Oxy-Combustion Integration for Direct Fired sCO2 Cycles

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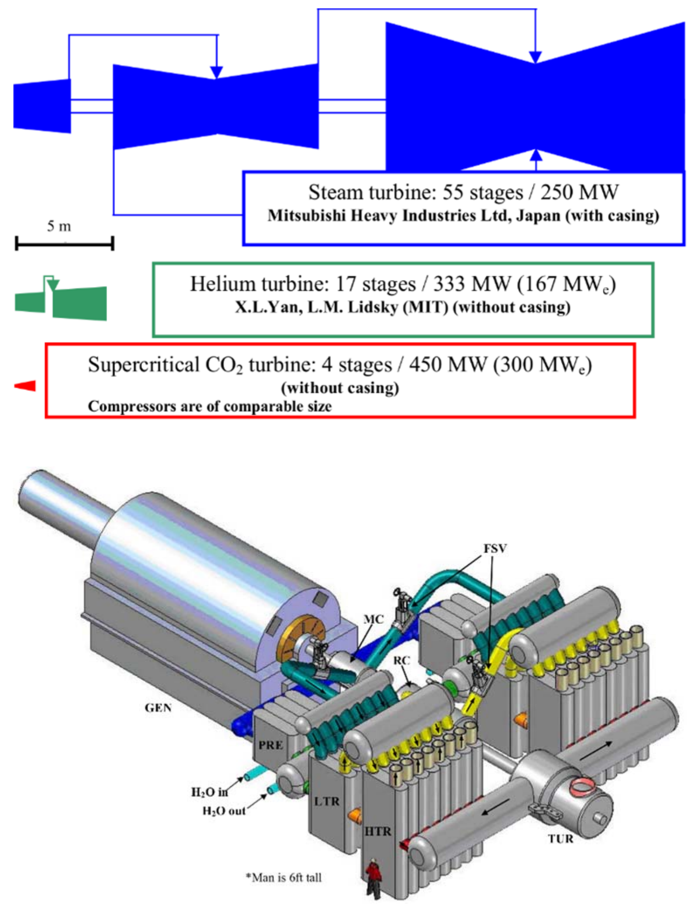
Outline

- sCO2 Cycles
- Oxy-combustion
- Direct Fired Cycles Evaluation
- Wrap-up

DIRECT FIRED SCO2 POWER CYCLES

sCO2 Power Cycles

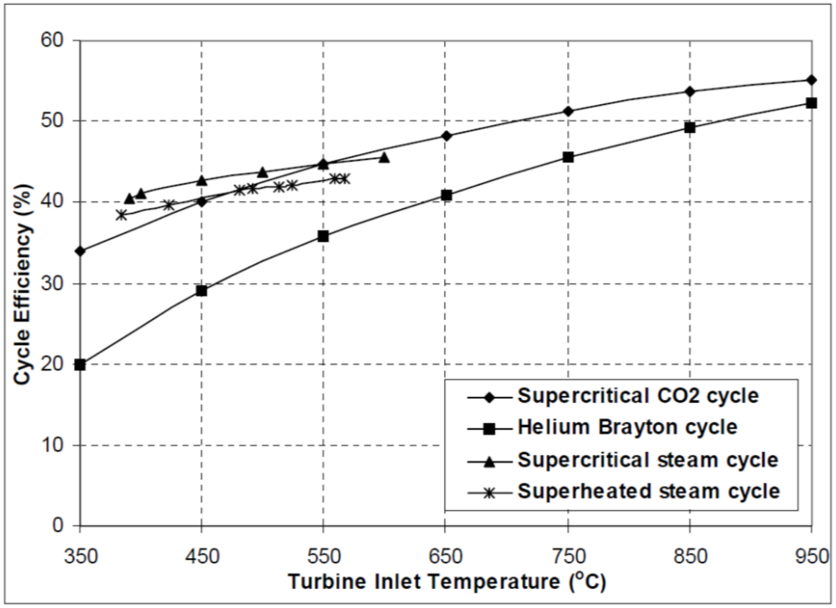
- Offer +3 to +5 percentage points over supercritical steam for indirect coal fired applications
- High fluid densities lead to compact turbomachinery
- Efficient cycles require significant recuperation
- Compatible with dry cooling techniques



