A Comparison of Supercritical Carbon Dioxide Power Cycle Configurations with an Emphasis on CSP Applications

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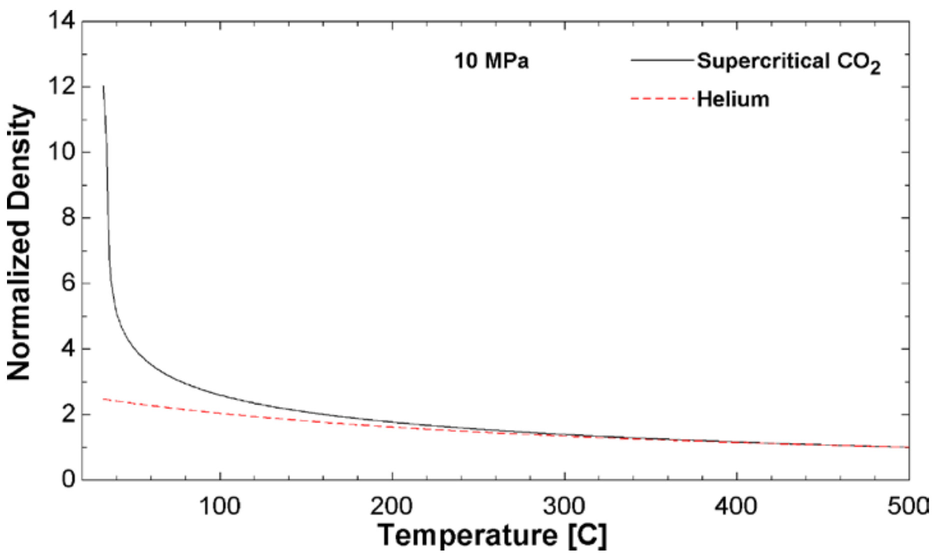
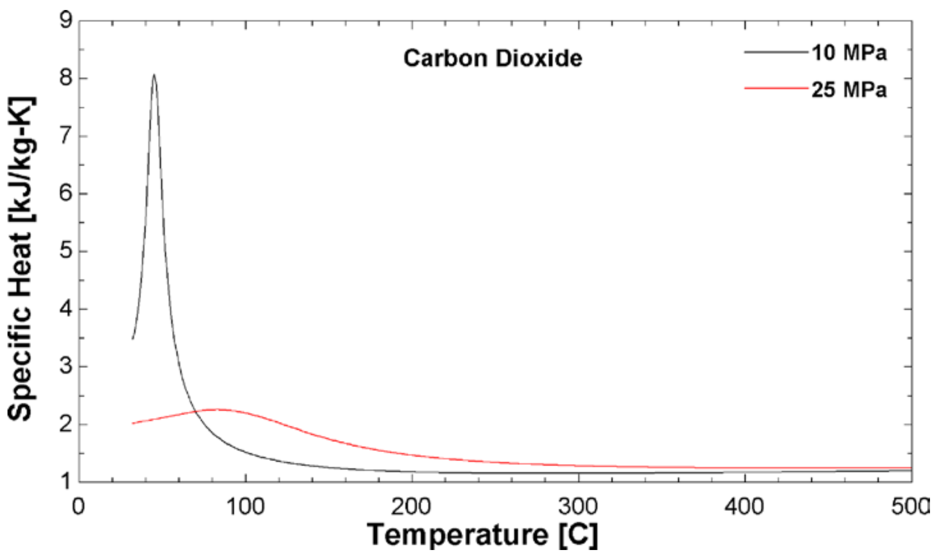
Supercritical Carbon Dioxide Background

- Thermodynamic properties of CO_2 deviate from normal trends near the critical point (31°C, 7.4 MPa)
  - Increased density allows for high back work ratio in the cycle, which boosts efficiency
  - Increased thermal capacitance results in pinch points in heat exchangers and also impacts heat rejection decisions





Attractive Features of s-CO_2 Brayton Cycle

- Simpler cycle design than steam Rankine
- Potentially achieves higher efficiency than steam Rankine
- High density working fluid yields compact turbomachinery
- Viable turbine designs from 10 to 300 MWe
- Low-cost, low-toxicity, low-corrosivity fluid; thermally stable at temperatures of interest to CSP (550°C to 750°C)
- Single phase reduces operational complexity; integrates well with sensible heat storage in CSP systems
- Multiple high-efficiency cycle configurations possible to match to a specific application

