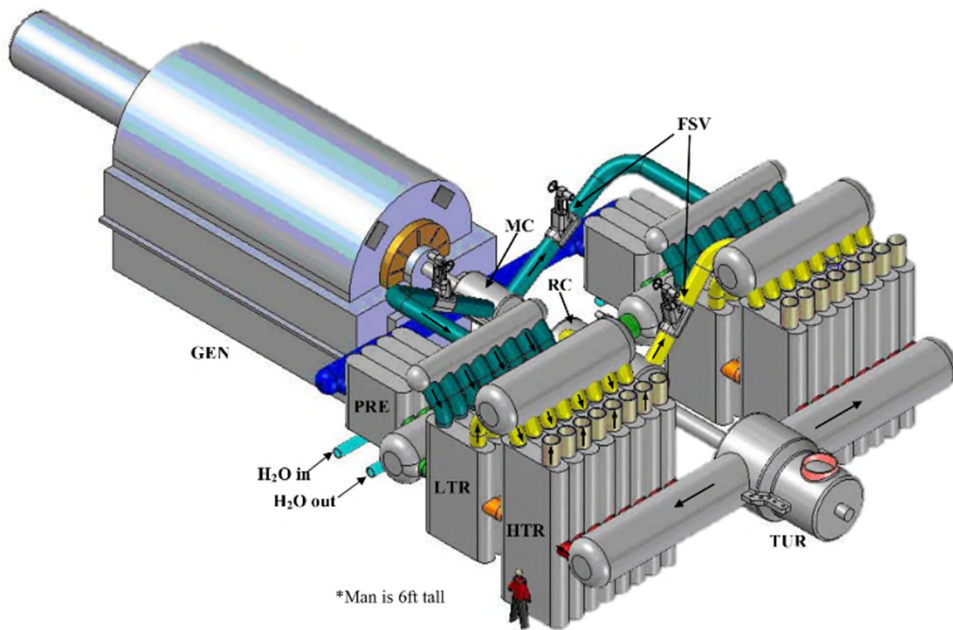
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Southwest Research Institute

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Colorado School of Mines



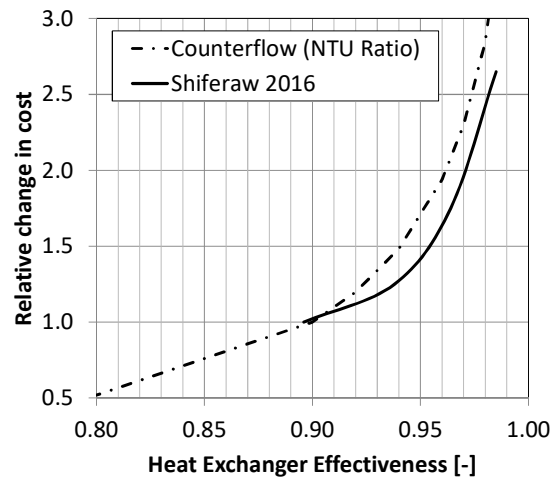
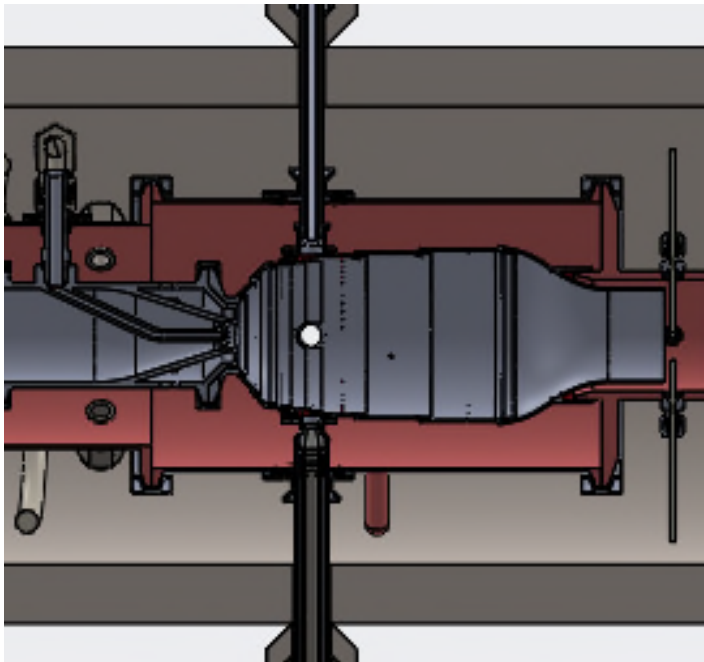
Advantages of sCO₂ Power Cycles

- sCO₂ has better thermodynamic properties (low compressibility near the critical point) that allow for higher thermal efficiency—up to 50% in some designs.
- Higher fluid density leads to compact turbomachinery
 - Supercritical steam cycle: 260 bara at 560 °C, density = 81 kg/m³
 - Supercritical sCO₂ cycle: 260 bara at 560 °C, density = 157 kg/m³



Advantages of sCO₂ Power Cycles

- Offer +3 to +5 percentage points over supercritical steam for indirect coal fired applications

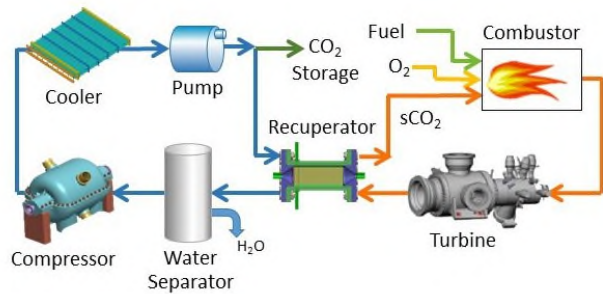


2.5MWt Sunshot Heater
Inconel 740H Bare Tube HX

Advantages of sCO₂ Power Cycles

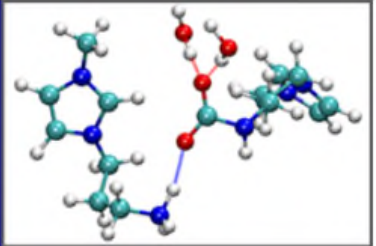
Nearly 100% carbon capture

Direct-fired



Petra Nova power plant (Houston)
240 MW, 90% CC, \$1 billion retrofit cost

SOLVENTS



SORBENTS



MEMBRANES

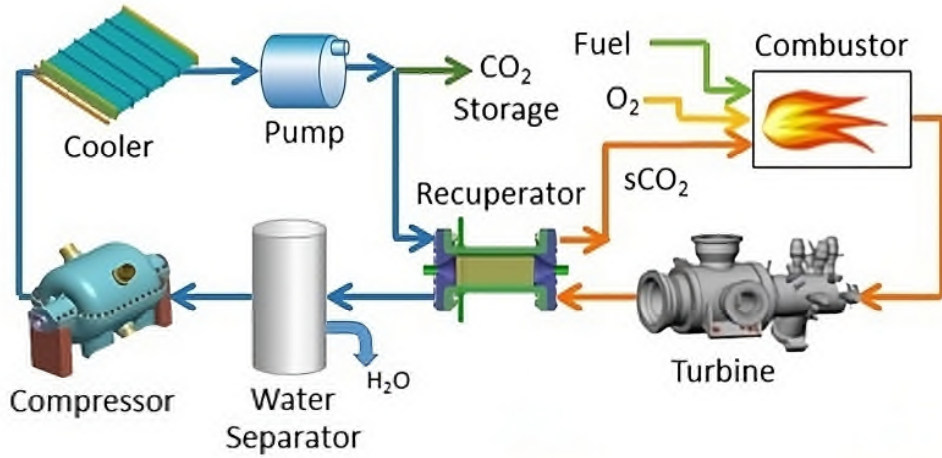


NOVEL CONCEPTS



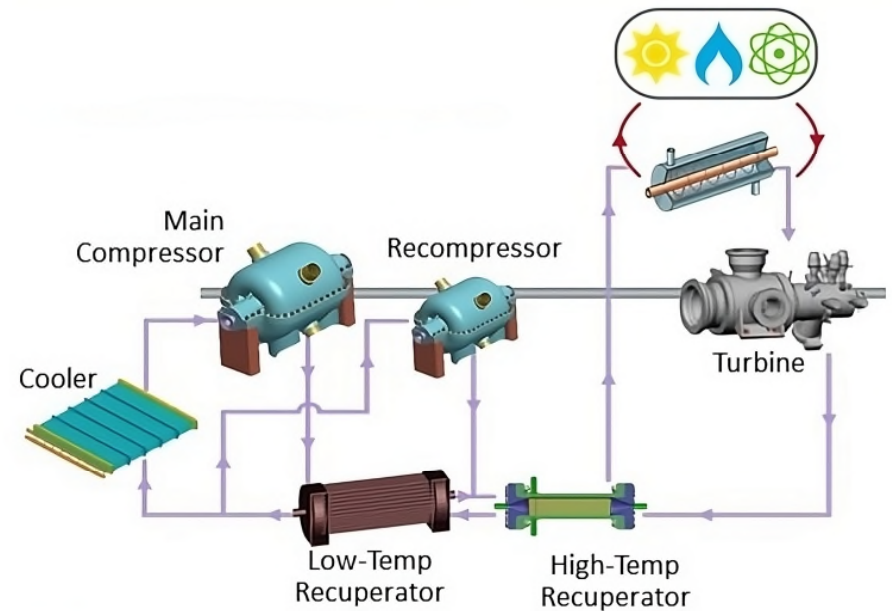
Direct vs Indirect-Fired sCO₂ Power Cycles

Direct-fired



- Higher thermal efficiency (no losses from heat exchanger)

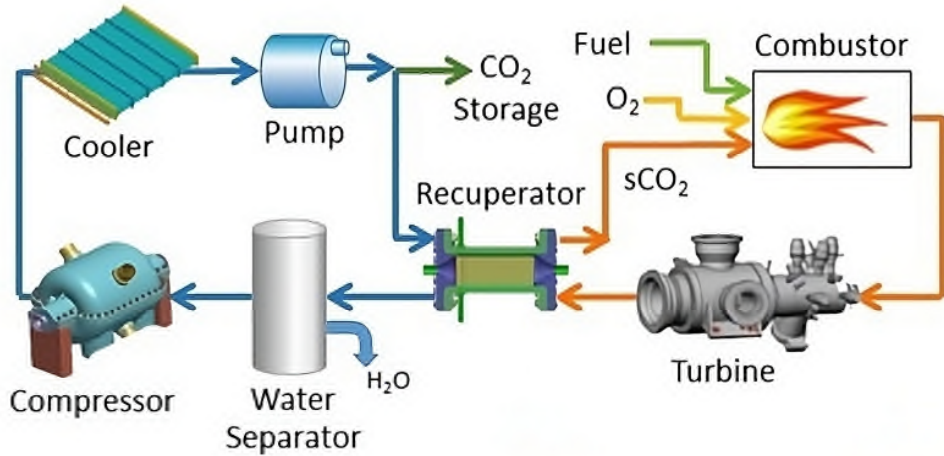
Indirect-fired



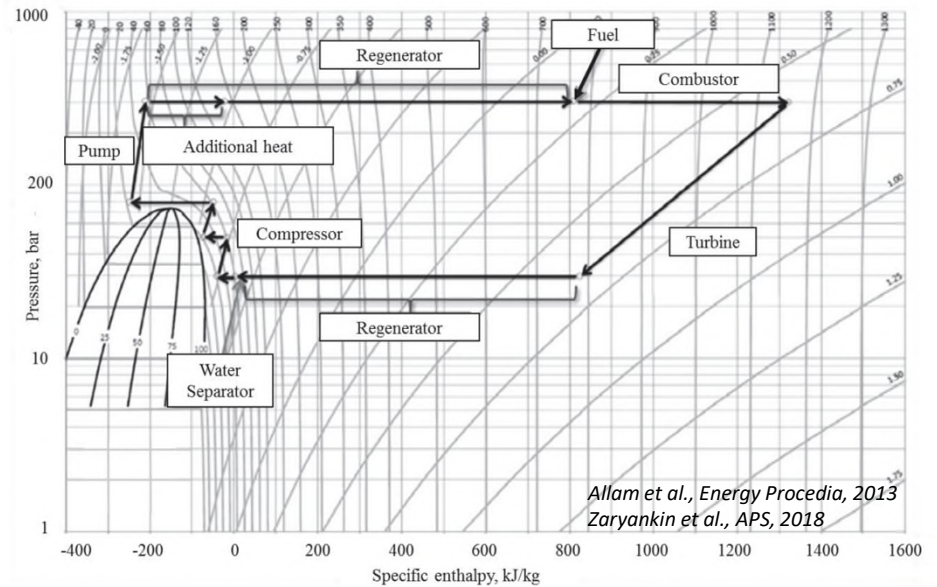
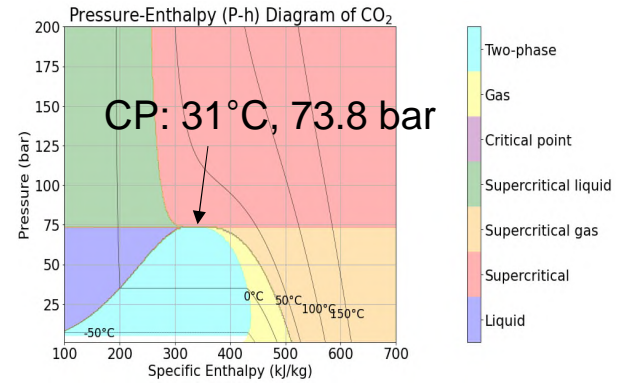
- High pressure oxy-fuel combustion

Direct (Allam-Fetvedt) sCO₂ Power Cycles

Direct-fired



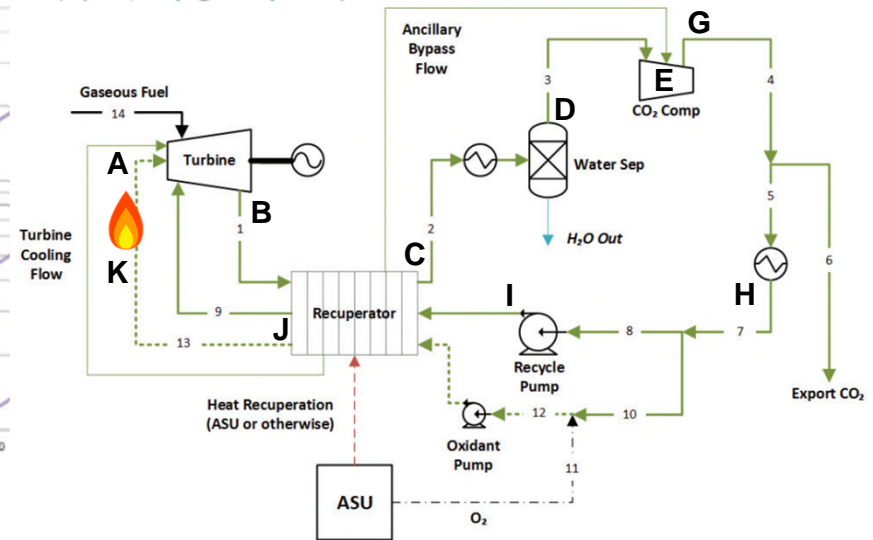
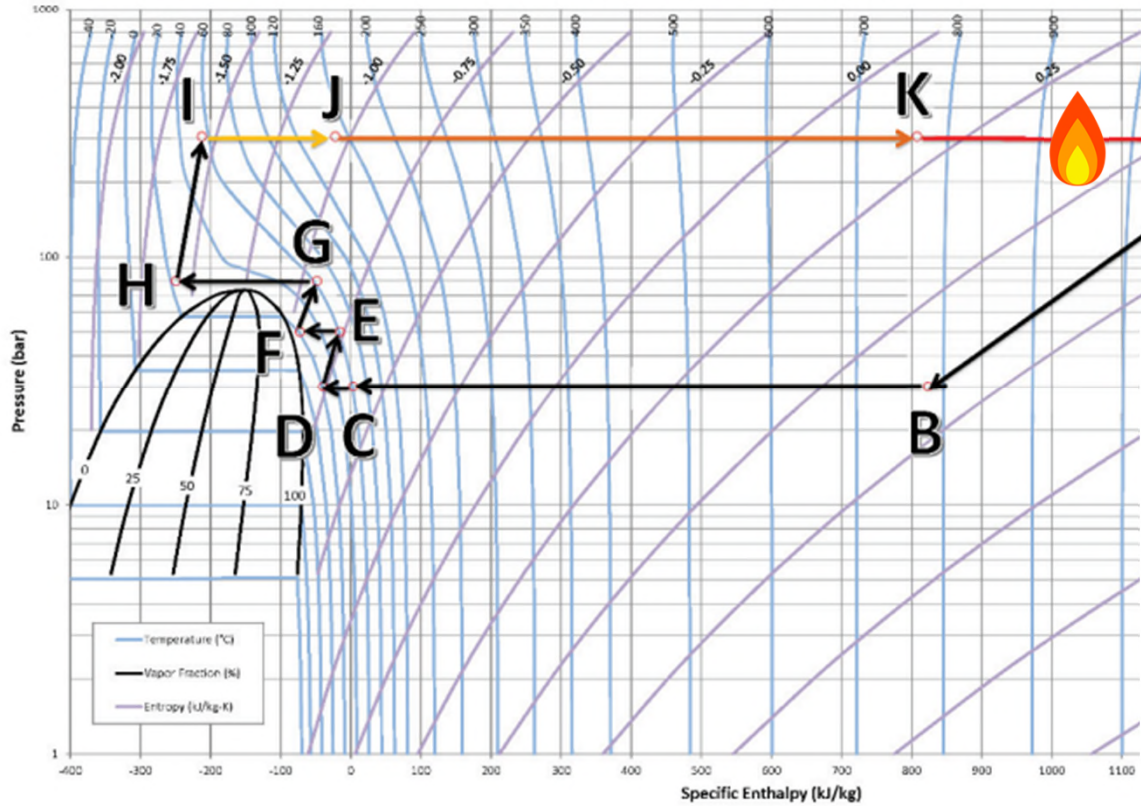
- Variety of thermodynamic conditions
- High level of dilutions