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

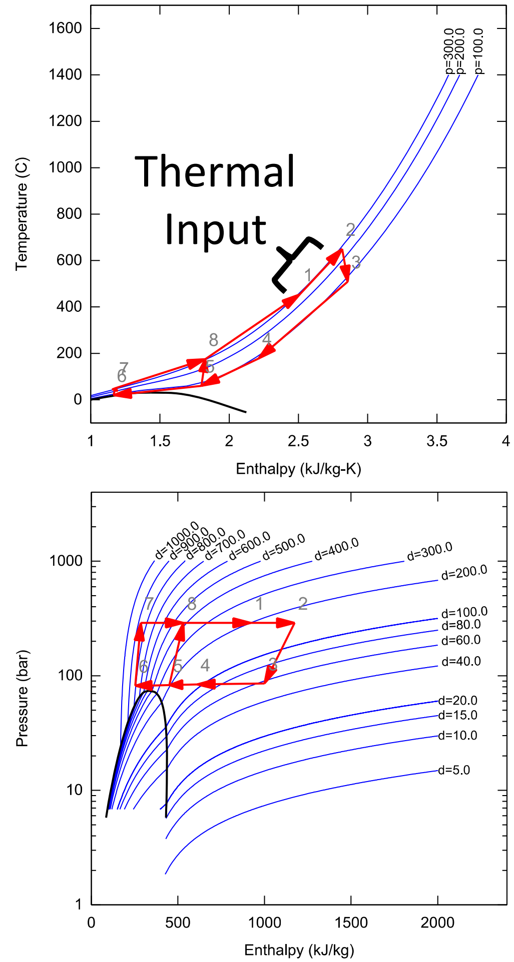
Fossil Based sCO2 Power Cycles

- Competition
  - Indirect: Supercritical Steam with CCS
  - Direct: Natural Gas Combined Cycle
- Advantages
  - High power efficiencies at "Moderate" temperatures
  - Oxy-combustion facilitates integrated carbon capture
  - Compact turbomachinery lead to compact power blocks



Challenges

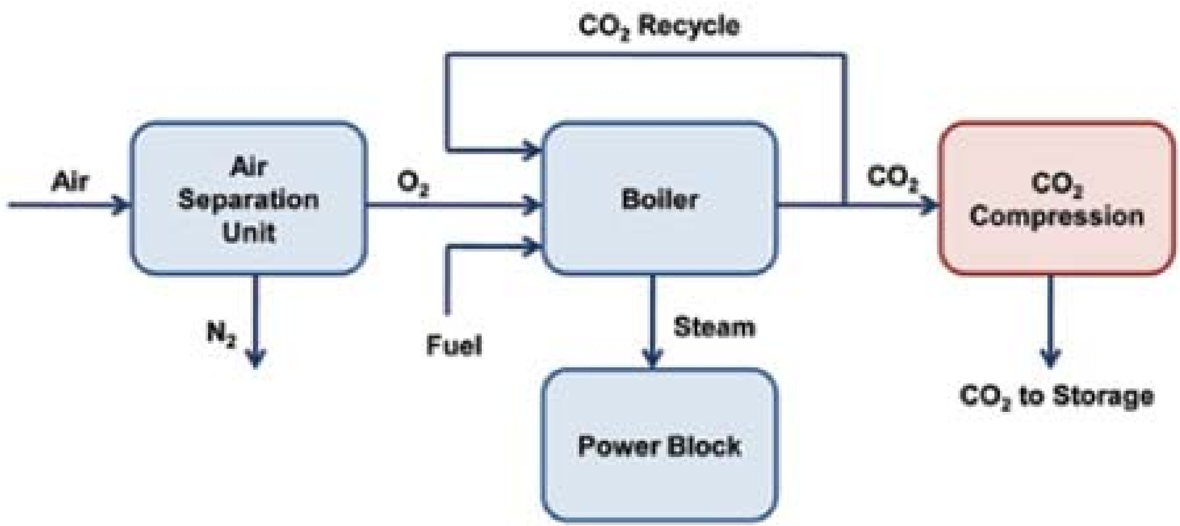
- Challenges
  - 250 C thermal input temperature widow (recompression cycle) is not ideal for combustion based systems
    - 400 C Combustor inlet for 650 C Turbine Inlet
    - 950 C Combustor inlet for 1200 C Turbine inlet
  - Flue gas cleanup for direct fired systems
  - Non-trivial efficiency losses for indirect cycles
  - Compact power block offset by recuperation requirements