Considerations for CSP Integration

Factors for integrating s-CO2 power cycles into CSP plants

1. Superior performance vs. steam Rankine *at dry cooling*
2. Economic integration of TES

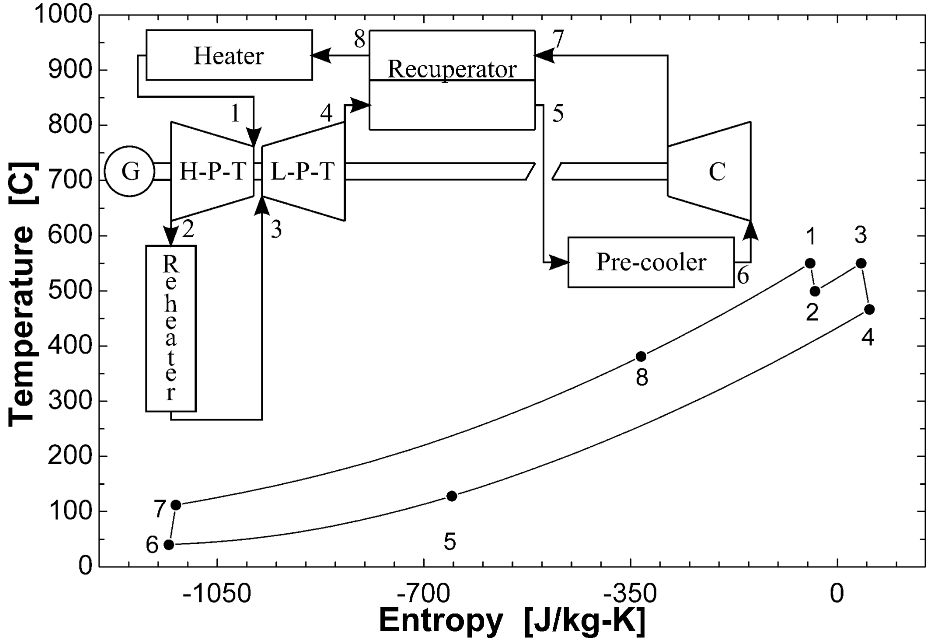
$$Energy_{TES} = mass * specific\ heat\ * (T_{hot} - T_{cold})$$

For sensible heat storage:

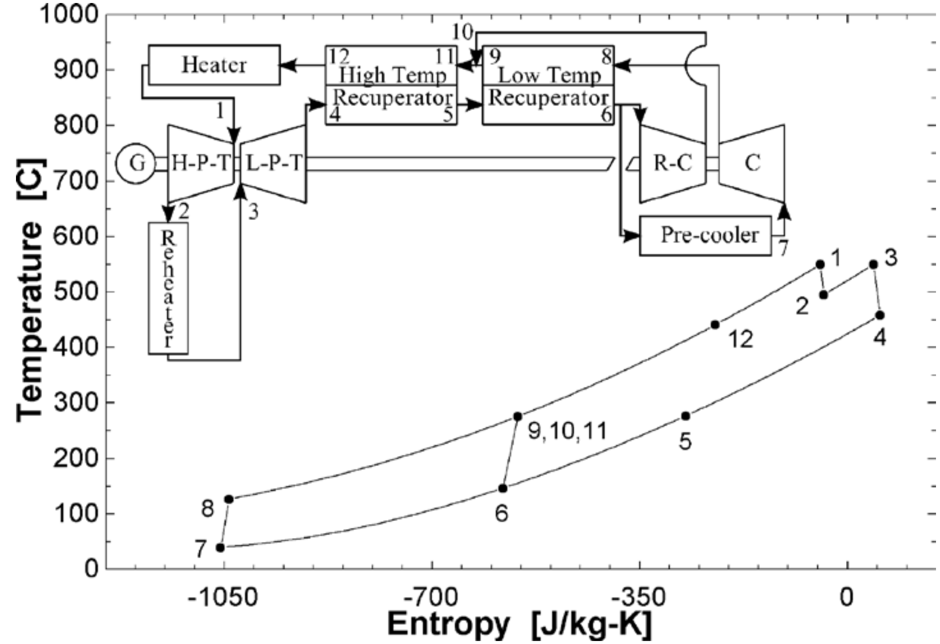
- The required mass of HTF is proportional to the hot and cold tank temperatures.
- All else equal, a cycle with a larger temperature difference is preferred to a cycle with a smaller temperature difference