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

Allam-Fetvedt Cycle

log P-h Diagram for Carbon Dioxide



<https://doi.org/10.1016/j.egypro.2017.03.1731>

Case Studies and Facilities for sCO₂ Combustion

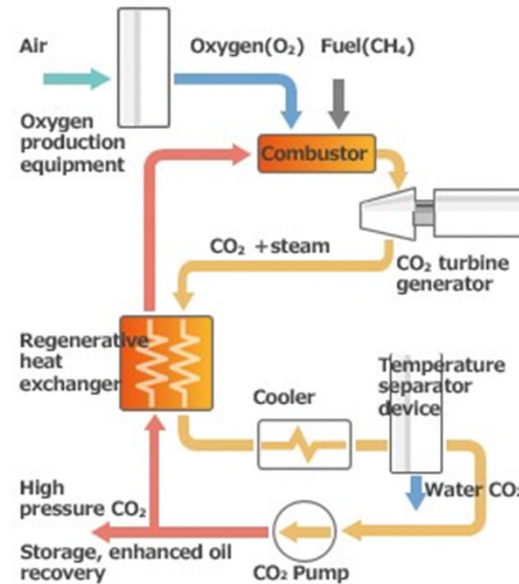
Summary of limited data available

Toshiba - Netpower (1/3)



Testing facility at La Porte, TX

- Develop combustor and turbine system for power generation and CO₂ capture
- Maintain high efficiency
- Reduce costs related to power generation
- Reduce or eliminate emissions of nitrogen oxides, CO₂, and other pollutants
- Integration of 50 MWth combustion pilot plant system



- Use of Allam-Fetvedt Cycle (developed by NET Power)
- Use of closed cycle such that CO₂ is recycled rather than stored
- Operate system and show successful operation at 30 MPa and 1150C
 - Typical turbine working pressure is 2 MPa
 - Used staged development program testing a small scale 5 MWth combustor before their 50 MWth pilot plant combustor

<https://doi.org/10.1016/j.egypro.2017.03.1731>

Isles, *Gas Turbine World*, 2014

Suzuki et al., *Proceedings of International Gas Turbine Congress*, 2019

Flin, *Gas Turbine World*, 2019

Martin et al., *14th International Conference on Greenhouse Gas Control Technologies*

<https://doi.org/10.1115/GT2015-43160>

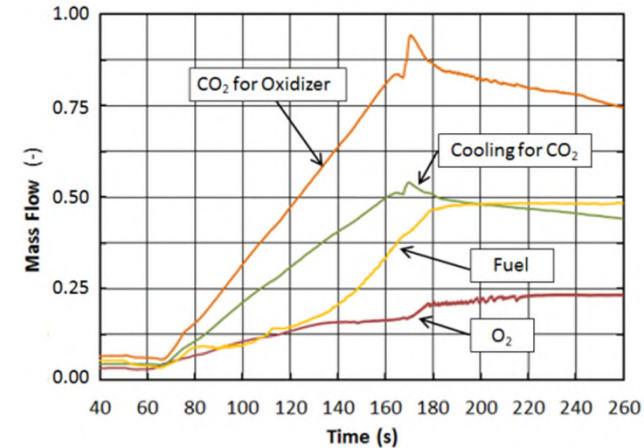
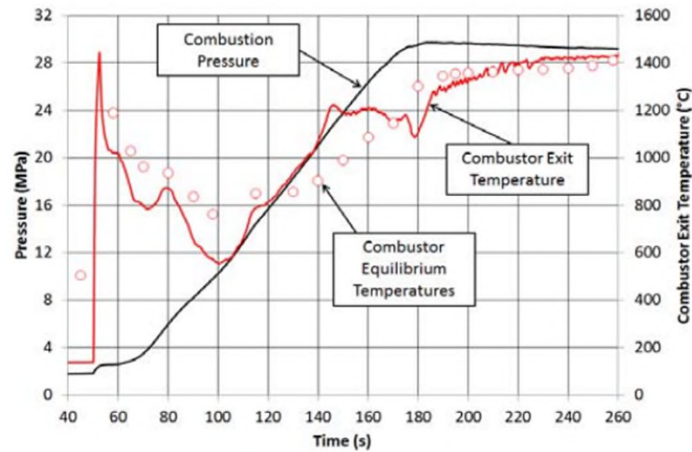
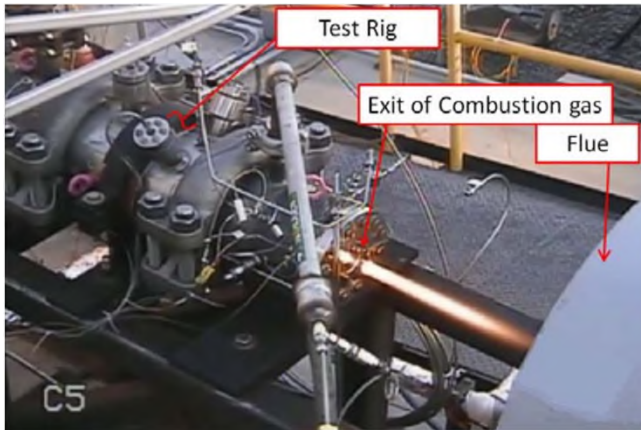
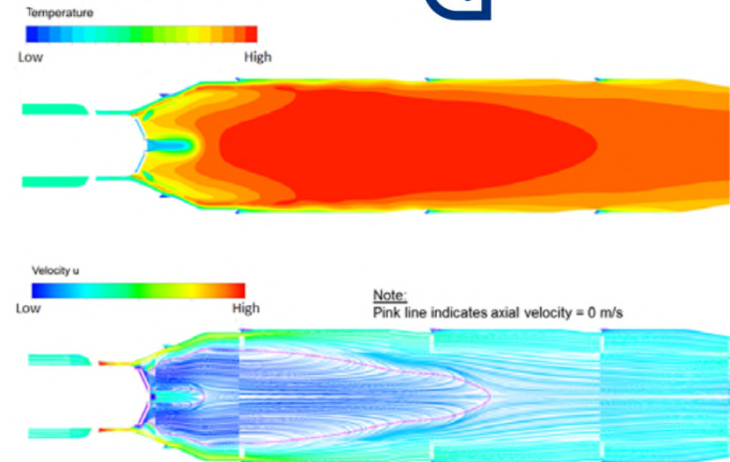
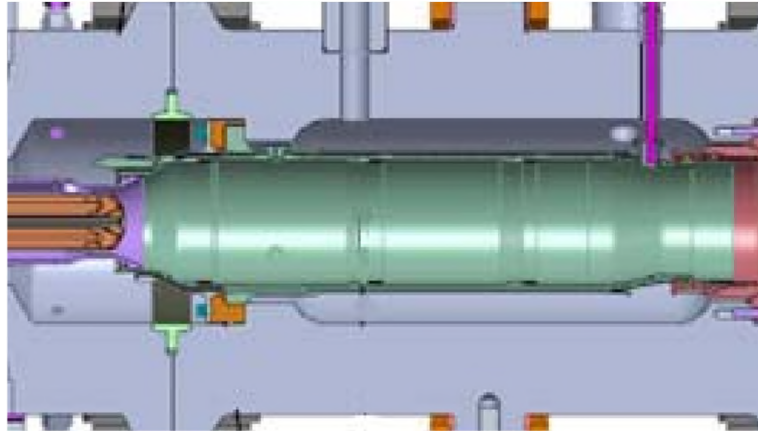
Toshiba – Netpower (2/3)



- Near 100% carbon capture efficiency
- Plant efficiency: ~50% efficient using coal and ~59% efficient using natural gas
- Negligible NO_x emissions because using oxygen rather than air in working fluid

- HPT development
 - Double shell structure
 - space between inner and outer casing is filled with CO₂ cooling flow
 - Inner casing made from Ni
 - Inner and outer casings made using CrMoV casting

Toshiba – Netpower (3/3)



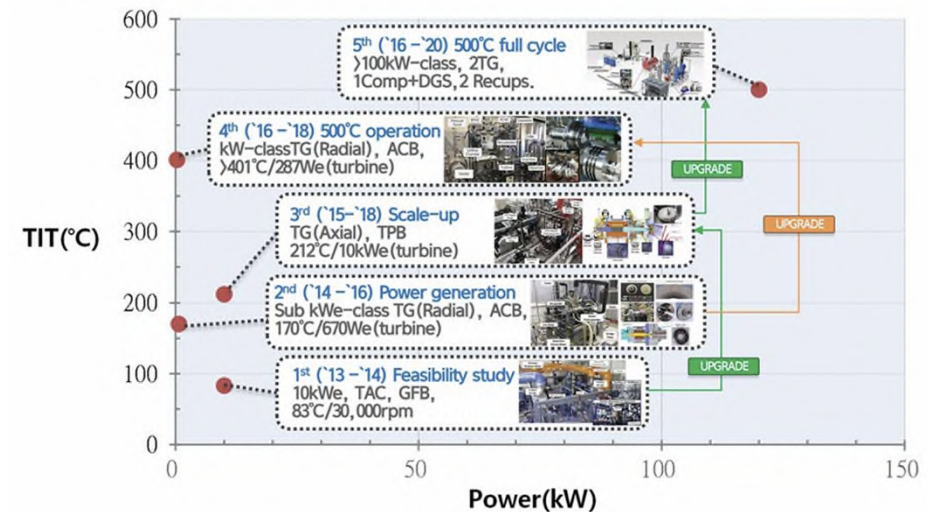
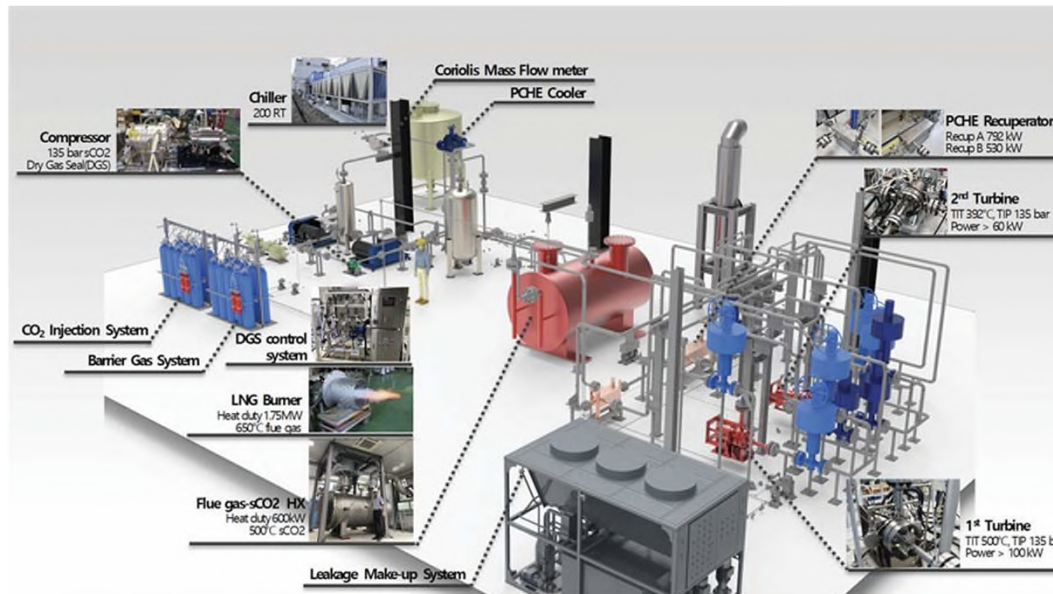
10MWth sCO₂ oxy-fuel combustor testing

Korea Institute of Energy Research (1/5)



Project objectives

- Build a commercially scalable sCO₂ power system, targeting 120 kWe dual Brayton cycle at 500°C and 135 bar
- Fix known turbomachinery problems (bearing failures, seal leakage, high axial forces) that prevent scaling to MW class plants
- Demonstrate reliable continuous power generation for waste heat recovery and distributed power
- Test chemical looping combustion (CLC) as a way to capture CO₂ and eliminate NO_x emissions

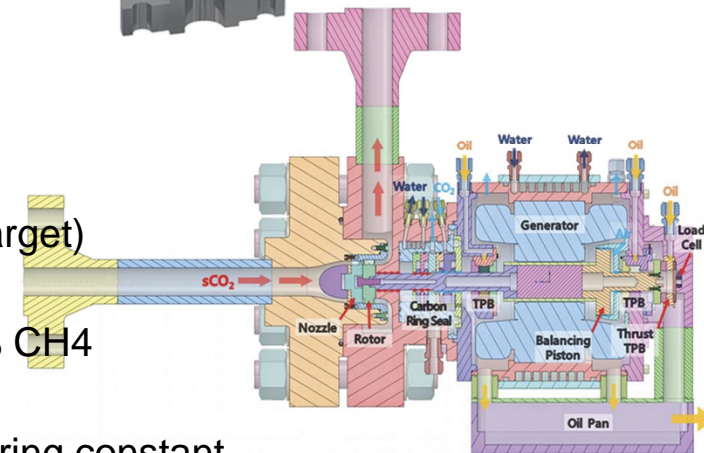
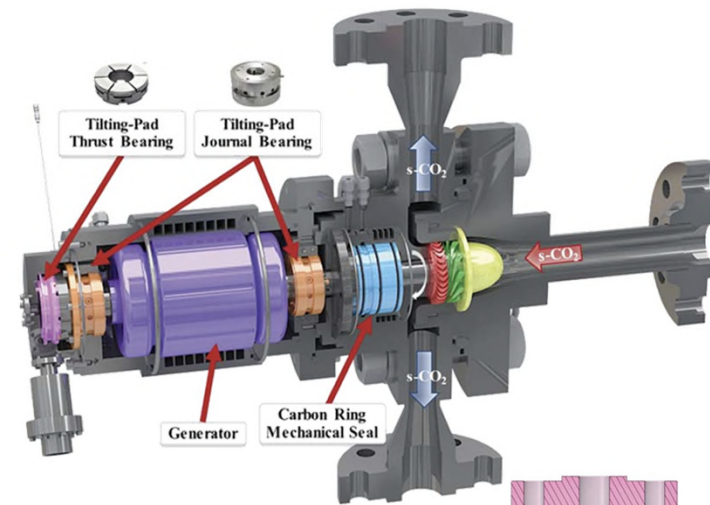
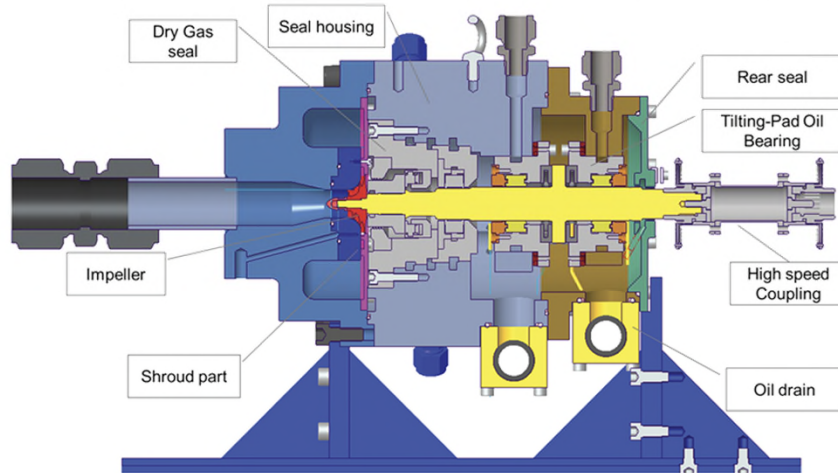


<https://doi.org/10.1063/5.0085681>

Cho et al., sCO₂ Symposium, 2018

Cho et al., 3rd European supercritical CO₂ Conference, 2019

Korea Institute of Energy Research (2/5)

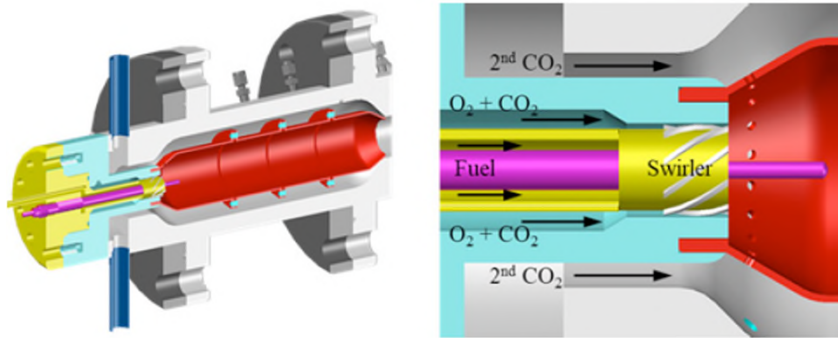


- 86 We for 30 min at 320°C (small radial turbine)
- 287 We at 401°C/112 bar (radial turbine approaching 500°C target)
- 11 kWe for 45 min at 205°C/100 bar (first axial turbine test)
- 12.6 kWe for 4.2 hours at 212°C/123 bar (axial turbine, beating 2 hour target)
- Compressor pushed 3.72 kg/s of CO₂ to 96 bar at 70,000 rpm
- CLC system ran 3.5+ hours with ~98% CO₂ purity out of reducer, 99.7% CH₄ conversion, and NO_x essentially undetectable
- Main ongoing problem: seal leakage always higher than predicted, requiring constant CO₂ top up