OXY-COMBUSTION

Oxy-combustion

- Combustion in an oxygen rich environment
  - Used for industrial applications for achieving high combustion temperatures
  - Commonly used in metal, glass, and cement industries
- Atmospheric Nitrogen is replaced by the combustion flue gas which is primarily Carbon Dioxide
  - Provides CO2 rich stream for capture and sequestration
  - Minimizes NOx formation

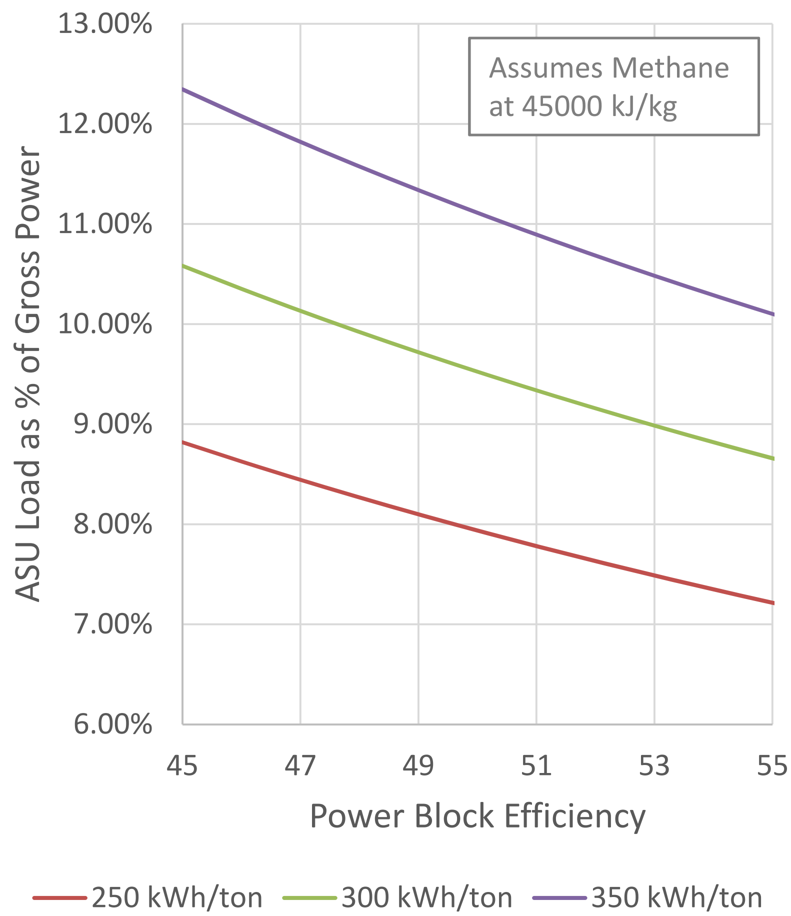


Flavors of Oxy-Combustion

- Flue Gas Recirculation
  - Combustion at near ambient pressures
  - Recycled flue gas is mixed with incoming air
  - Increases flame temperatures
  - Increases CO_2 concentration for CCS
- Pressurized Oxy-combustion
  - Combustion at elevated pressure (~ 10 bar)
