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Parameterized Study of Partially Recuperated Supercritical CO_2 Power Cycle Performance

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ABSTRACT

Contemporary interest in a practical supercritical carbon dioxide cycle has spurred literary discussion regarding a plethora of proposed thermodynamic network topologies. Crespi, Gavagnin, Martínez, and Sánchez evaluate sCO_2 cycles by mapping thermal efficiency and specific work across a range of peak pressure and turbine inlet temperature (TIT). Parameterized curves identify cycles that maximize thermal efficiency and specific work against metallurgical considerations. This systematic analysis establishes a methodological framework for comparing cycles' relative utilization of material capability. Sánchez et al. recommended development of cycles whose performance characteristics maximize advancements in material capability, i.e. those cycles with performance headroom yet to be realized. The present work analyzes Peregrine Turbine Technologies' Partially Recuperated (PR) sCO_2 power cycle. An NPSS cycle model characterizes performance across a range of compressor discharge pressures and TITs using assumptions comparable to those set forth by Sánchez et al. The work at hand presents and compares cycle performance curves for variable pressure ratio at 750°C TIT to the curves obtained for several cycles of interest identified by Sánchez.

BACKGROUND

Sánchez et al. developed a logical framework for comparing impact of TIT and compressor pressure ratio on thermal efficiency and specific work characteristics of different cycle layouts. Applying several unifying assumptions across cycle models, that paper elucidated pointed observations linking achievable performance characteristics of cycles to their potential performance capabilities given advancements in materials and mechanical design. That study compared twelve cycles' Thermal Efficiency-Specific Work curves parameterized by total pressure ratio at fixed TITs. Comparing cycles in this unqualified manner highlights achievable thermal efficiency and turbomachinery size with and without consideration of material limitations.

Below, Fig. 1 reproduces Sanchez et al's plot of thermal efficiency and specific work curves for SCO_2 power cycles as a function of compressor discharge total pressure (P_t). Solid data markers indicate ≤40 MPa compressor discharge P_t. Conversely, hollow markers indicate >40 MPa compressor discharge, identified by Sánchez as a limitation of contemporary materials for 750°C TIT.