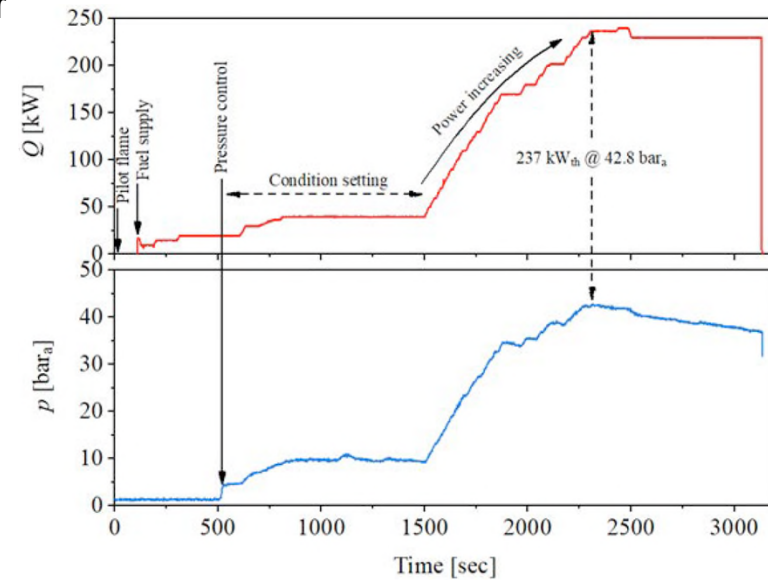
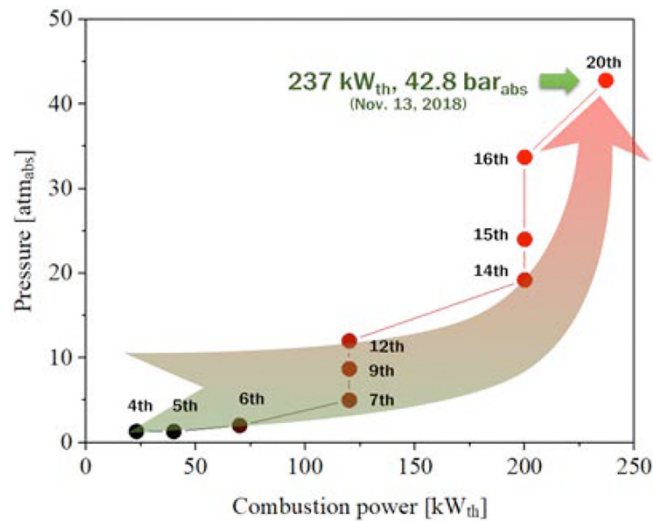
Korea Institute of Energy Research (3/5)



- Korean Government Project: Phase I: \$3.3 M/3 years, Phase II: \$1.5 M/2 years



Design of 200kWth 50 bar oxy-fuel combustor



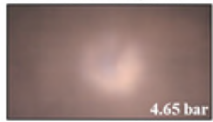
Korea Institute of Energy Research (4/5)



20 kW_{th}, $\phi=0.35$, $X_{O_2,1st}=1$, $F=17$



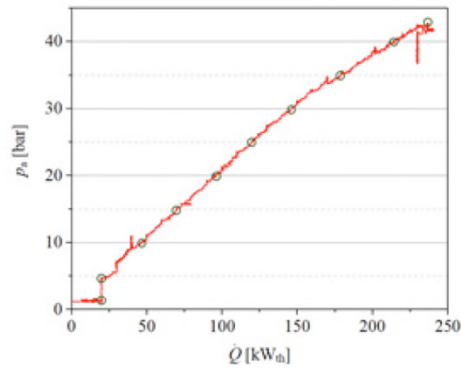
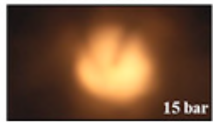
20 kW_{th}, $\phi=0.35$, $X_{O_2,1st}=1$, $F=17$



46 kW_{th}, $\phi=0.7$, $X_{O_2,1st}=0.5$, $F=20$



70 kW_{th}, $\phi=0.7$, $X_{O_2,1st}=0.5$, $F=20$



237 kW_{th}, $\phi=0.7$, $X_{O_2,1st}=0.6$, $F=20$



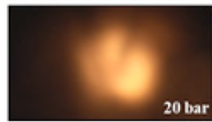
215 kW_{th}, $\phi=0.7$, $X_{O_2,1st}=0.6$, $F=20$



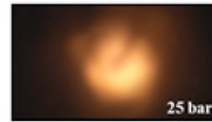
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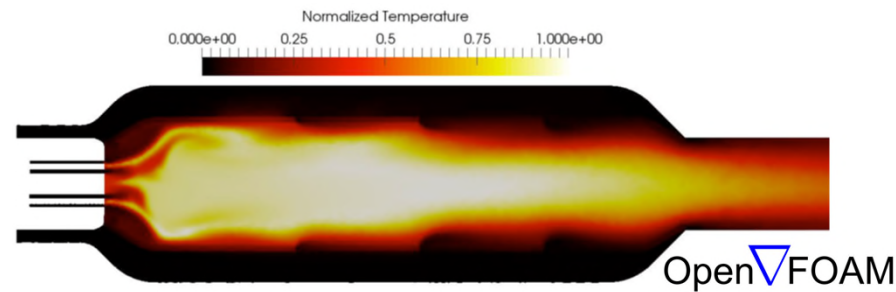
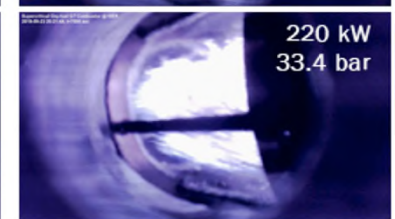
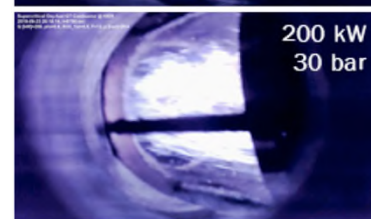
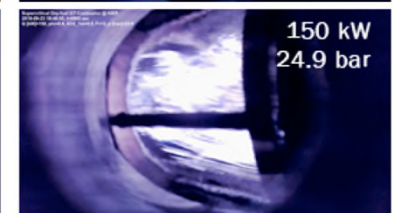
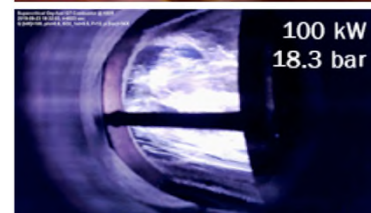
96 kW_{th}, $\phi=0.7$, $X_{O_2,1st}=0.5$, $F=20$



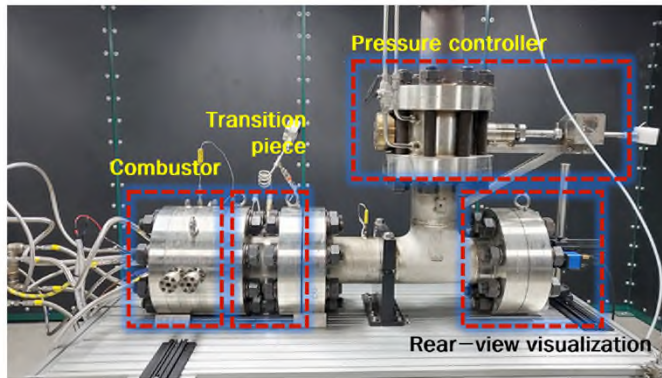
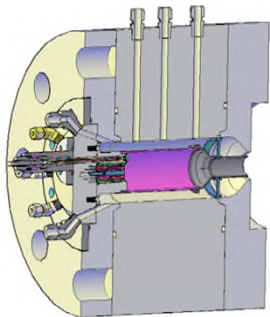
120 kW_{th}, $\phi=0.7$, $X_{O_2,1st}=0.5$, $F=20$



147 kW_{th}, $\phi=0.7$, $X_{O_2,1st}=0.5$, $F=20$



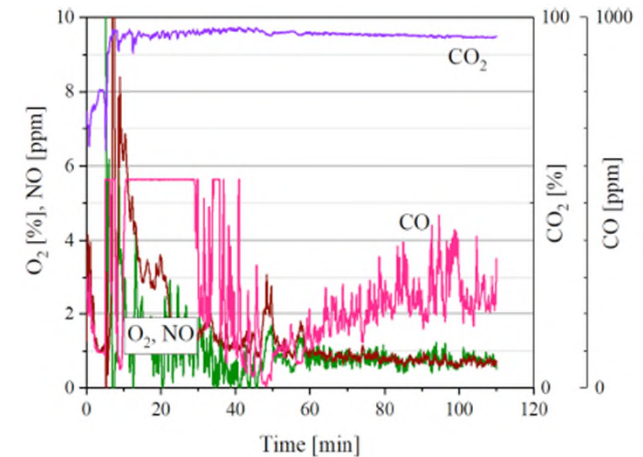
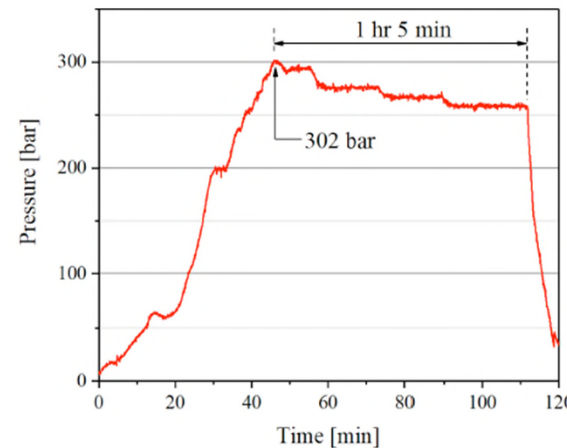
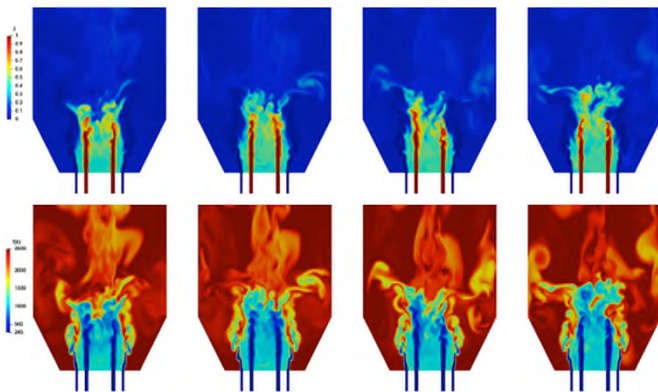
Korea Institute of Energy Research (5/5)



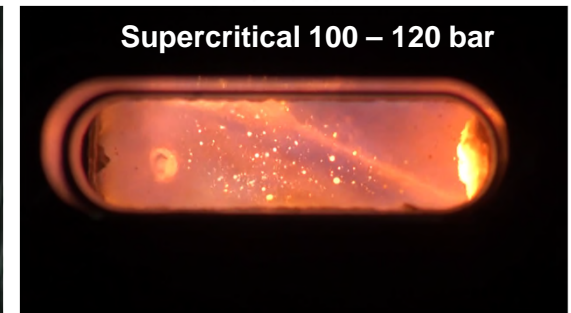
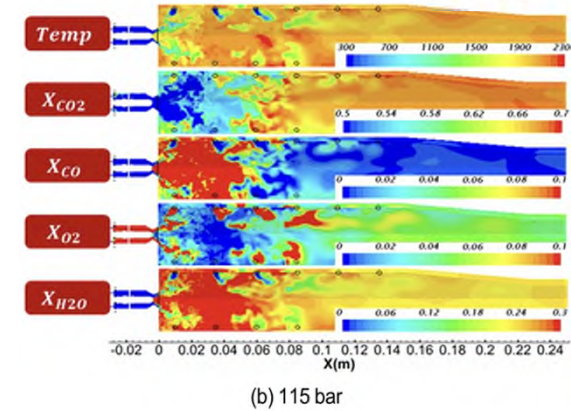
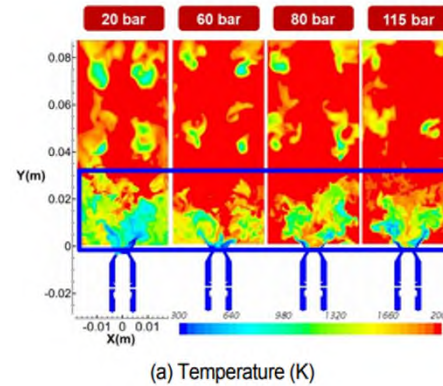
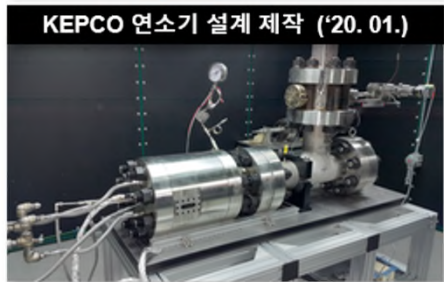
Design of 300 bar oxy-fuel combustor

- Quartz optical window for flame visualization
- Temperature measurement
- Emissions measurement

- Dual-swirl injector to promote mixing process
- Pilot burner for stable ignition
- Cooled borescope design for visualization



KEPCO – KIER – SNU



*Designed and tested with Dr. Dae Keun Lee at Korea Institute of Energy Research (KIER)

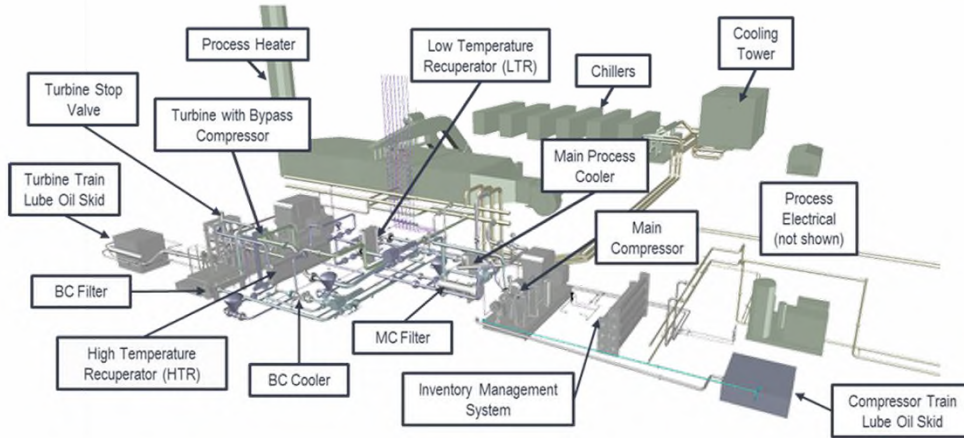
Supported by Korea Electric Power Corporation (KEPCO)

Project goals

- Design a high-pressure oxy fuel combustor that works inside a direct fired sCO₂ power cycle
- Support Korea's broader push (with Hanwha Power Systems) to build a 10 MWe direct fired sCO₂ system
- Help with international scale up efforts in the STEP Demo project

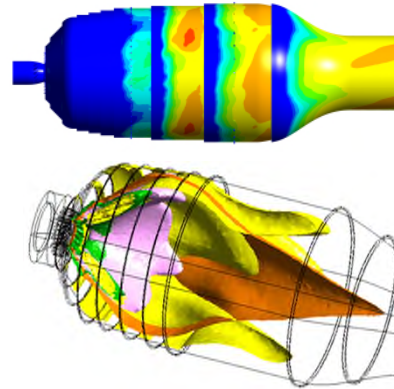
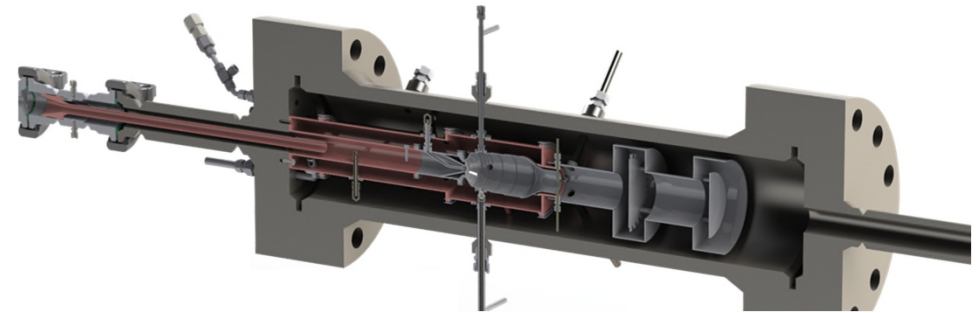
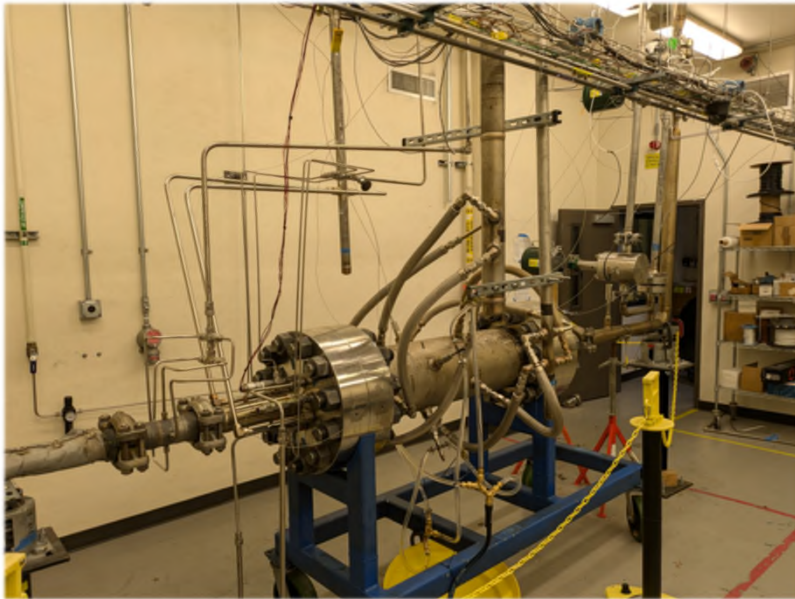
Do, Combustion Institute

SwRI: sCO2 research



SwRI sCO₂ combustion (MW)

- Designed for 1 MW_{th} combustor
- Cold commissioning activities reached a combustor pressure of 193 bar (2813 psi) at a max inlet temperature of 1180°F
- Combustor inlet flow rate of CO₂ at 0.5 lbm/s