  - Latent heat is recoverable and heat transfer rates are increased
  - Minimizes air in-leakage
- Supercritical Oxy-combustion
  - Combustion occurs at supercritical pressures (>74 bar)
  - Required for direct fired sCO_2 cycles, compatible with indirect cycles
  - CO_2 acts as a solvent in dense phase, accelerating certain reactions
  - Compression requirements drive closed combustion solutions
  - Flue gas cleanup and de-watering at pressure may be challenging

Challenges

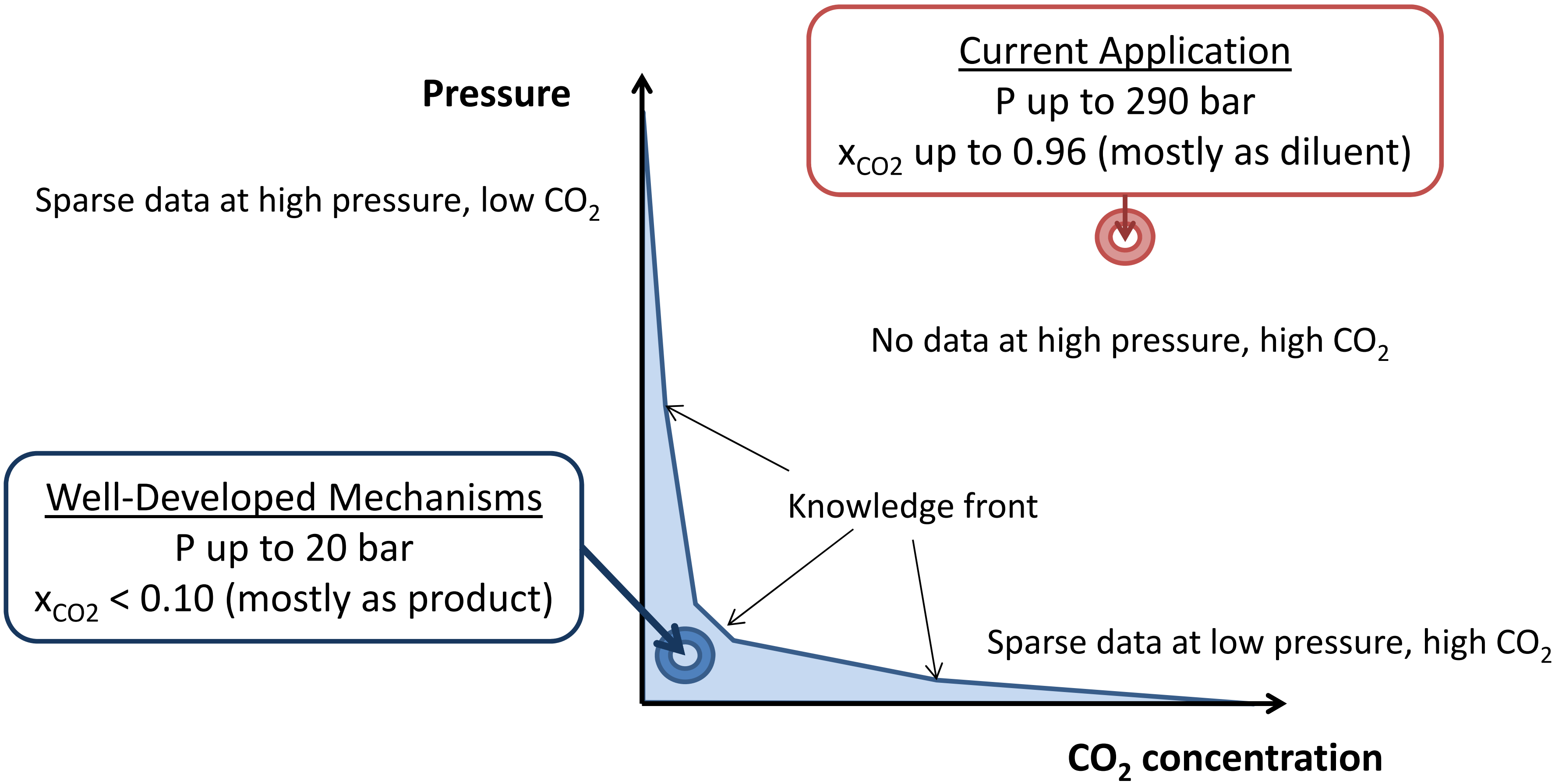
- Oxygen generation is not cheap
  - Cryogenic oxygen separation is current state of the art for commercial Air Separation Units
  - 250 to 360 kWh/ton of O2
- Higher power block efficiencies required to offset ASU power usage