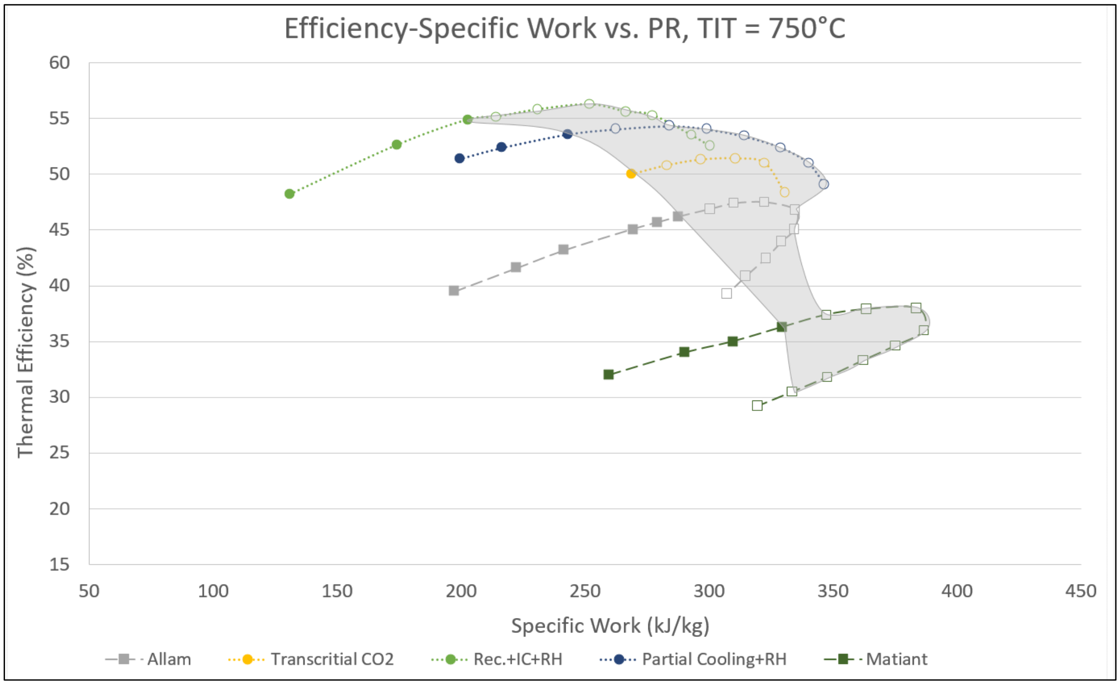


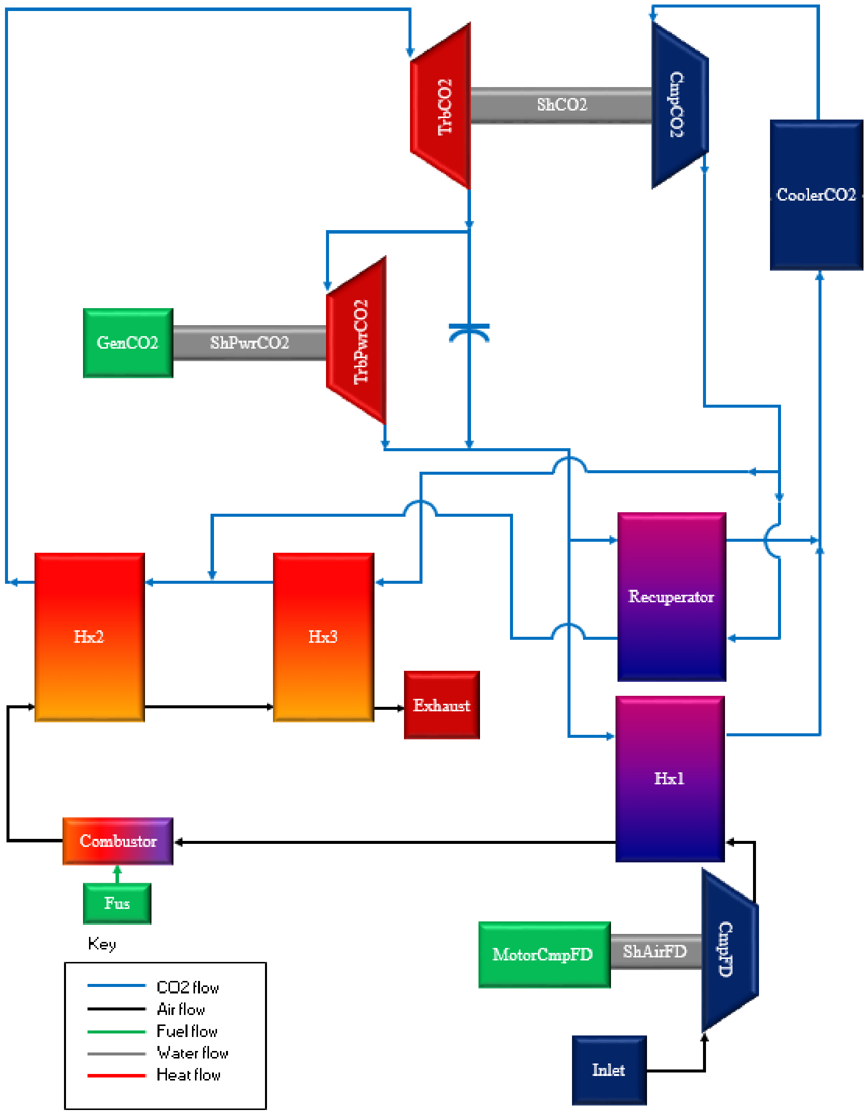
Figure 1: Sánchez et al. studied twelve cycles, five of which promise to yield the greatest gains in thermal efficiency and specific work at 750 °C TIT with forthcoming design and material improvements.

Figure 1 includes only the cycles that Sánchez identified will stand to gain efficiency and specific work improvements alongside advancements in design and materials for peak pressures beyond 40 MPa. Each curve begins with its lowest pressure ratio at the data marker nearest to the Thermal Efficiency ordinate; Sánchez observed that all cycles' curves eventually pass through an inflection point, curling downward and leftward with elevated pressure ratios. Sánchez demarcated a Thermal Efficiency-Specific Work boundary through the five cycles that maximize thermal efficiency or specific work at 40 MPa compressor discharge. Seven other cycle models analyzed by Sánchez et al. produced curves that curl back toward the origin without reaching into the grey high-performance region reproduced in Figure 1 above.