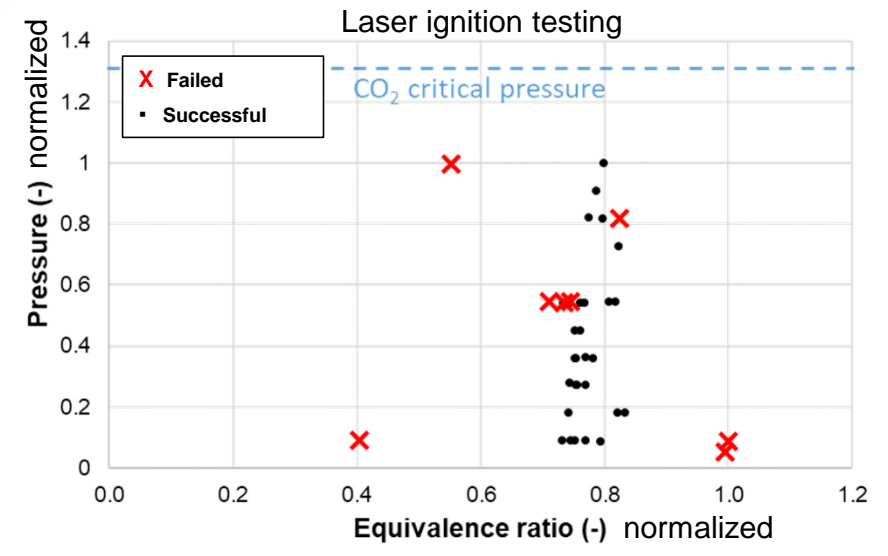
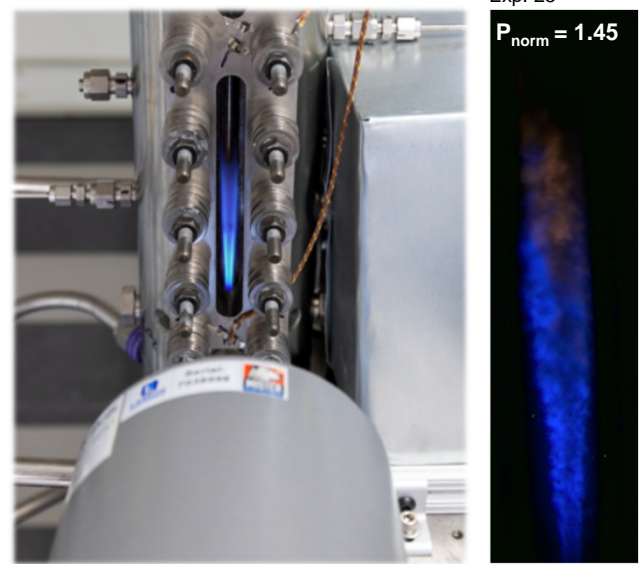
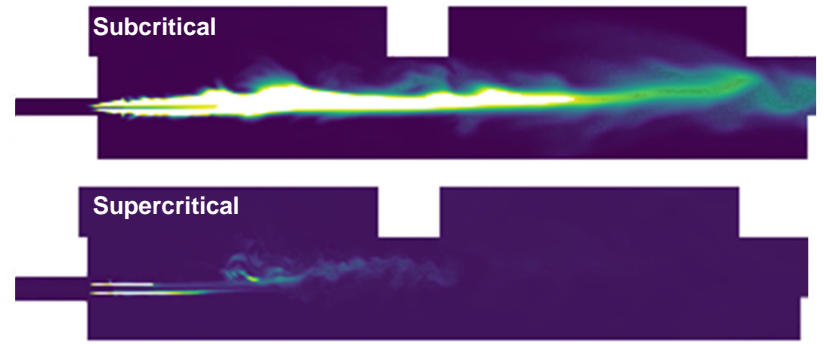
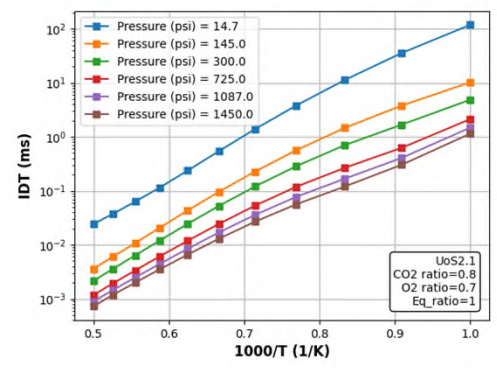
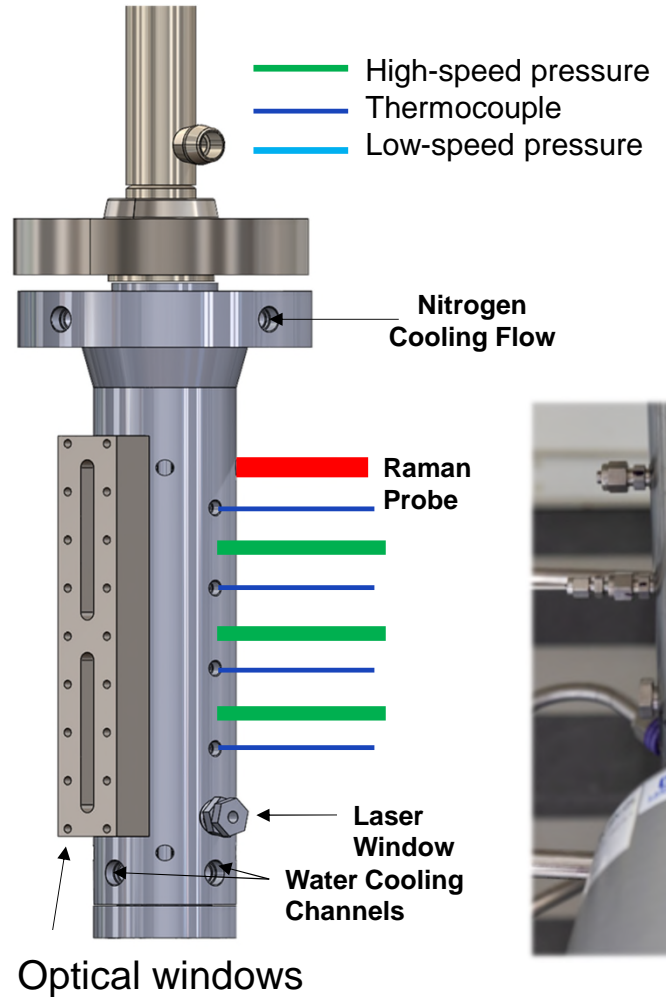


CFD and design study



Design and fabrication

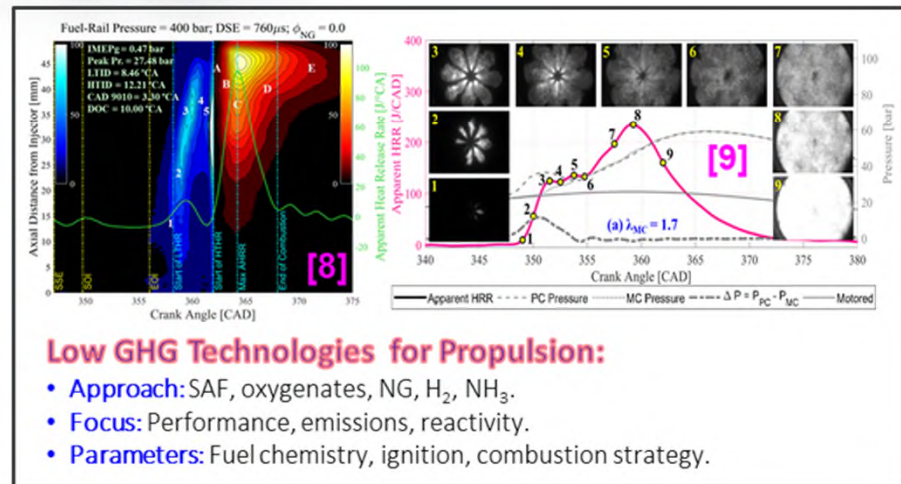
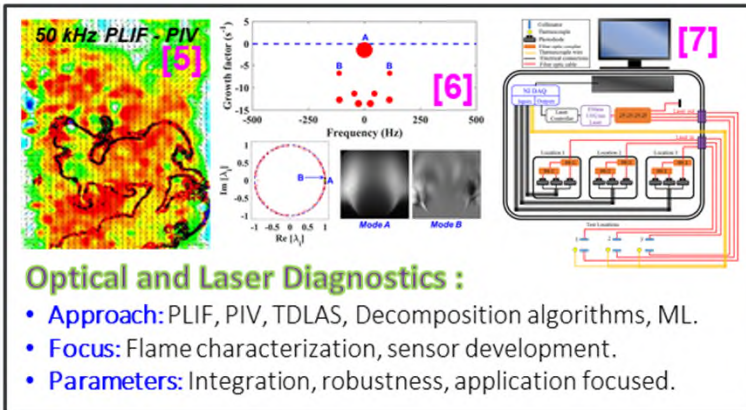
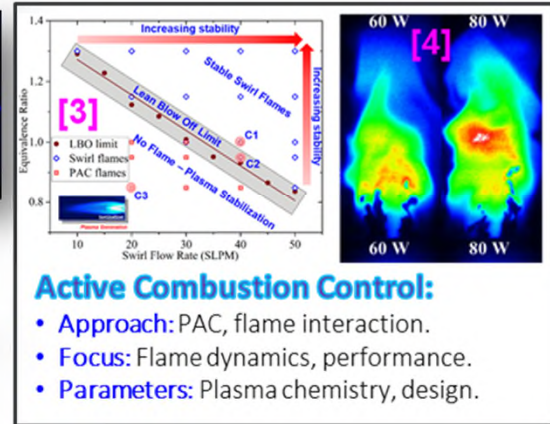
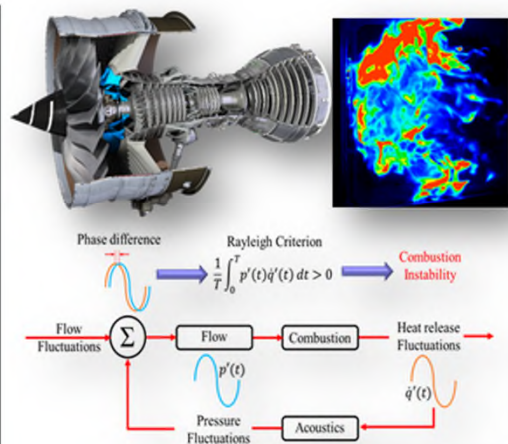
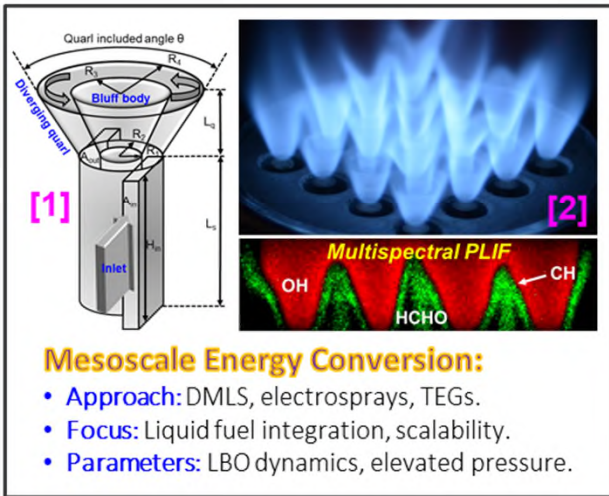
SwRI sCO₂ combustion (kW)



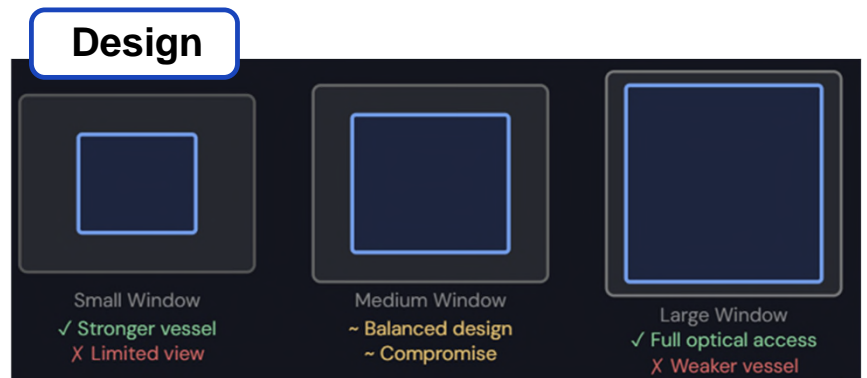
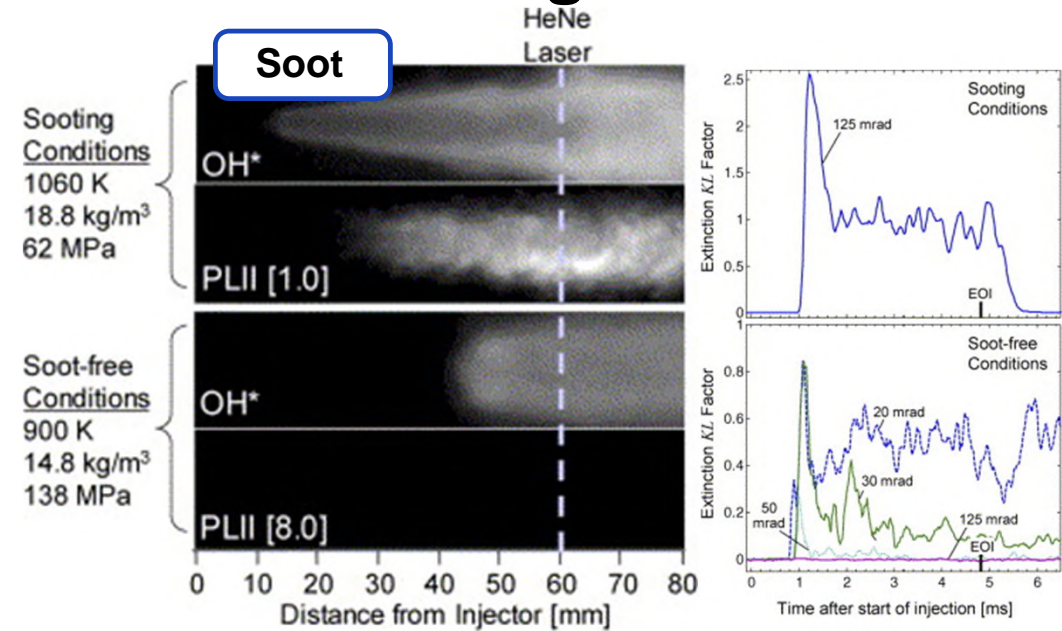
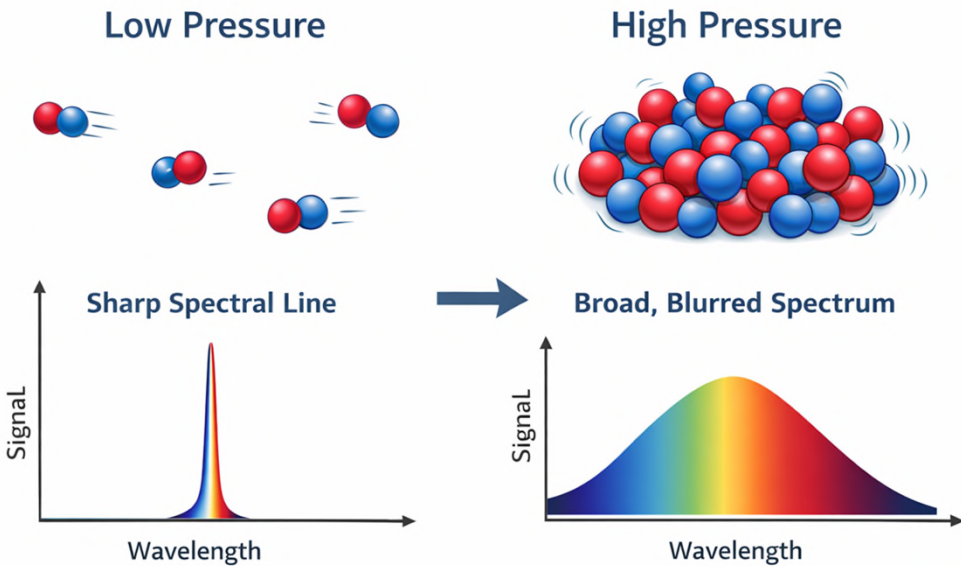
Stay tuned for tomorrow's presentation!