Supercritical Natural Gas Oxy-combustion

- Natural gas simplifies fuel feed system, enables higher operating pressures
  - Requires Oxygen compression
- Simplifies flue gas cleanup
  - No solids removal
  - Fewer impurities to consider than coal
- Combustion system must operate at cycle conditions between 200 and 300 bar
- To achieve plant efficiencies approaching 55%
  - Drives cycles to turbine inlet temperatures near 1200 C to achieve power block efficiencies near 65%
  - ASU is still a significant power sink at 250 to 360 kWh/ton
- Oxy-combustor operating at 200+ bar is a significant technical risk
  - Oxy-combustor inlet temperatures enable an auto-ignition style combustor
  - Reaction rates and mechanism are well outside current literature
  - Radiant effects uncertain

Kinetics Knowledge Base



No data available at conditions relevant to this application.

Development Path

- System Design and Thermodynamic Analysis
  - Evaluate cycles to determine combustor design parameters
- System level Technology Gap Assessment
- Kinetics Models
  - Evaluate kinetic models to determine applicability
  - Initial kinetic evaluation at combustor inlet conditions
- Combustor Concept
  - Material constraints at 1000 C 200 bar inlet, 1200 C 200 bar outlet conditions
- Combustor demonstration

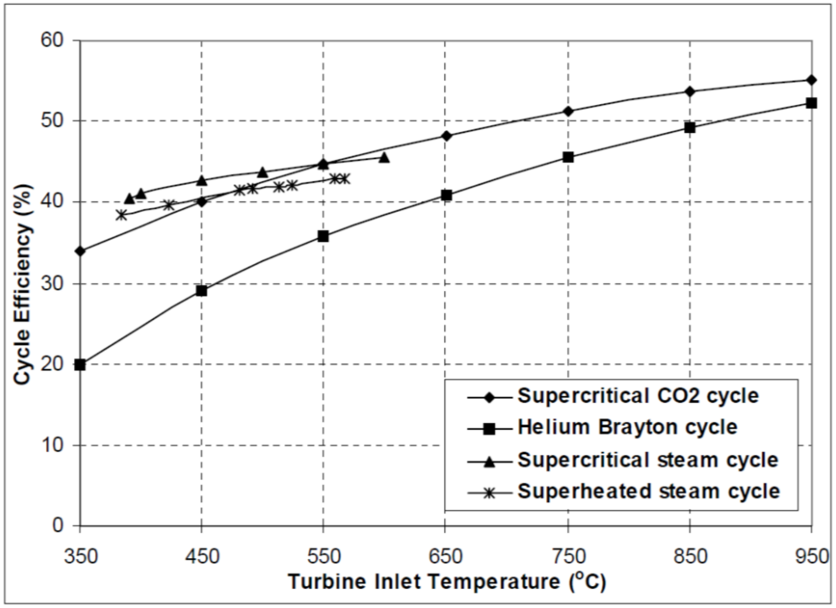
SYSTEM ENGINEERING DESIGN AND THERMODYNAMIC ANALYSIS

Thermodynamic Analysis

- Establish combustor operating parameters
  - Inlet Temperature, Pressure, mass flow
  - Thermal duty
- Plant models were developed and evaluated using ASPEN Plus
  - Incorporated secondary systems
    - ASU, Cooling, Fuel Compression
  - Incorporated equilibrium combustion model