An indirect fired sCO_2 cycle, the Partially Recuperated (PR) cycle optimizes recuperation alongside two flow splits to enhance thermal efficiency when used with air-combustible fuels. The cycle schematic in Figure 2, below, illustrates the flow split of turbine exhaust between an sCO_2-to-sCO_2 recuperator and an sCO_2-to-air heat exchanger (HX1). HX1 delivers heat from hot, expanded sCO_2 to the compressed air entering the combustor. By recycling lower-grade heat from sCO2 to air, HX1 reduces fuel consumption required to heat intake air to design point temperature.

The cycle also splits compressor discharge into two flows between the recuperator and an air-to-sCO_2 heat exchanger– HX3. Low temperature compressed flow entering HX3 recovers lower-grade heat from hot flue leaving the primary heat exchanger, HX2. In other indirect-fired cycles, full recuperation increases the temperature of sCO_2 entering the primary heat exchanger. The split flows of the PR cycle increase the temperature window for heat addition, an invaluable feature for fossil fuel and waste heat recovery applications where maximizing capture of heat of combustion or lower-grade process heat can prove challenging for indirect-fired sCO_2 cycles with full recuperation.

Figure 2: Partially-recuperated sCO_2 power cycle topology balances recuperation and two flow splits to enable high efficiencies with air-combustible fuels. In practice, the compressor could be powered by an air breathing turbine. Converting heat directly to mechanical energy would eliminate exergy destruction associated with an electrically-driven compressor. Replacing the compressor and motor with a co-shaft turbo-compressor pair increases thermal efficiency by about 0.5%.



RESULTS AND DISCUSSION

Running the PR cycle model with incremental increases to pressure ratio with flow splits optimized for thermal efficiency grants a comparison with the findings developed by Sánchez et al. The NPSS model uses isentropic sCO2 turbomachinery efficiency rather than polytropic efficiency used by Sanchez et al. A polytropic efficiency rating for a given compressor or turbine will be slightly higher than its isentropic efficiency. The NPSS model of the PR cycle used 90% isentropic efficiency for turbines and 89% isentropic efficiency for the sCO2 compressor, rather than 90% and 89% polytropic, respectively used by Sánchez.

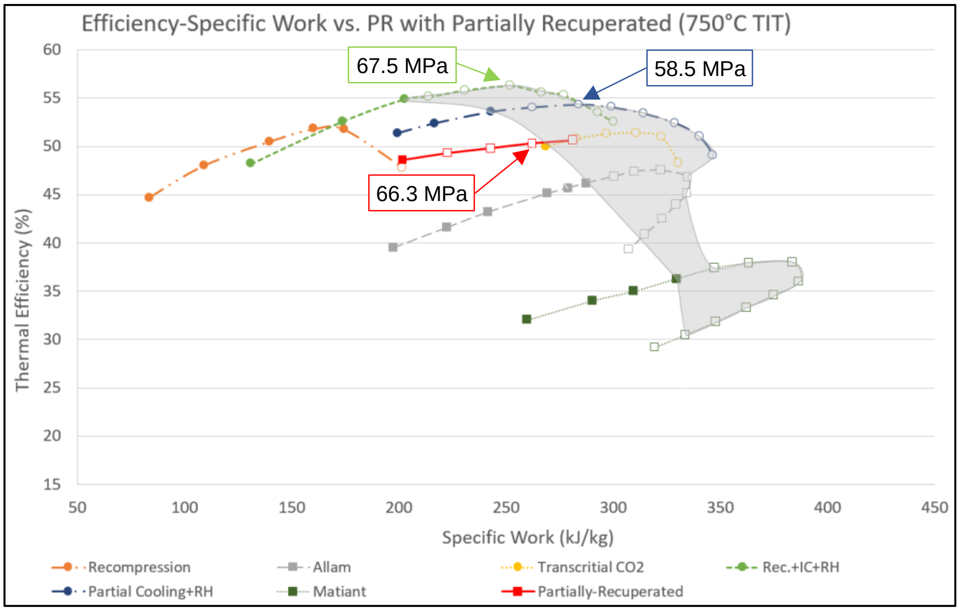


Figure 3: Peregrine's Partially Recuperated cycle (solid red line, square markers) reaches beyond the Efficiency-Specific Work boundary for 750 °C TIT. Standard Recompression cycle (orange dashed + double dotted line, circular markers) added to contrast with Recompression with Intercooling and Reheat.