High-pressure combustion diagnostics

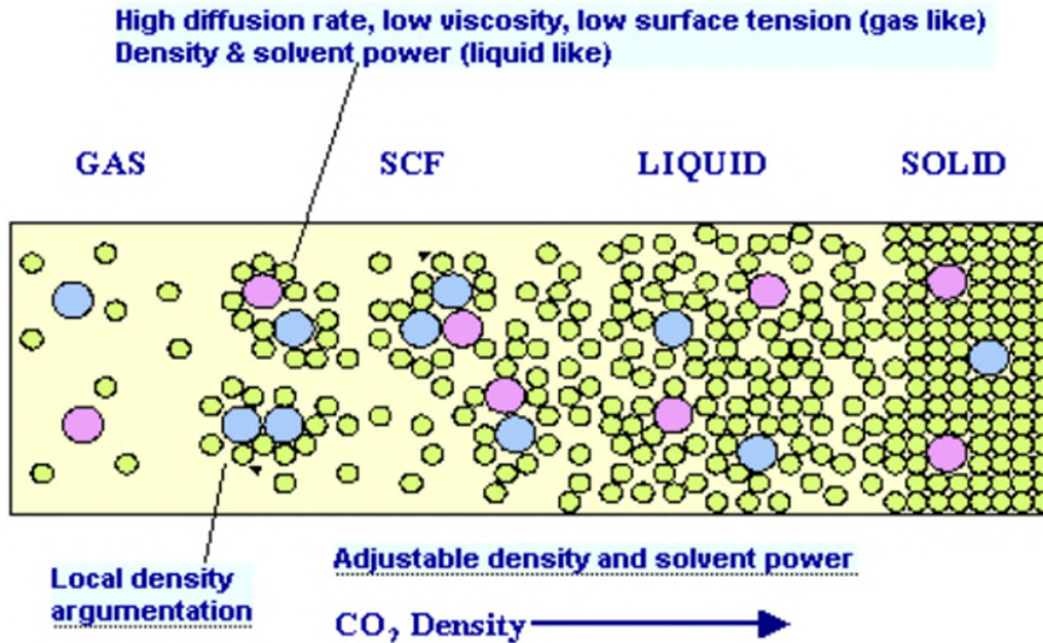




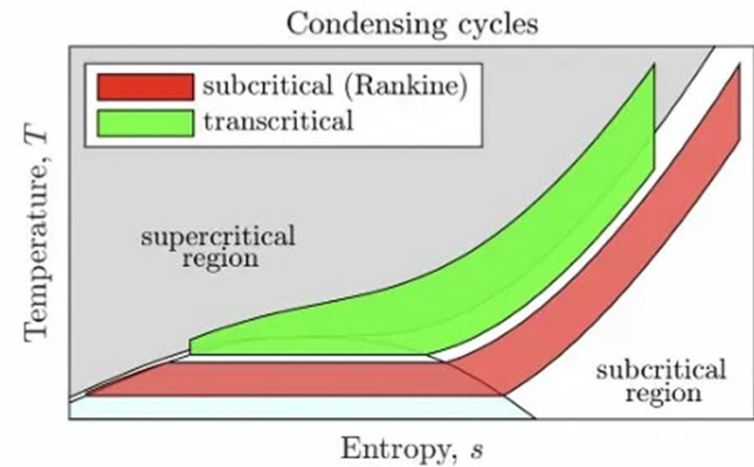
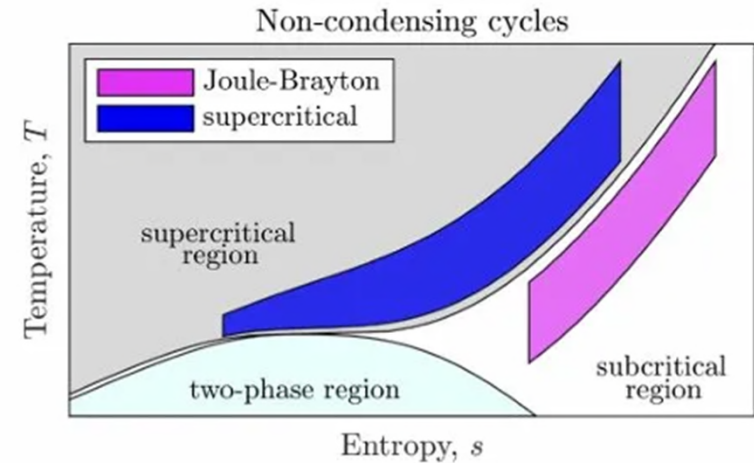
Challenges for high-pressure combustion diagnostics



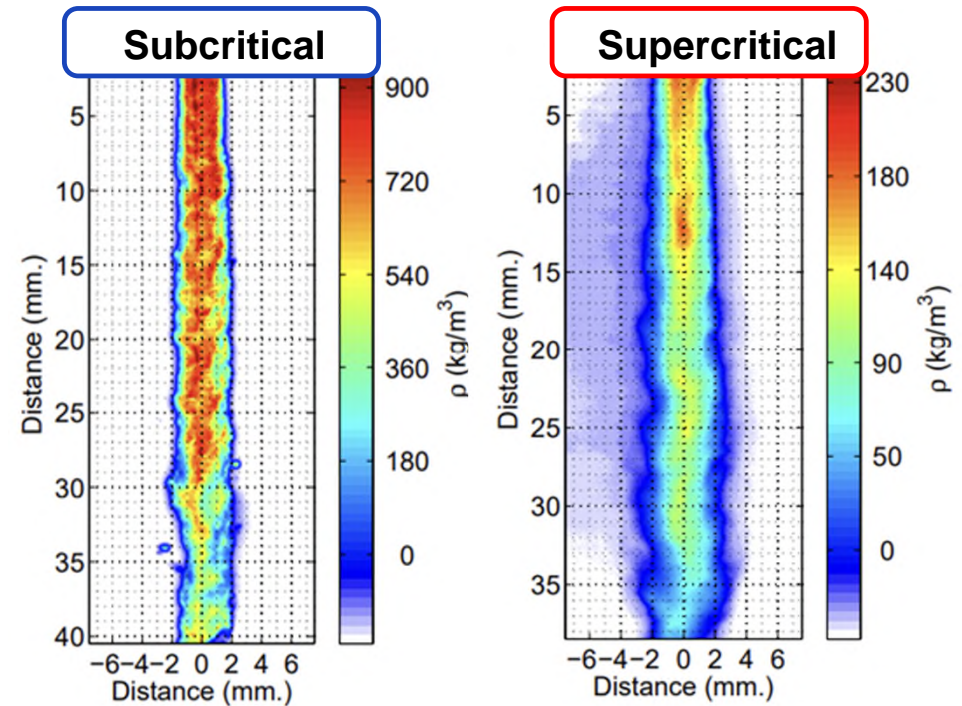
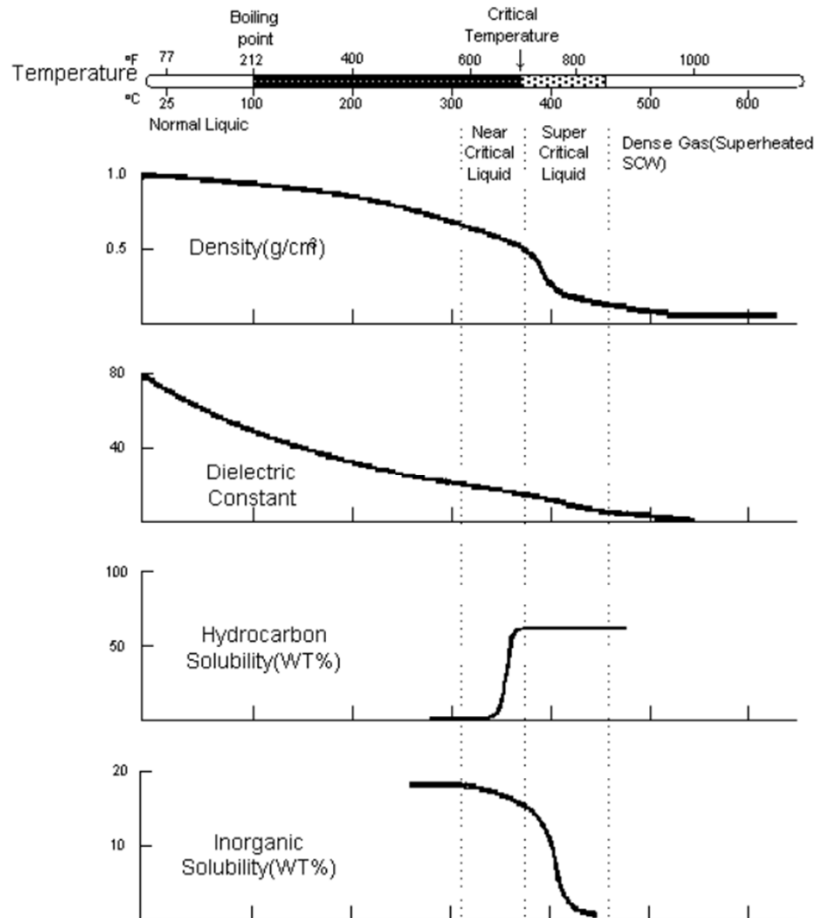
Supercritical?



- Real fluid behavior defies ideal models
- Enables compact, high-efficiency cycles
- Gas-like diffusion, liquid-like density
- Properties shift rapidly near critical
- Extreme density complicates diagnostics

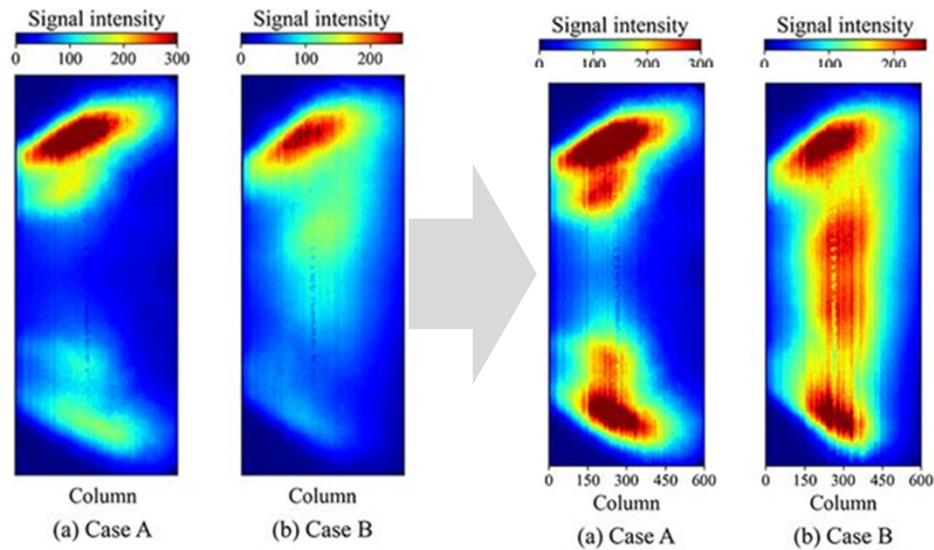


Steep change occurs during phase transition.

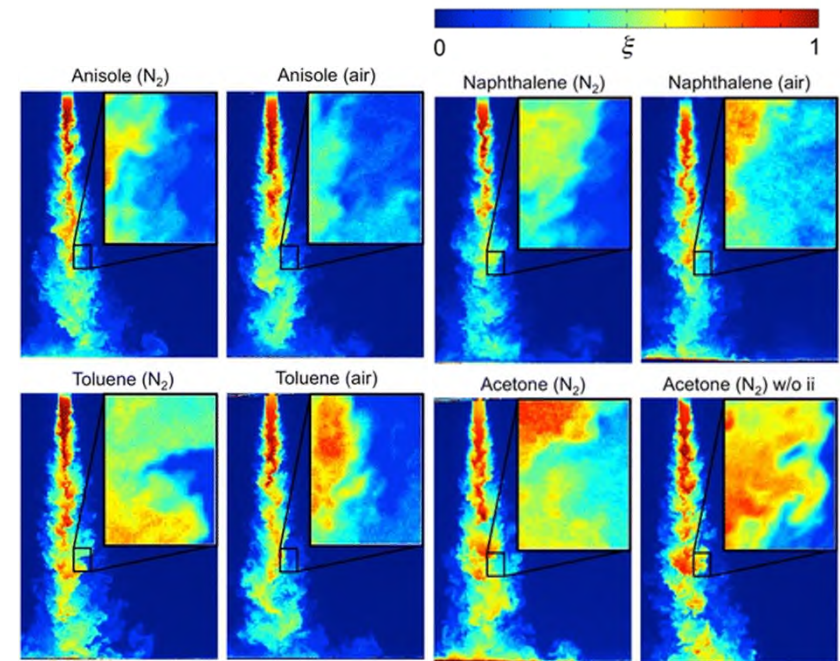


- A jet will exhibit different characteristics under subcritical and supercritical regimes.

Ways to improve diagnostics

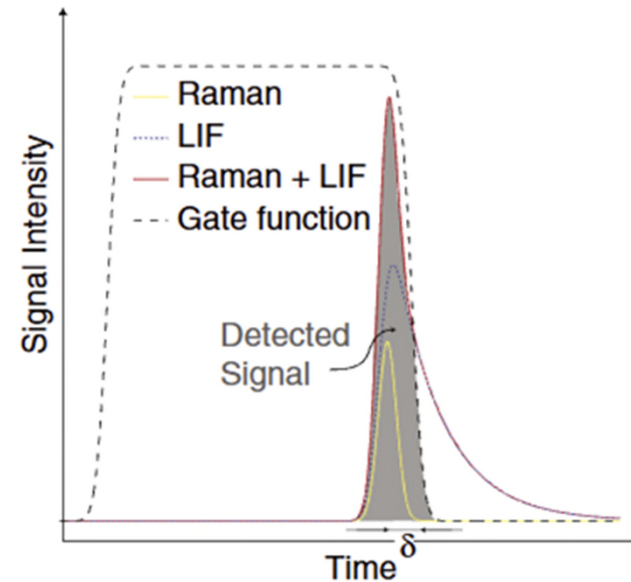
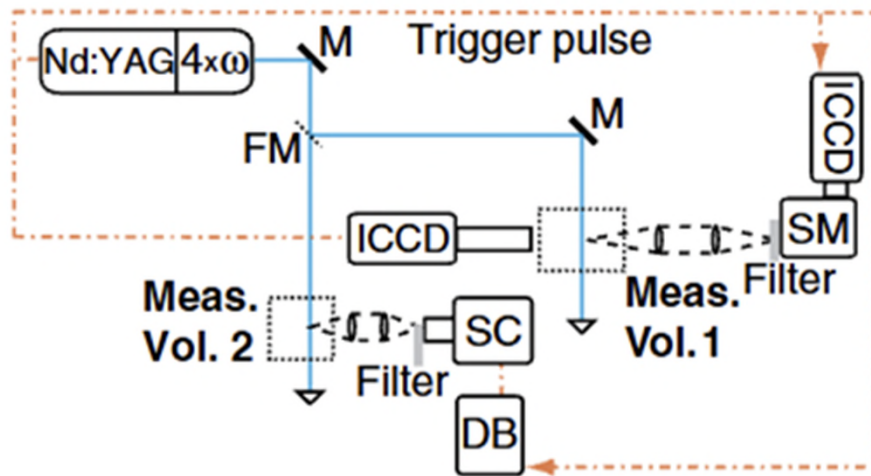


- Selection of specific wavelengths or correction algorithms can clean up distorted signals and minimize spectral overlap.



- Specific seeded tracer molecules can be introduced to allow for easier and more clear analysis of combustion processes.

Ways to improve diagnostics



- Short Gate ICCD Detection uses a camera with a very quick shutter time to pick up laser pulse with less background light interference

Challenges in Chemical Kinetics



What is chemical kinetic mechanism?

$aA + bB \rightarrow \text{products}$

Rate of reaction = $k[A]^m[B]^n$,
where $k = A \exp(-E_a/RT)$

```
! Reactions of CH
!  
CH+H = C+H2          1.100E+14  0.000  0.00 !GRI  
CH+O = CO+H          5.700E+13  0.000  0.00 !GRI  
CH+OH = HCO+H        3.000E+13  0.000  0.00 !GRI  
CH+H2 = CH2+H        1.107E+08  1.790  1670.00 !GRI  
CH+H2O = CH2O+H      5.710E+12  0.000  -755.00 !GRI  
CH+O2 = HCO+O        3.300E+13  0.000  0.00 !GRI  
-----
```

Allowing solving evolution of species and reactions in reacting flow (e.g., combustion) in 0D, 1D and 3D simulations

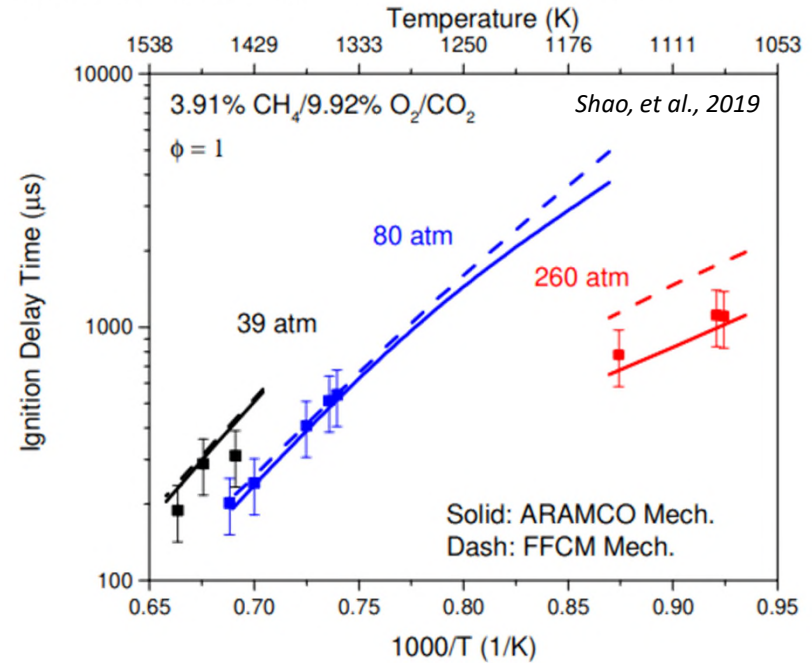
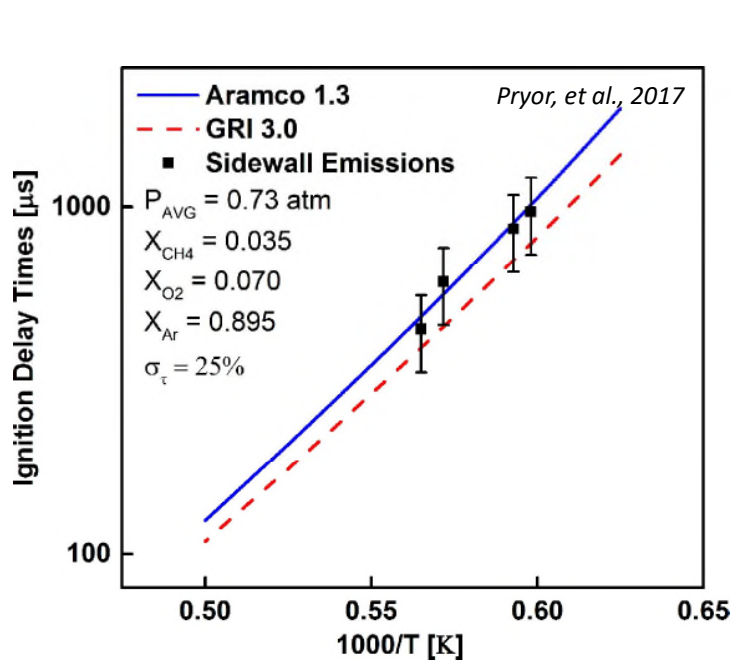
How do we identify combustion during simulation?