Direct Fired Supercritical Oxy-Combustion

- Plant optimization focused on thermal efficiency
  - *Target 52% plant efficiency to compete with NGCC*
  - Drives 64% power cycle thermal efficiency
  - *Turbine inlet near 1200°C*

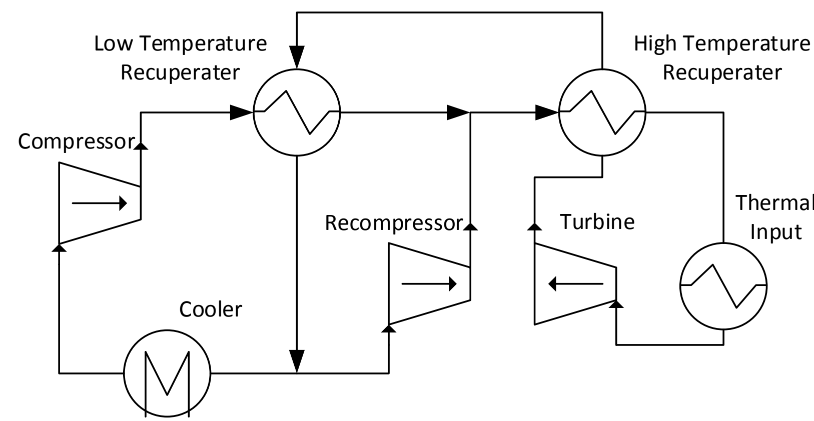


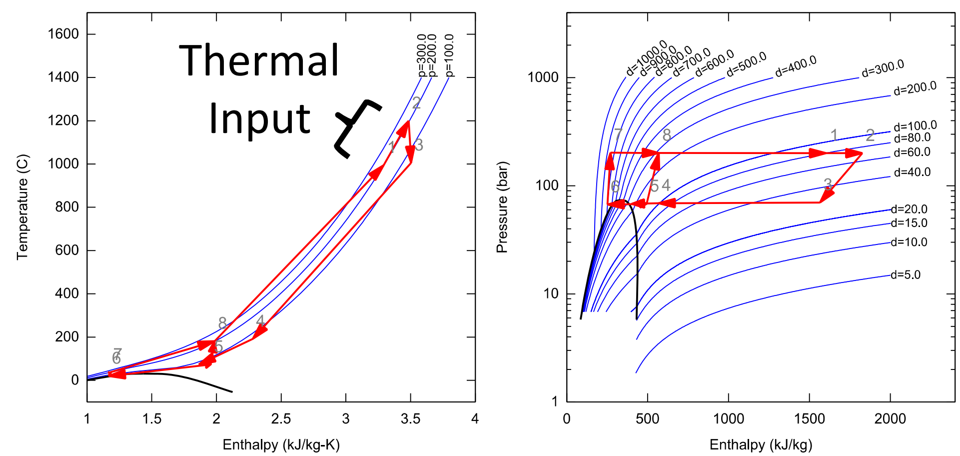
Metrics for Cycle Evaluation

- Combustor inlet temperature
- Overall cycle efficiency
- Overall heat exchanger area
- Volume flowrate per power out (turbine size)
- Power per mass flowrate
- Amount of high temperature piping/components needed