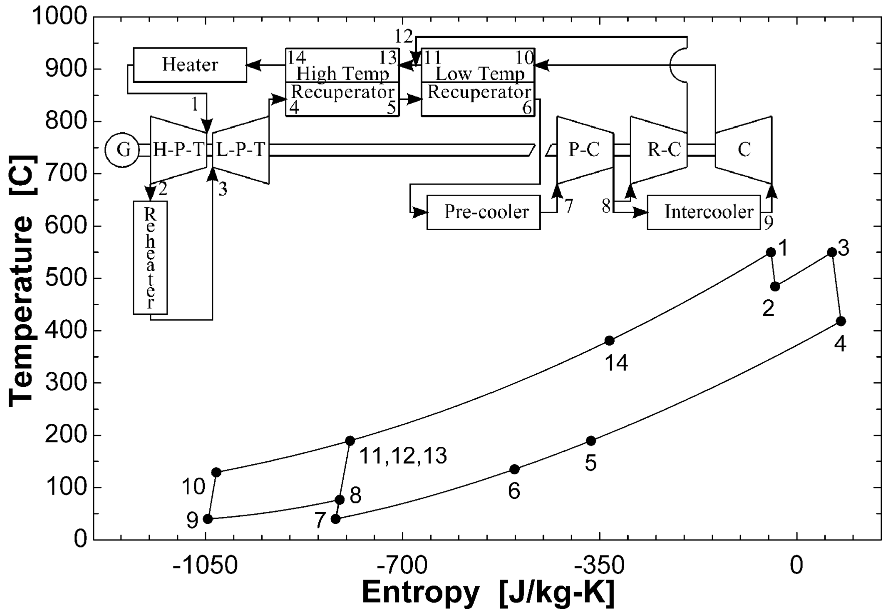
Configurations

Simple



Recompression





Partial Cooling

Modeling Background and Research Objective

Modeling Background

- One reheat stage increased efficiency around 1.2% for a recompression cycle (Dostal, 2004)
- Partial cooling cycle achieves competitive efficiency with the recompression cycle while offering larger HTF temperature differences (Dostal, 2011)
- Dry-cooled partial cooling and recompression cycles have potential to achieve > 50% efficiency (NREL, 2013)

Summary

- Recompression and partial cooling efficiencies are similar, but studies have not investigated the heat exchanger requirements

Objective

- Model the heat exchangers using a conductance (UA) model and compare the efficiency, HTF temperature difference, and other useful cycle performance metrics as a function of allocated conductance

Recuperator Modeling Approaches

1. Select HX effectiveness and minimum temperature difference
   - Simplest approach to approximate HX performance
   - Does not consider temperature profile within HX (e.g. pinch points)
   - Non-dimensional metric – does not correlate to HX size
2. Select HX conductance (UA)
   - Calculates HX performance based on approximation of HX size
   - Correlates performance and size without requiring specific physical dimensions – useful for relative comparisons
   - Does not capture effects of specific design decisions or varying fluid properties
3. Select a HX design
   - Requires realistic dimensions and heat exchanger material properties
   - Most complex and computationally expensive approach
   - Provides the best data with which to compare different cycles