- First stage ignition \rightarrow steep increase in CH_2O
- Second stage ignition \rightarrow Steep change in OH, significant increase in T (or dT/dt), oxidation of CO to CO_2

Current state-of-the-art mechanisms

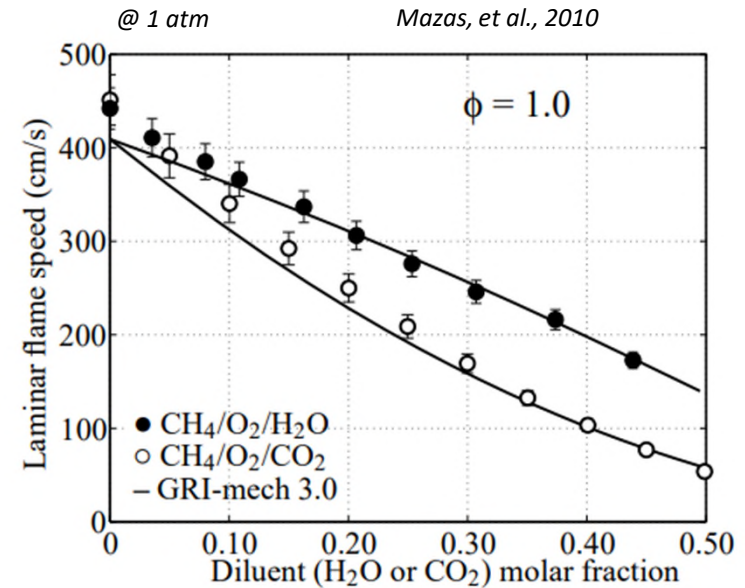
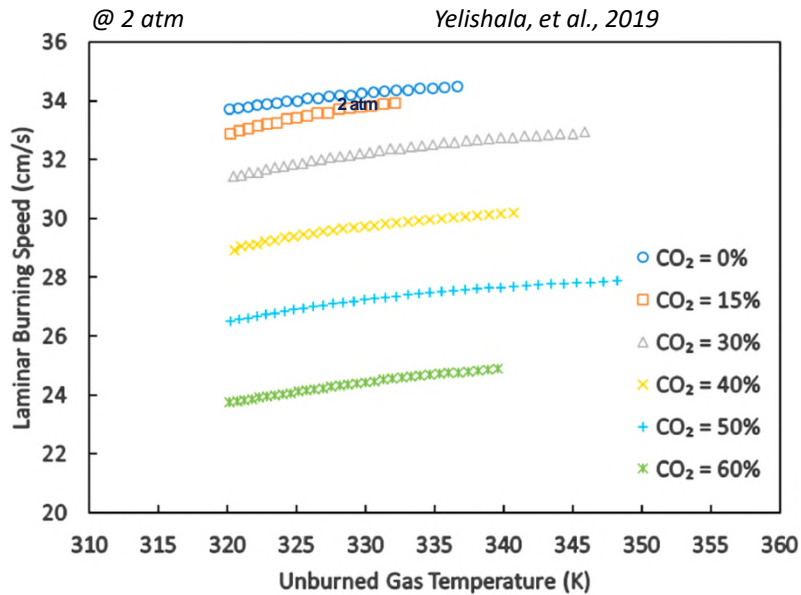
- **AramcoMech 2.0/3.0** 493 species and 2714 reactions
 - Optimized (and validated) for relatively low pressures and air as oxidizer
 - Large mechanism, not suitable for CFD
 - Not designed considering real gas effects
- **UCF mechanism (v2.0)** 23 species and 142 reactions
 - Real gas effects
 - Not extensively validated at operating pressures
 - More suitable for CFD approach by its simplicity
- **University of Sheffield (v2.1)** 113 species and 817 reactions
 - Real gas effects
 - Validated but with limited data especially at high pressure
- N_2 and CO impurities can also have a significant impact on combustion properties such as ignition delay (IDT) and laminar flame speed (LFS, S_L)

Chemical kinetic mechanisms and validation



- Very limited data at elevated pressures
- No data around the critical point
- More data at elevated pressures are needed.
- New measurements (Frequency combs, machine learning) techniques can help.

Laminar Flame Speed (S_L) measurements



- No data at elevated pressures
- No data around the critical point
- Limited data at relevant CO₂ dilution levels
- New techniques should be developed to measure flame speed at relevant conditions

Validation data are needed.

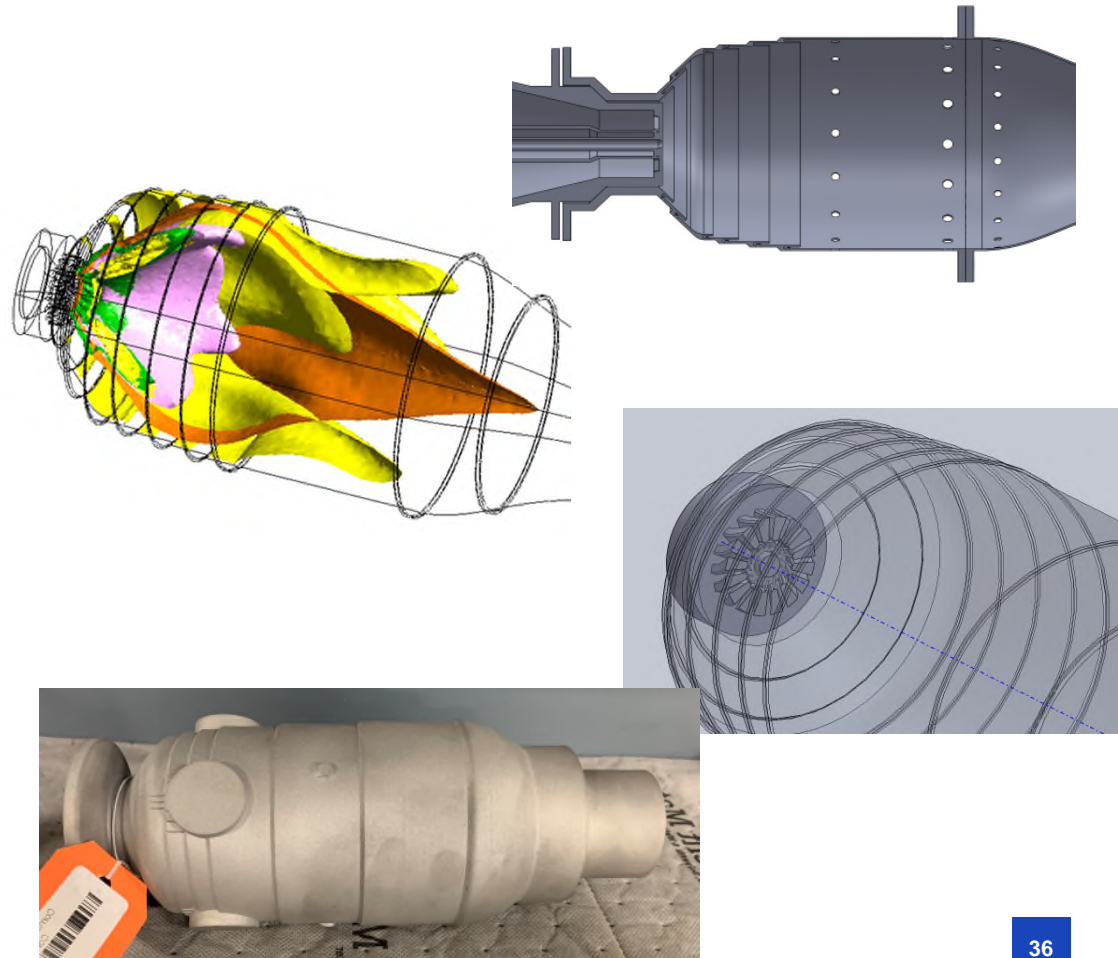
- Validation data are available at relatively low pressures for flame speed measurements.
- Higher pressures have been reached for IDT (is IDT relevant?)
- Real gas effects have to be included.
- New methods to accurately measure reaction rates and other relevant parameters (IDT, flame speed,...)
- Validation data at relevant pressures (around the critical point as well)
- Dedicated mechanisms

Design Challenges



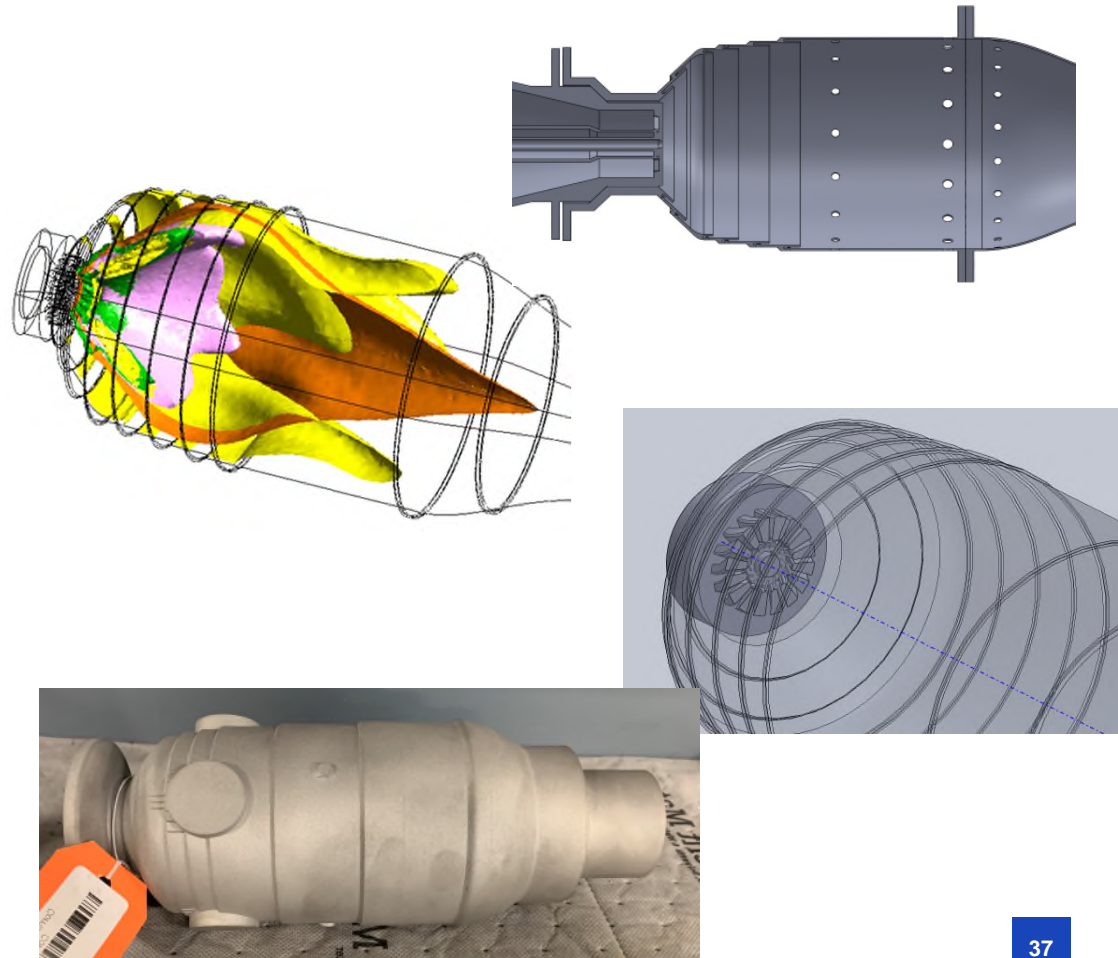
Combustor Design Key Consideration

- Mechanical casing
- Combustion performance
- Fuel injector
- Oxygen injection
- Combustor liner thermal management
- Optical access
- Acoustic resonance
- Instrumentation
- Design for additive manufacturing



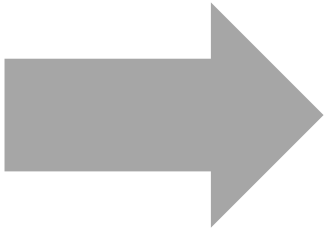
Combustor Design Key Consideration

- Mechanical casing
- **Combustion performance**
- Fuel injector
- Oxygen injection
- Combustor liner thermal management
- Optical access
- Acoustic resonance
- Instrumentation
- Design for additive manufacturing



CFD simulations are challenging

- Extreme conditions, including phase change and high densities
- No validation data available but no burner/combustor for relevant conditions can be designed without CFD
- Critical transition with real gas effects
- Simplified chemical mechanisms



- Complete combustion to avoid CO and H_2CO_3 generation and accumulation
- Flame blow off must be avoided.
- Transition from ignition to steady state

CFD Design

Injection and Swirl

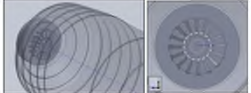


Figure 1-4. Separated Fuel Injection Scheme. Left: Isometric View with Chamber Walls Visible in Wireframe. Right: View of Injection Plane from Combustor Exit

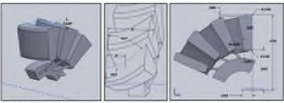


Figure 1-5. Details of the Swirling and Fuel Injection Schemes. Left: 10° Swirling Down Angle. Center: 40° Swirl Angle and Facial Spray. Right: Sweater Wall Facial Features

Startup Conditions

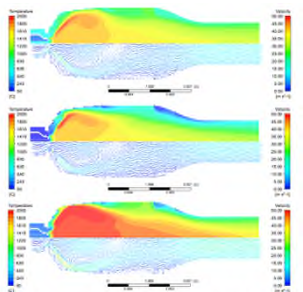
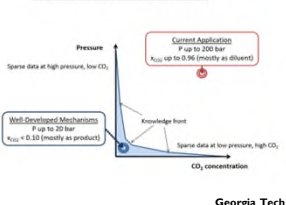


Figure 1-16. Comparison of Temperature Contours and Velocity Vectors for the Three Operating Condition Cases: Design Conditions (Top), Cold Start (Middle), Fast Start (Bottom)

Chemical Kinetics

Kinetics Knowledge Base



Chemical Reaction Kinetics

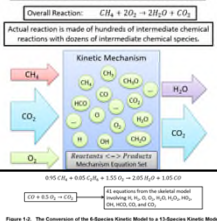
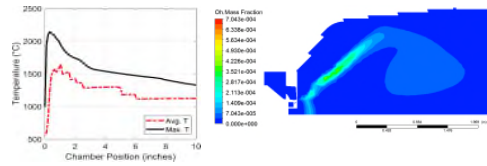


Figure 1-7. Predicted Mole Fraction CO versus Time Results

Heat Release And Flame Holding



Cooling/Recirculation Schemes

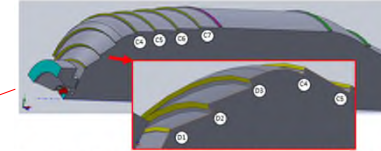


Figure 1-7. Details of the Fluid Inlets, Purposed Indicated by Face Color: CO₂+O₂ Inlet (Teal), Fuel Inlet (Red), Wall Cooling (Yellow), Recirculation Control (Magenta), and Dilution (Bright Green)

Mesh Sensitivity

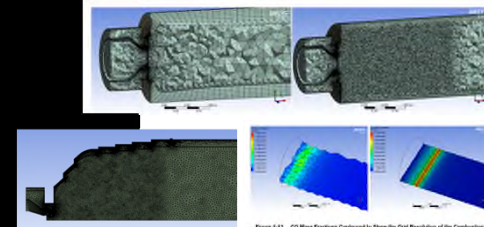


Figure 1-11. CO Mole Fraction Contours to Show the Grid Refinement of the Combustion Reaction. Coarse Grid (left) and Fine Grid (right)

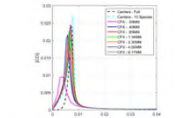
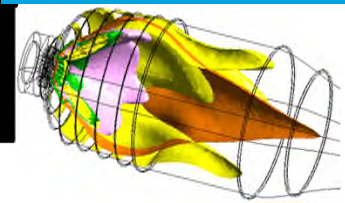
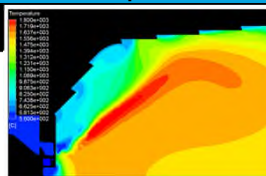


Figure 1-12. Predicted Mole Fraction of CO versus Time Results for various reactions

Unreacted Products



Wall Temperatures

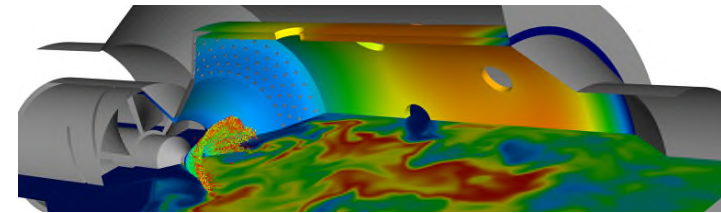


Equation of State and Turbulence

- Steady State vs. Transient
- ANSYS FLUENT
- Real gas effects
- $k-\epsilon$ RANS

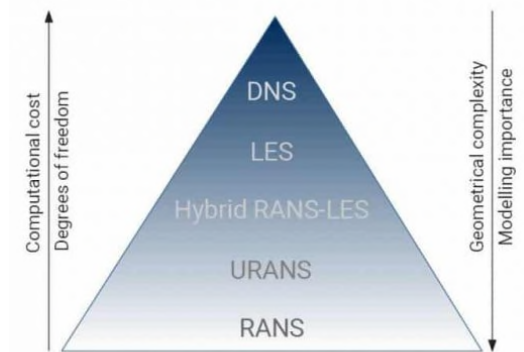
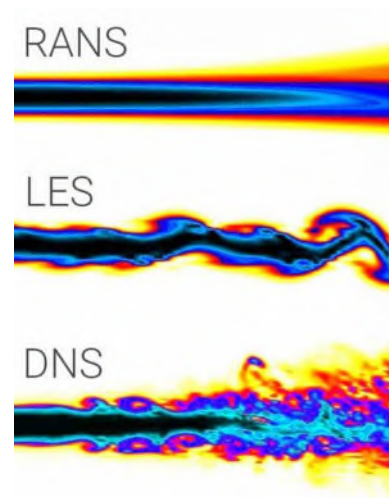
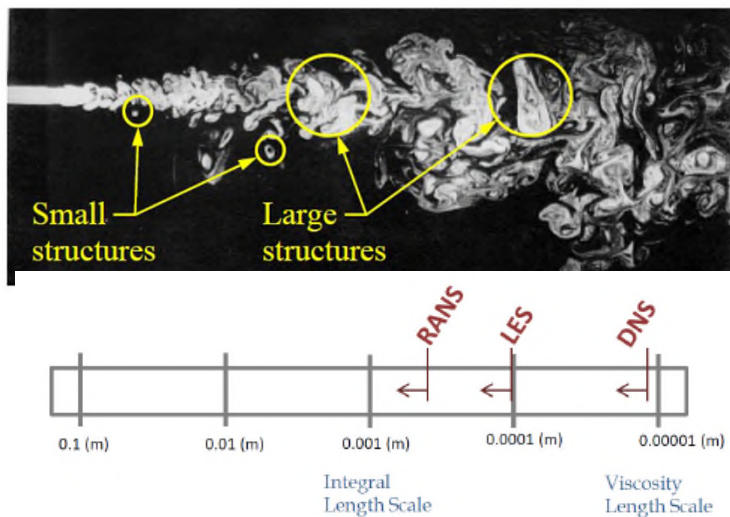
Turbulent Combustion

- For combustion is associated with **chemical reaction**, and **transport phenomena**,
Length scale varies
 - Smallest Kolmogorov length scale to integral turbulent length scale
 - Laminar flame thicknessTime scale varies
 - Kolmogorov time scale to integral turbulent time scale
 - Laminar flame speed
- To completely solve the combustion process , all **chemical species and reactions** need to be included and both time and length scale needs to be resolved
- To do that, **Direct Numerical Simulation (DNS)** needs to be performed which is computationally prohibitive
- To make it computationally feasible; combustion and turbulence modeling is required
- Careful selection of turbulence chemical kinetics models is needed! Flame speed measurements are very uncertain!