Running the model with a 1% reduction in compressor isentropic efficiency reduces cycle thermal efficiency by 0.4%. A 1% reduction in turbines' isentropic efficiencies decrements cycle thermal efficiency by 1%. Fig. 3 below however illustrates that the PR cycle's curve (shown in red) reaches into the boundary established in Fig. 1 with ample margin. The model also differs from Sánchez's assumptions in that the PR curve's solid red marker represents 42.9 MPa peak pressure opposed to 40 MPa. Each marker on the PR cycle's curve represents a 7.8 MPa increment in compressor discharge pressure.

Figure 4, right, gives a first-order approximation of the impact of air-combustible fuels on other cycles' thermal efficiencies. Brun, Freidman, and Dennis posit that a recompression cycle paired with a modified Pulverized-Coal Circulating Fluidized Bed boiler can reach approximately 80% heat addition. In other words, fully-recuperated, indirect-fired cycles with an advanced boiler design may require 20% greater fuel consumption to develop the heat energy necessary for a given shaft power.

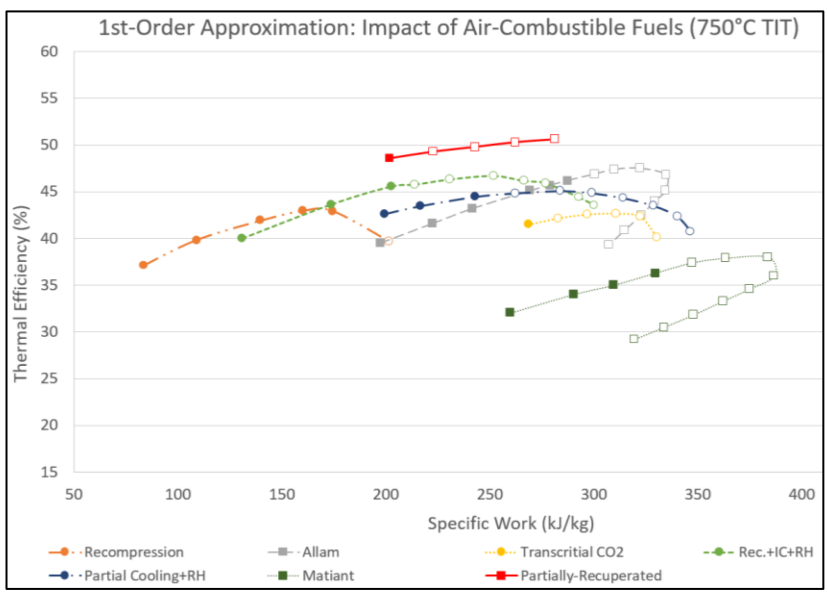


Figure 4: The thermal efficiency of the Partially Recuperated cycle does not suffer when paired with an air-combustible fuel heat source.

CONCLUSION

The narrow temperature range available for heat addition in traditional indirect-fired recuperated sCO2 Brayton cycles suits them perfectly to concentrated solar and nuclear energy applications. However, the increased temperature of recuperated sCO_2 entering the primary heat exchanger poses a challenge when adapting such cycles for use with air-combustible fuels. Due to the high temperature of recuperated sCO_2 at the inlet of the primary heat exchanger, fully recuperated indirect-fired cycles require advanced air-to-air preheating methods to capture even eighty percent of available heat of combustion.

The PR cycle negates this downside of full recuperation by way of two additional air-to-CO_2 heat exchangers, HX3 and HX1. The flow splits in the PR cycle allow recuperation to underpin cycle efficiency while also reducing exergy destruction in both the heat rejection and heat addition processes. HX1 and HX3 increase efficiency over a recuperated sCO_2 Brayton cycle by reducing fuel consumption and lowering air-side exhaust temperature given identical mass flow rate and TIT. By obviating flue recuperators and regenerators, the PR cycle grants high thermal efficiency even when paired with air-combustible fuels. Future work will analyze the Partially Recuperated cycle paired with enhancements such as reheat and intercooling.

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