Design and Optimized Parameters for Case Studies

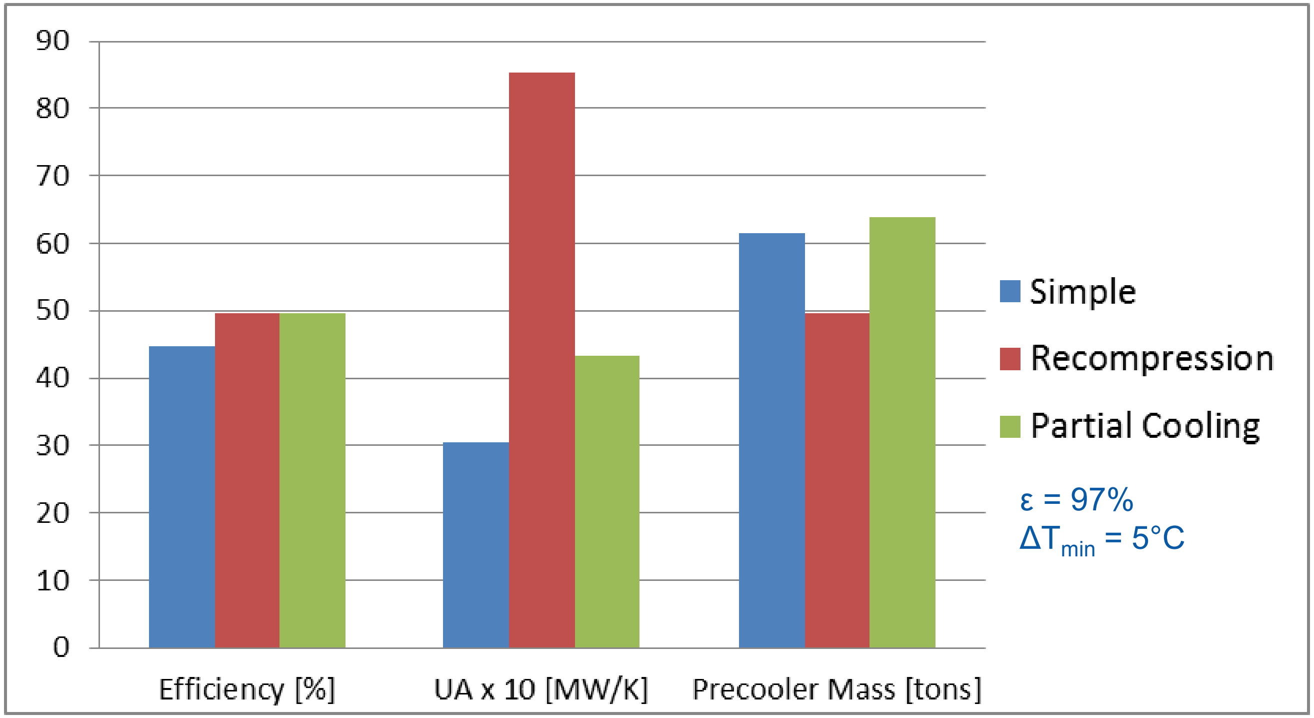
Design Parameters	Value	Comments
Turbine efficiency	93%	Projection of mature, commercial size axial flow turbine efficiency
Compressor efficiency	89%	Projection of mature, commercial size radial compressor
Heat exchanger effectiveness	97%	5°C minimum temperature difference, neglect pressure drops
Heat exchanger conductance (UA)	Varied MW/K	Neglect pressure drops
Turbine inlet temperature	650°C	SunShot target for CSP power tower outlet temperatures
Compressor inlet temperature	50°C	Possible under dry cooling with 35°C ambient temperature
Upper pressure	25 MPa	Upper limit given available and economic piping
Turbine Stages	2	One stage of reheat at average of high and low side pressures
Net power output	35 MW	Estimate of power cycle requirements for a 100 MW-thermal SunShot target power tower with a solar multiple of 1.5

Optimized Parameters	Relevant Cycles
Pressure ratio (PR)	All
Fraction of total UA allocated to HTR	Recompression, Partial Cooling (not applicable for effectiveness approach)
Ratio of pressure ratios (rpr)	Partial Cooling (sets intermediate pressure)

Results – Recuperator *Effectiveness* Model

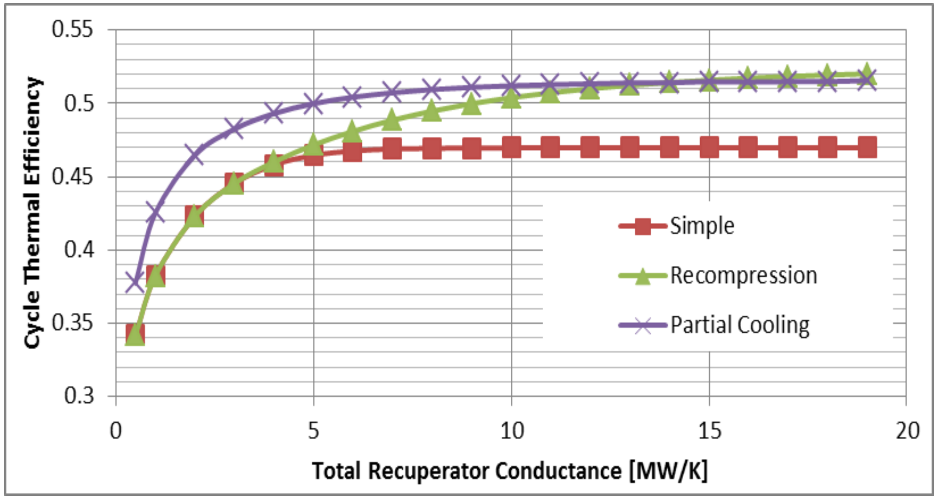
- Similar efficiencies for complex cycles
- Much larger recuperator for the recompression cycle
- Smaller pre-cooler for recompressoin cycle (rejects more heat at higher temperatures, Seidel 2010)