Turbulence Modeling

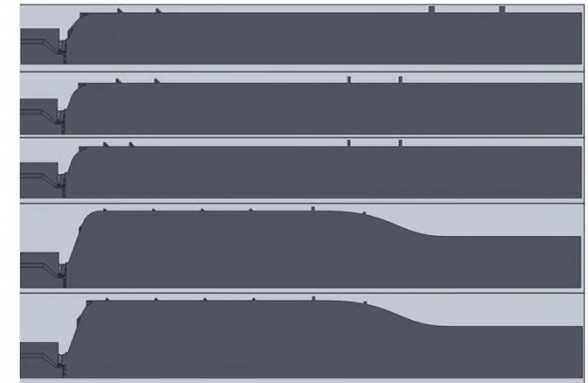
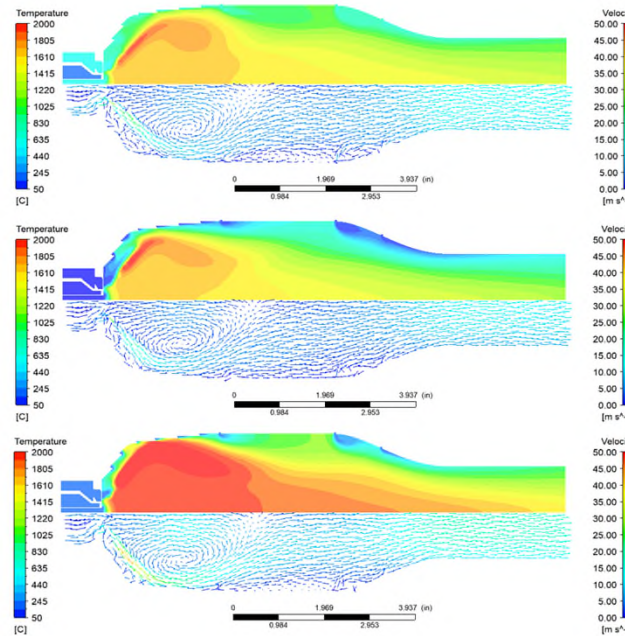
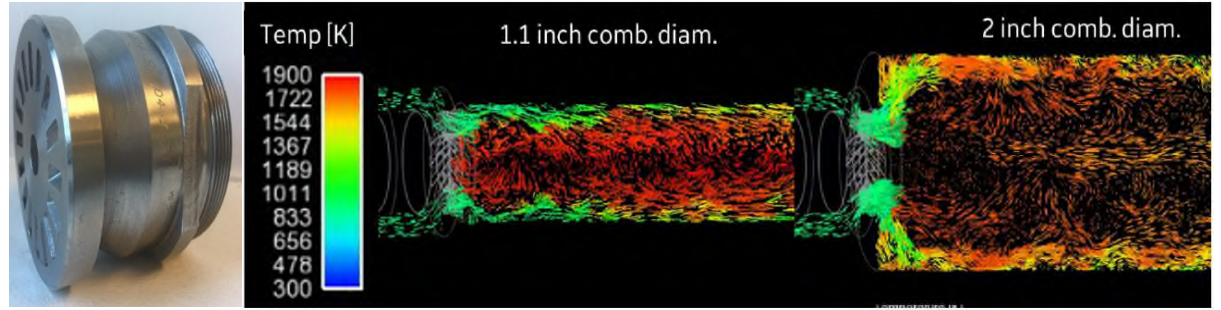
- Turbulent eddies in the flow enhances the rate of mixing of momentum, energy, and species
- These eddies are present at different length scales from small to large
 - **Reynolds-Averaged Navier-Stokes (RANS):** This model is used to account for mixing by introducing turbulent diffusion coefficients for momentum, energy, and species
 - **Large Eddy Simulations (LES) turbulence model:** Resolve the large length scale and model the small length scale
- Turbulence also affects flame speed and chemistry, but that is worthy of its own presentation



Idealsimulations.com
Convergent Science, Inc.

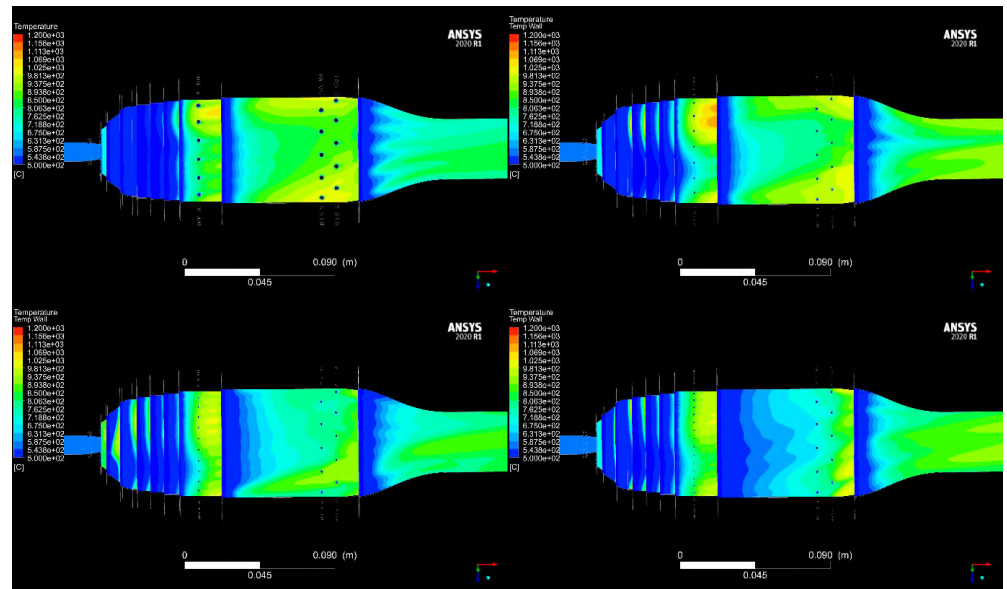
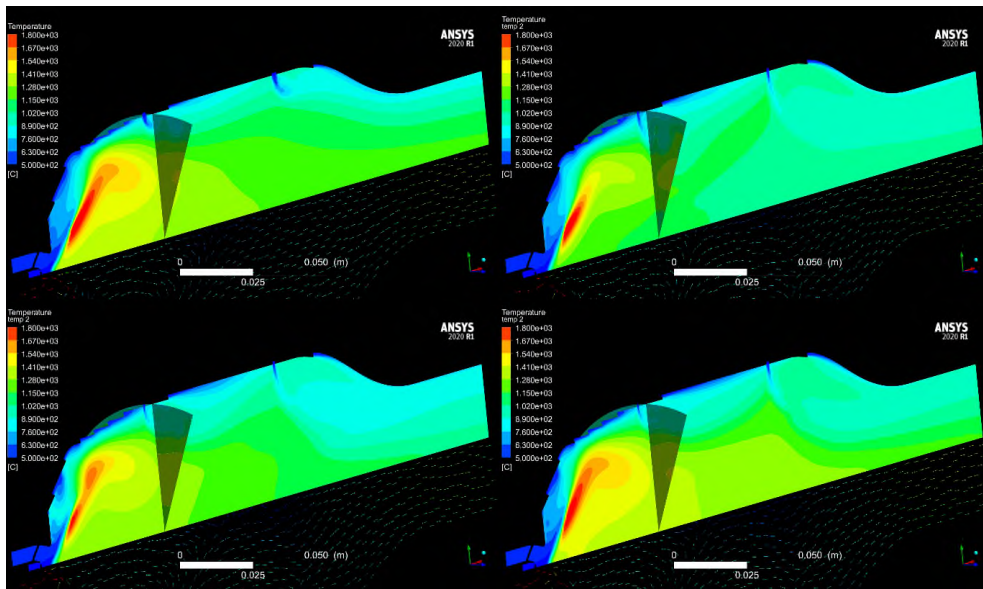
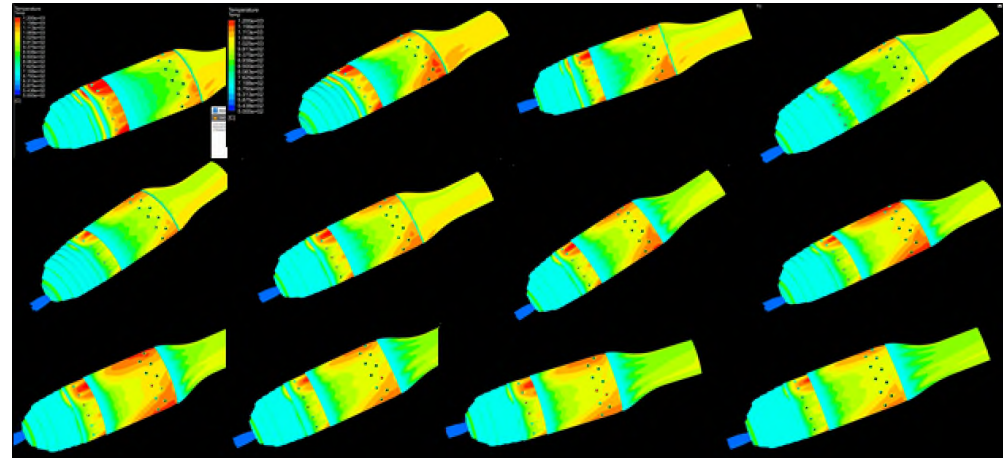
Flow Field

- Swirler design, combustor shape, fuel injection, and cooling flow allocation control the flow field inside the combustor
- Light-off should be conducted at low temperatures and pressures. But what about real gas effects? Operation near the critical point is poorly understood.
- Fuel injection and flow must accommodate all operating conditions, including startup.
- Relevant fluid physics need to be modeled with increasing fidelity as design process proceeds.

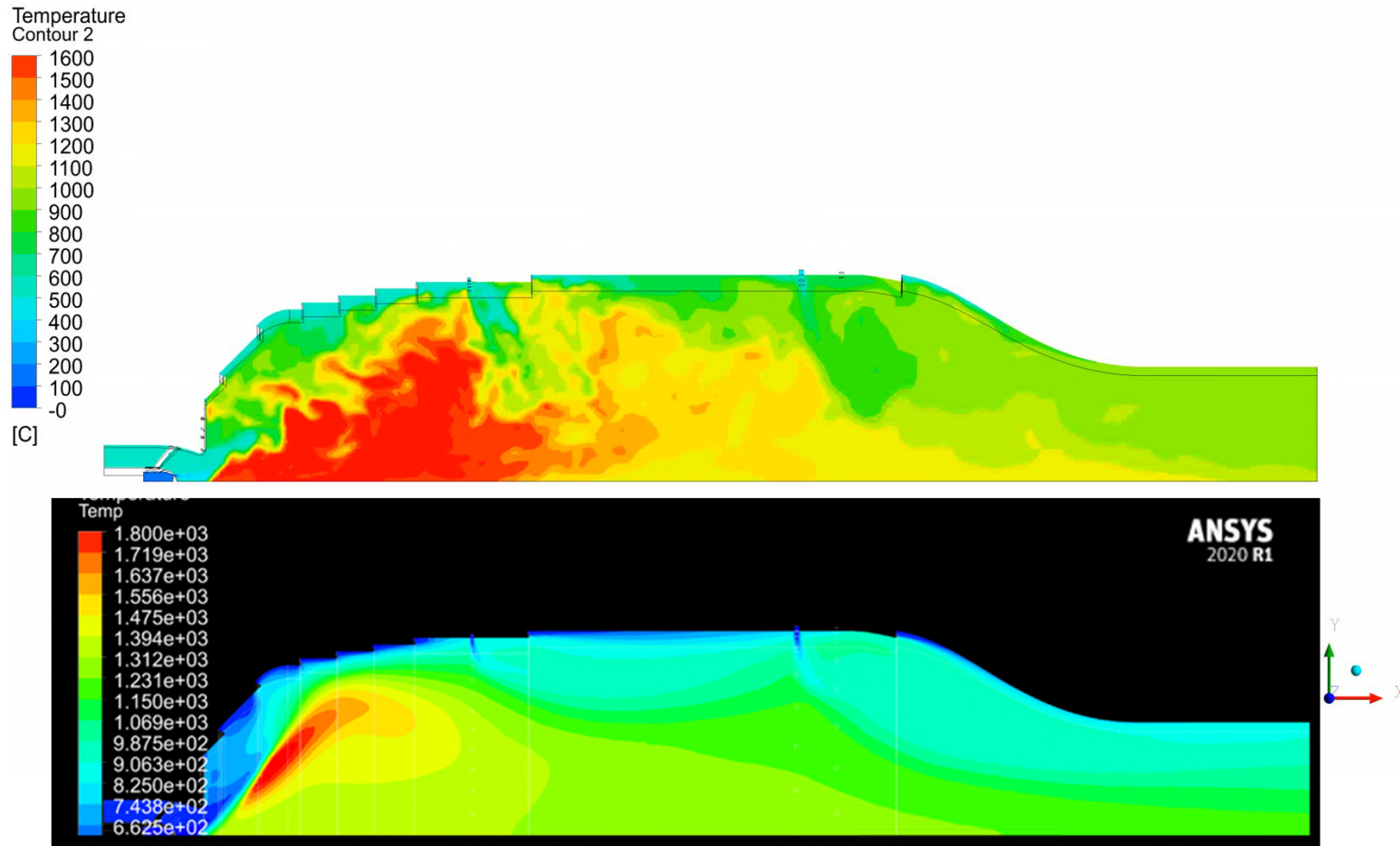


Design and Optimization

- Preliminary approaches can explore the design space using low-cost, low-fidelity steady RANS simulations.
- Especially the work can benefit from RANS if multi-disciplinary simulation is needed (e.g. flow + combustion + heat transfer).



Unsteady Combustion Simulations

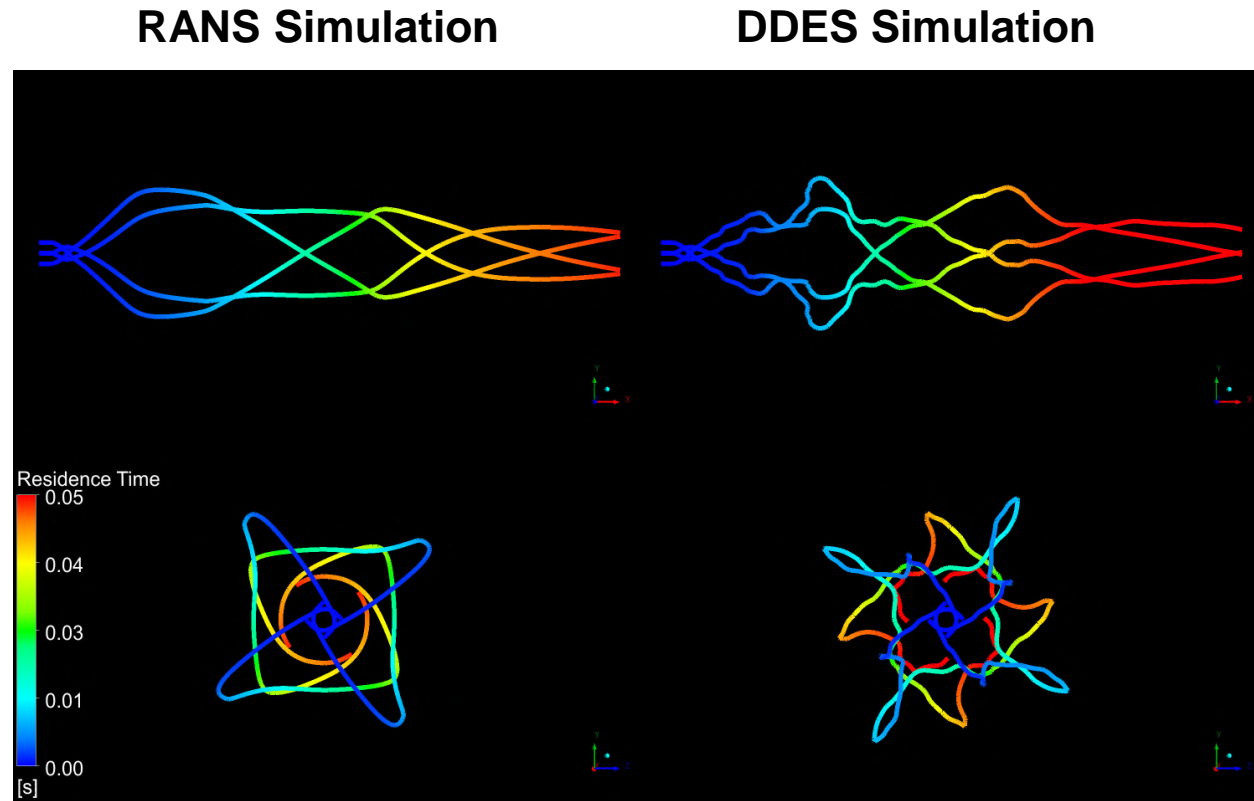


RANS vs Higher-fidelity

When switching from RANS to an unsteady simulation are the key flow features preserved? In our case:

- **Swirl – Yes**
- **Mixing – No**

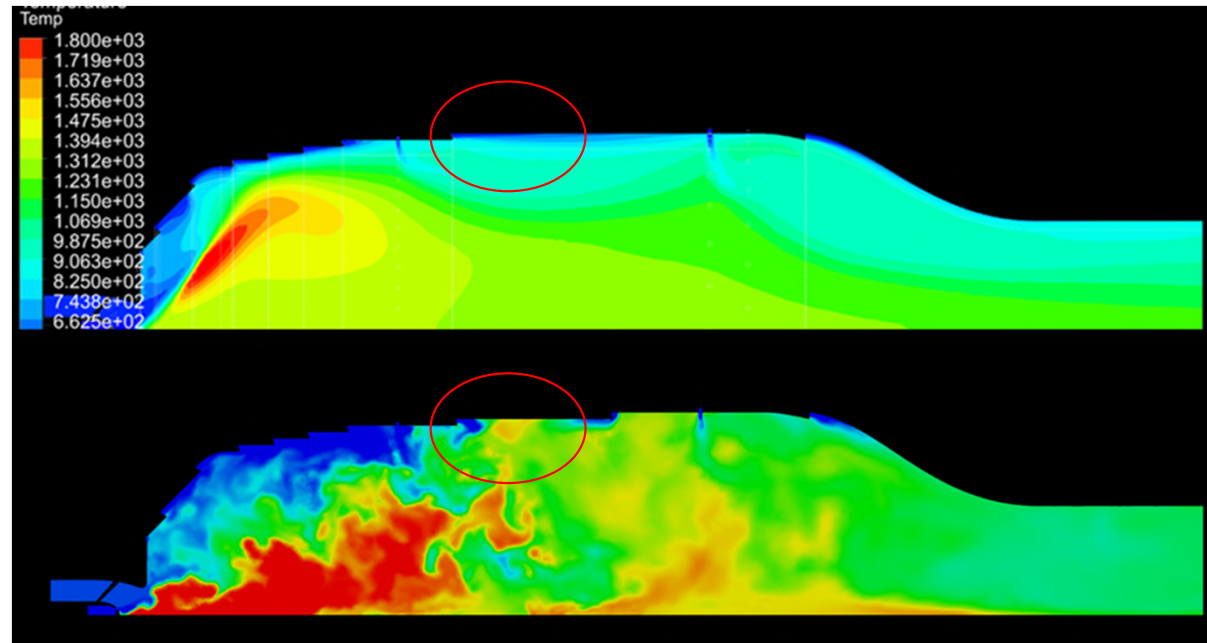
Therefore, combustion: generally no



Streamlines Comparison

RANS vs Higher-fidelity

RANS



DDES

- Averaged/steady vs unsteady. Cost .vs. time
- Steady-state assumptions might only be valid for some cases.
- DNS as benchmark but not for designing of large combustors

RANS vs Higher-fidelity

RANS

Validation data (experimental) at relevant conditions are needed.