Recompression Cycle

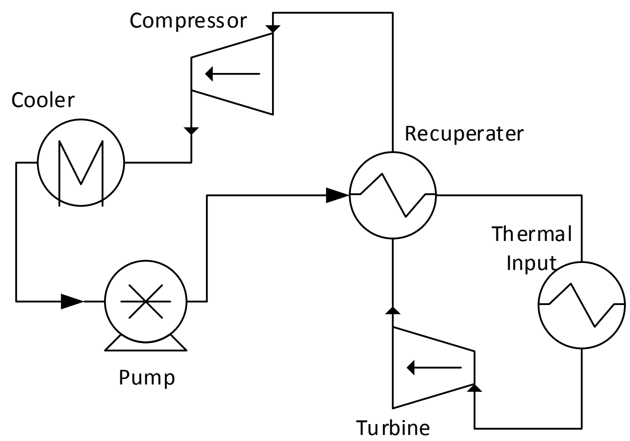
- Leverages recent SunShot and DOE-NE cycles development
- High efficiencies possible for the power block, 60% at 1100C, 65% at 1300C
- High degree of recuperation drives a narrow thermal input window (~250C) and high mass flow requirements
- Combustor inlet ~ 950 C for 1220 C Firing Temperature

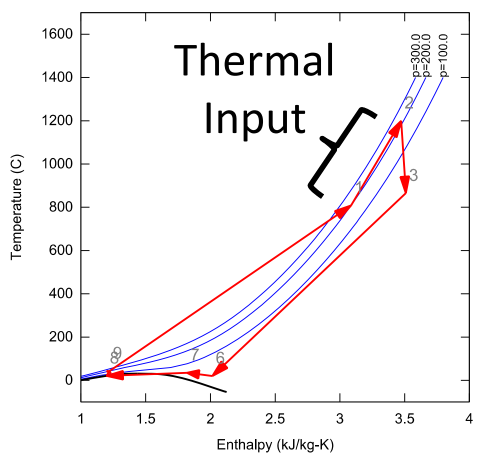


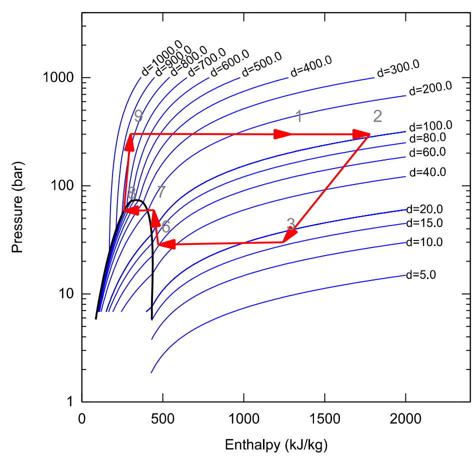


Partial Condensation Cycle

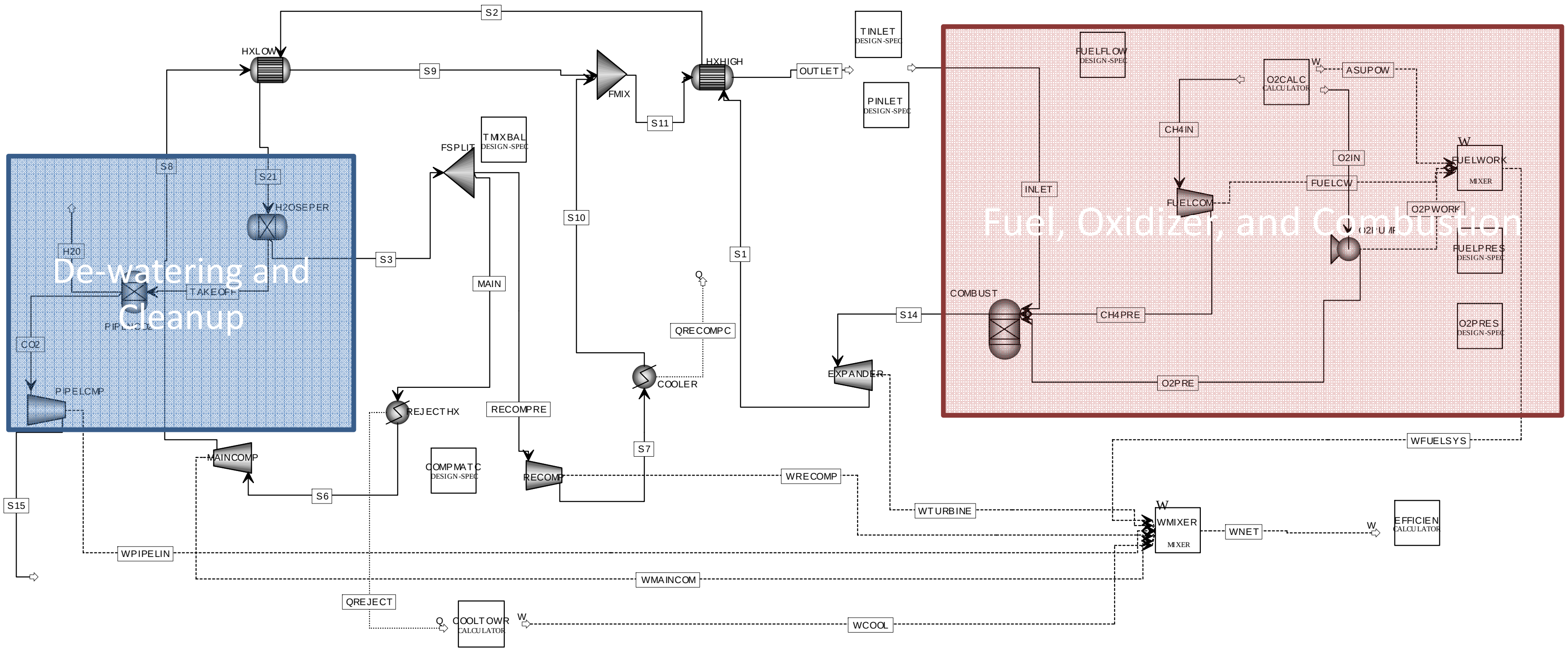
- Trans-critical cycle
- Optimization schedules the vapor phase compression, cooling for liquefaction, and liquid pumping to reduce compression power requirements







Oxy-Combustion Plant Model



Cycle Analysis Results

- Recompression cycle has highest efficiency by 1.8% at 200 bar, 2.7% at 300 bar
- Condensation cycle is 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.

Cycle Comparison

	Single Recuperator Condensation	Single Recuperator Condensation	Recompression	Recompression
Net fuel to bus bar plant efficiency	54.03%	51.60%	56.73%	53.44%
Total Recouperation (kW)	989.91	1078.16	1163.44	1205.34
HE Duty per Net Power Ratio (kW/kW)	2.48	3.21	4.34	6.55
Power per Mass Flow Ratio (kJ/kg)	399.06	335.38	268.08	183.92
Combustor Inlet Temp. (°C)	755.18	808.60	918.16	994.37
Combustor Inlet Pres. (bar)	300.00	200.00	300.00	200.00

** Cycles evaluated at 1200°C Turbine Inlet Temperature and unit 1 kg/s mass flow

Modeling Considerations

- Combustion Models
- Equation of State
- Component Assumptions
- Dewatering and Cleanup
- Off design
- Transients

Takeaway

- Supercritical oxy-combustion has specific challenges that must be addressed through component development
- ASU power requirements drive the cycle conditions
- Supercritical natural gas oxy-combustion is feasible, has significant development requirements
  - Uncertainties related to the dense phase oxy-combustor
  - Fundamental combustion properties
  - Design for high temperature and high pressure
- Impact of water and flue gas impurities must be considered for material selection and corrosion
- High operating temperatures required to compete with NGCC
  - Requires material development, characterization, and certification
  - Impact of corrosion in hot CO2 environment not well understood
  - Requires advanced turbine cooling technologies for blades and seals
- Intermediate temperature combustor demonstration is a stepping stone

THANK YOU FOR YOUR ATTENTION