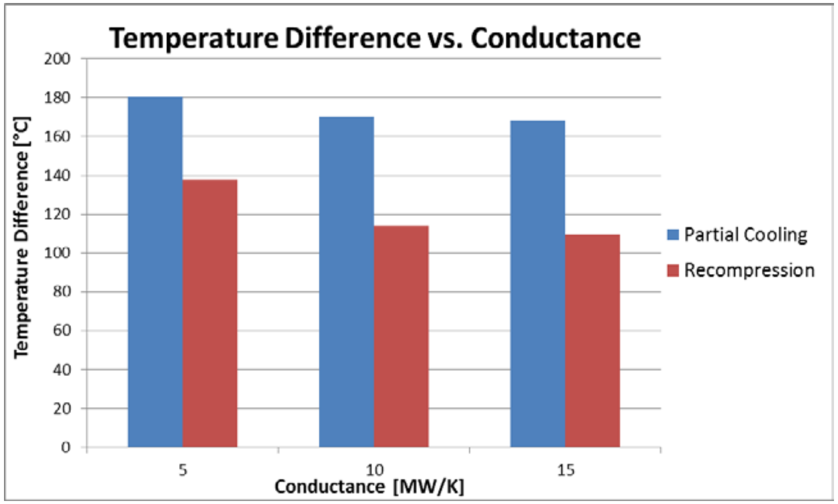
Effectiveness model does not give complete picture



Results – Recuperator *Conductance* Model

- Significantly different results when recuperator conductance is specified
- At smaller conductance values, the recompression cycle reverts to simple cycle behavior (Bryant 2011, Dyreby 2012)
- As conductance reaches largest values
  - Recompression cycle efficiency reaches partial cooling efficiency
  - Recompression ΔT decreases more rapidly than partial cooling ΔT



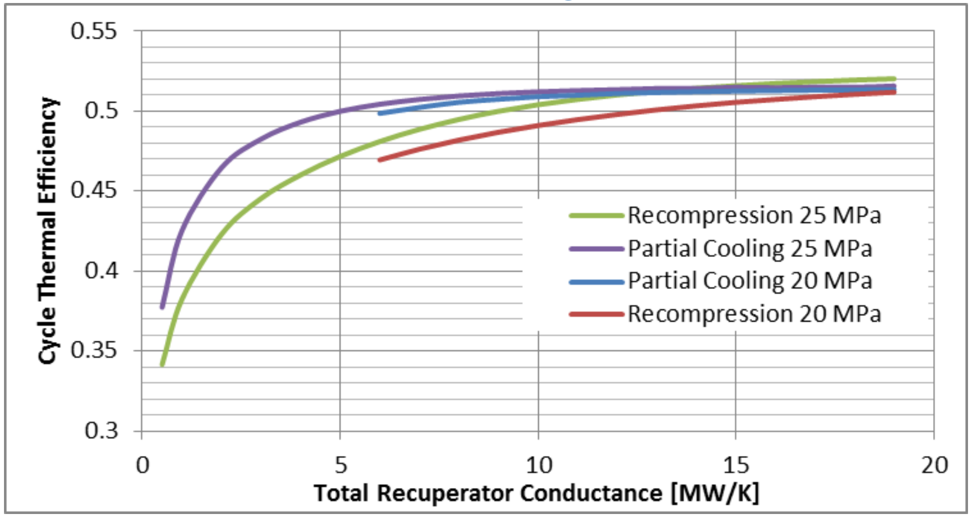


Modeling Limitations

- Neglecting pressure drops
  - Larger pressure difference in partial cooling cycle
  - Lower densities in partial cooling cycle may require more or larger channels
- Conductance HX model does not consider the impact of absolute pressures and pressure differentials
- Does not consider impact of varying fluid properties on heat transfer coefficients
- Pre-cooler model is not optimized with the cycle design
  - Trade-offs between cycle efficiency, pre-cooler size, and fan parasitics should be considered

Integration with Direct CO2 Receivers

- Ongoing research of direct s-CO2 receivers
  - NREL, Brayton Energy, OSU/PNNL, CSIRO
- Potential advantages of integration with partial cooling cycle:
  1. Lower average temperature of receiver may help reduce thermal losses
  2. Enables longer flow paths in receiver
     1. Stabilizes mass flow rate through parallel tubes
     2. Reduces deviation of absorbed energy per tube
  3. Lower total mass flow rate reduces header piping sizes
  4. Greater potential to decrease the high pressure in the receiver



Conclusions

- Using a conductance model for the recuperator provides a more equivalent comparison than an effectiveness model
- The partial cooling cycle outperforms the recompression cycle until large quantities of conductance are modeled
- The partial cooling cycle offers a larger temperature difference across the primary heat exchanger, which is critical to TES integration in CSP systems. It also may offer benefits to direct receiver designs.
- Studies of first-principle models are available for simple and recompression cycles. This work suggests that similar studies would be worthwhile for the partial cooling cycle in order to better understand heat exchanger dimensions and off-design performance.

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THANK YOU!