DDES

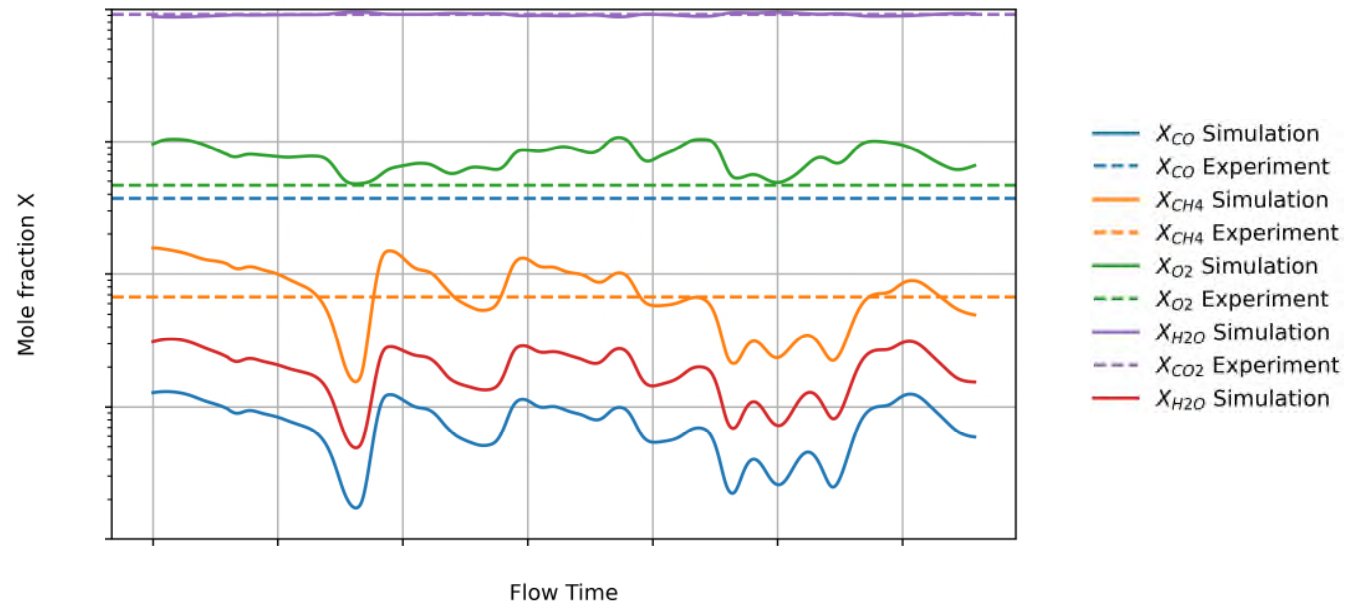
- Averaged/steady vs unsteady. Cost .vs. time
- Steady-state assumptions might only be valid for some cases.
- DNS as benchmark but not for designing of large combustors

Example of simulation vs experiments

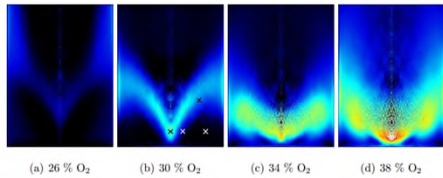
Flame shape



Emissions

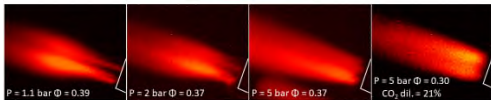


Burners

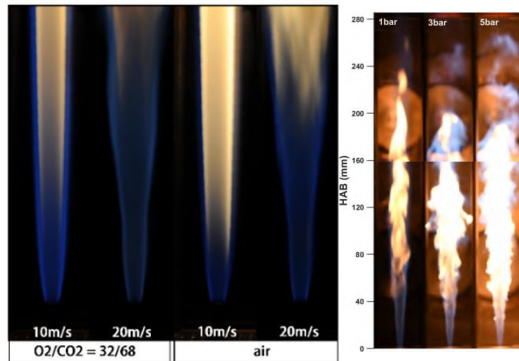


(a) 26 % O₂ (b) 30 % O₂ (c) 34 % O₂ (d) 38 % O₂

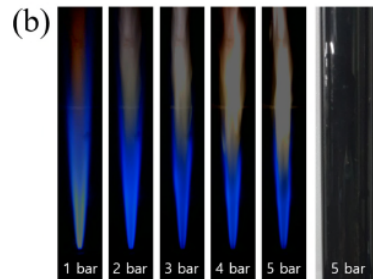
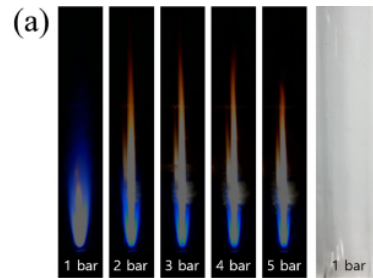
Kutne, et al., 2011



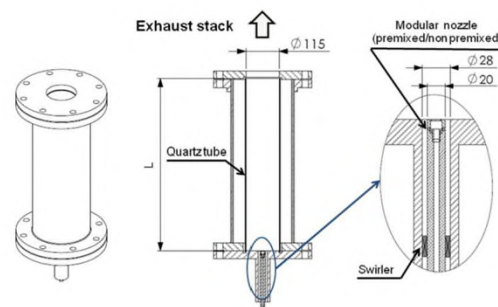
Di Sabatino, et al., 2024



Bukar, et al., 2022, 2023, 2026



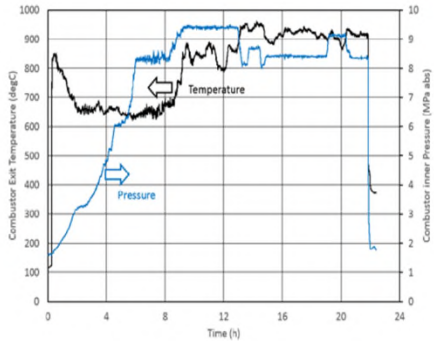
Lee, et al., 2021



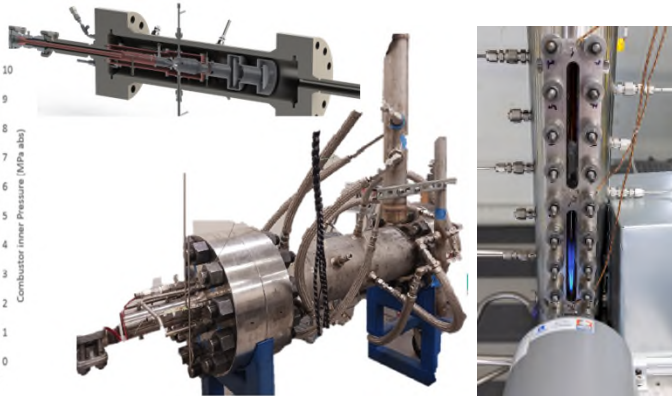
Amato, et al., 2010

- Limited to low pressures (up to 5 bar)
- Different configurations are not really comparable
- Stability limits
- Detailed diagnostics
- Critical point investigations are needed.
- A reference burner is needed
 - Develop diagnostics
 - Data for validation
 - Operational data
 - Stability limits

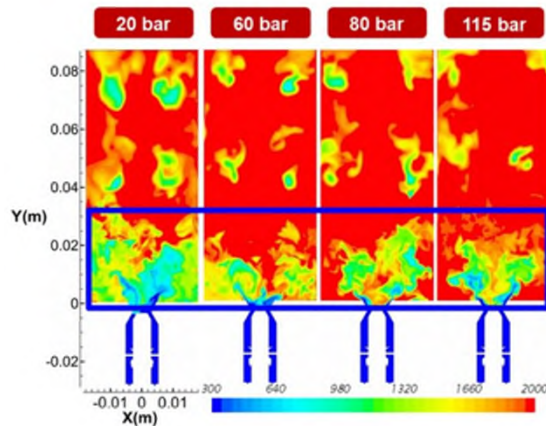
Combustors



Suzuki, et al., 2019



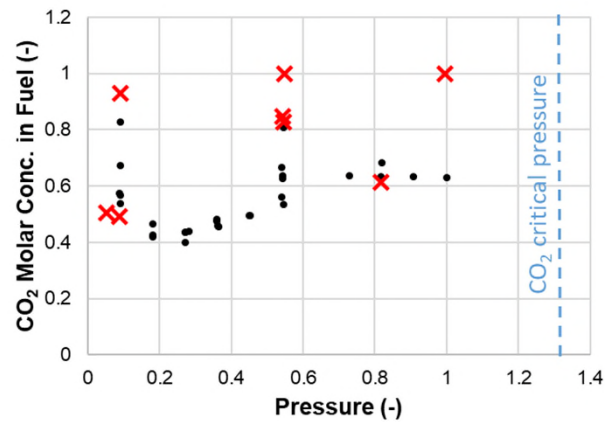
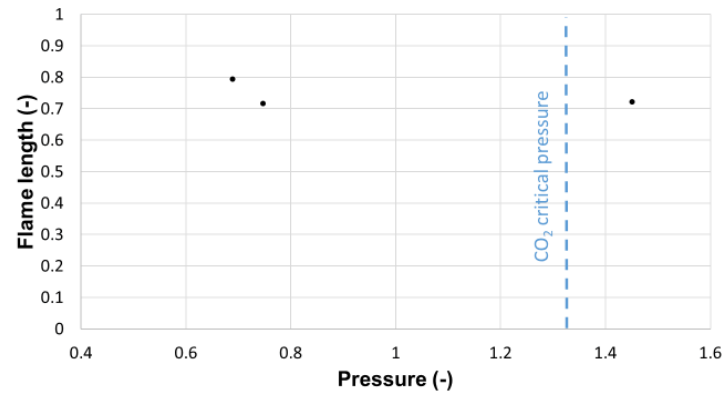
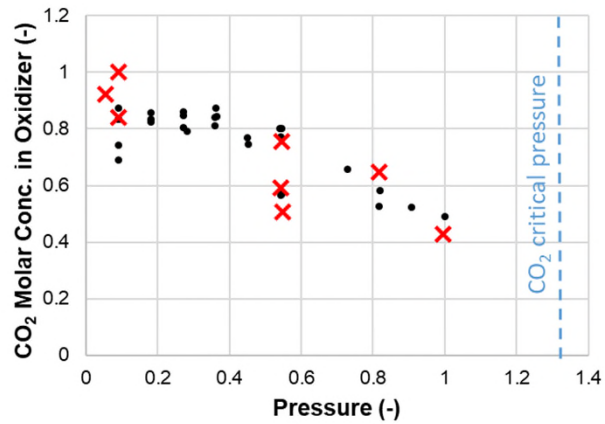
Southwest Research Institute



Keum, et al., 2022

- Complicated and expensive infrastructure
- Very harsh conditions for diagnostics
- Critical point investigations are needed.
- New combustors are needed.
 - Develop diagnostics
 - Data for validation
 - Operational data
 - Stability limits

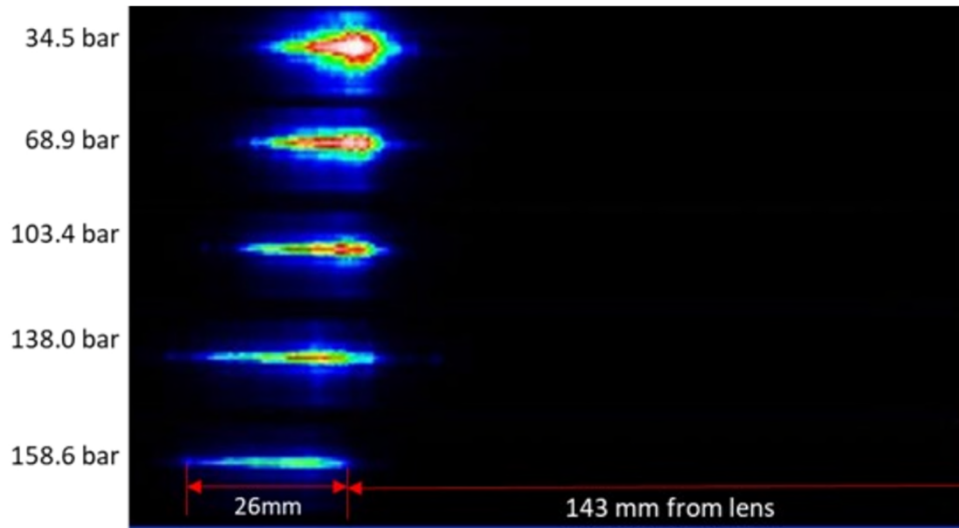
Experimental results



More on Tuesday morning!

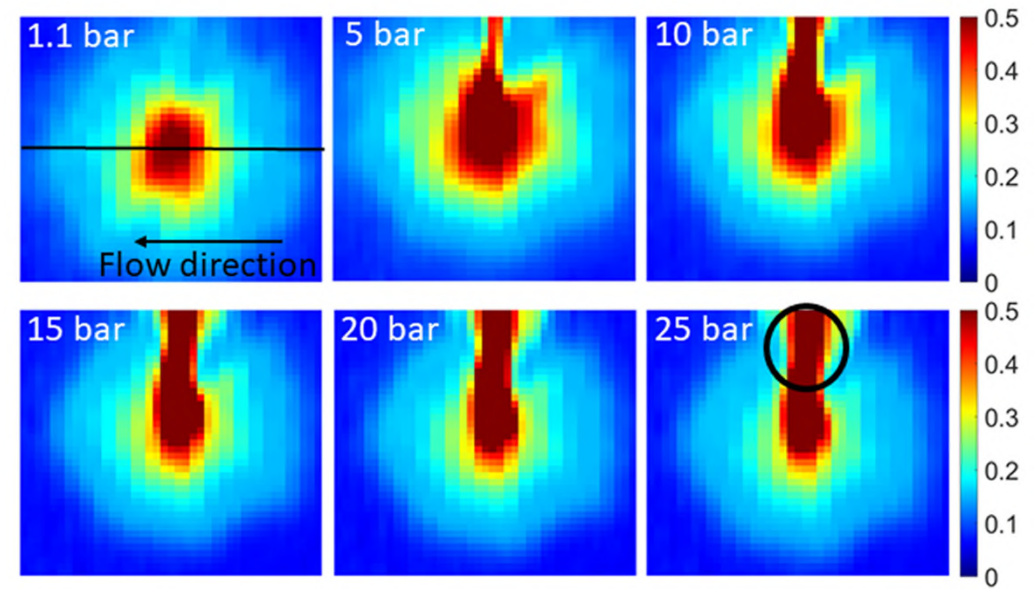
Ignition challenge

- Laser-based



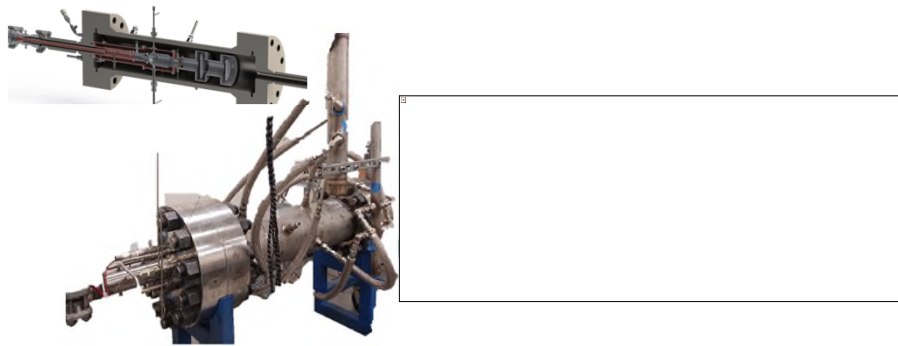
Gupta et al. 2022

- Actuated igniters



Di Sabatino et al. 2024

Combustor design



- Lack of validation data makes existing design tools unreliable
- High pressure/temperature and long-life requirements
- Additive manufacturing (limited in material selection)
- Existing commercially viable materials should be tested for sCO₂ combustion conditions.