A Study on Shaft Separation Layout of S-CO_2 Simple Recuperated Cycle for Flexible Operation

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1. Introduction

The supercritical carbon dioxide (S-CO_2) power cycle is designed to enhance efficiency by taking advantage of CO_2's properties near its critical point. This cycle offers several benefits [1], including a reduced footprint, less fouling, and higher efficiency across applications like nuclear energy [2]. The S-CO_2 simple recuperated cycle, which is one of the simplest layouts while maintaining the characteristics of the S-CO_2 power cycle, has garnered significant interest and is particularly considered as a leading candidate for demonstration studies [3]. Generally, this cycle is designed with a single shaft configuration, where the turbine and compressor are connected on a single shaft to provide the driving power for the compressor. However, it lacks flexibility in controlling the compressor's RPM due to the shared shaft with the turbine. In this study, to improve control, the study explores using a Compressor Driven Turbine (CDT) that operates independently from the power grid. This approach aims to enhance system performance under off-design conditions.

2. Methods and Results

2.1 Target layouts

For the S-CO_2 simple recuperated cycle, there are two possible approaches to incorporating a Compressor Driven Turbine (CDT). The first and most common approach involves a single shaft configuration, where a single turbine powers both the compressor and electricity generation, with any excess power directed to the latter. The second approach separates the CDT from the power turbine (PT). In this arrangement, the CDT is mounted on the same shaft as the compressor, while the PT operates on a separate shaft at a fixed RPM. This second approach can be further categorized based on the CDT's position relative to the PT. If the CDT is placed on the high-pressure side, it's referred to as the High-Pressure Compressor Driven Turbine (HPCDT) configuration. If it's on the low-pressure side, it's called the Low-Pressure Compressor Driven Turbine (LPCDT) layout. Figure 1 illustrates these three system configurations.

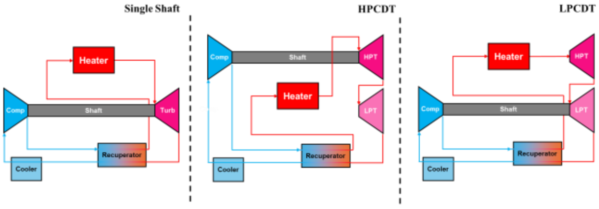

Figure 1. Three configurations of S-CO_2 simple recuperated cycle: Single Shaft, High-Pressure Compressor Driven Turbine (HPCDT) and Low-Pressure Compressor Driven Turbine (LPCDT)

2.2 Component design

Major design parameters of recuperator shown in Table 1.

Table 1. Recuperator design results

		Value
Hot side	Number of channels	600000
	Channel diameter (mm)	1.65
	Channel length (m)	0.4965
	Channel shape	Semicircular
Cold side	Number of channels	300000
	Channel diameter (mm)	1.65
	Channel length (m)	0.5615
	Channel shape	Semicircular
Plate	Plate minimum thickness	0.6832
	Thermal conductivity	14.600
Result	Effectiveness (%)	95.01

For turbomachinery design, 1D mean-line method is applied. Used sets of loss models from Cho [4] for compressor, and Lee [5] for turbines. Both sets of loss models are validated with experimental data via their own works [4,5].

2.3 Off-design analysis (Quasi-steady state analysis)

In this study, a quasi-steady state analysis method is employed, which allows for analyzing specific off-design scenarios without excessive complexity. The analysis disregards minor factors like pressure drop in heat exchangers and generator efficiency, which are less impactful on the quasi-steady state performance. Key assumptions include optimal management of control variables like total system flow and temperatures, while focusing on adding the compressor RPM control as the primary variable.

The study explores the impact of dividing the turbine into two stages in the HPCDT and LPCDT configurations on system efficiency and performance. This division lowers the pressure ratio each stage handles, potentially increasing efficiency but also altering the system's design point, particularly affecting the recuperator. To ensure a fair comparison across different layouts, consistent design parameters are maintained, avoiding external variables that could complicate the analysis. The study uses the baseline single shaft configuration for initial design, applying 1D methods for component design, and then adjusts the turbine design in the HPCDT and LPCDT layouts to match the compressor output. During this process, every loss-models for turbine design sets as same as original single shaft configuration's turbine. This approach allows for a comprehensive analysis of the effects on both on-design and off-design performance.

3. Result and Conclusion

Figure 2 shows the efficiency change during part-load scenario of separated shaft layouts (HPCDT and LPCDT) and single shaft configurations.

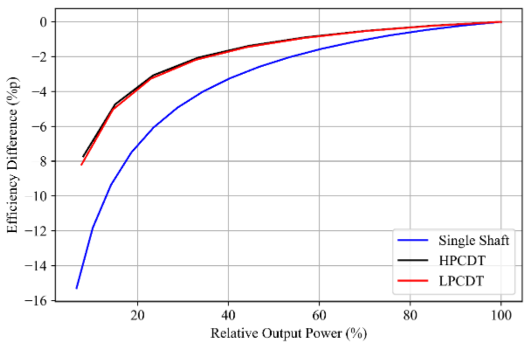

Figure 2. The efficiency changes of the HPCDT and LPCDT configurations at the optimal RPM points through the Relative Output Power

This study evaluated the efficiency improvements from adding a Compressor Driven Turbine (CDT) to S-CO_2 power cycles, focusing on simple recuperated cycle configurations. It compared the single shaft configuration with dual-turbine setups, specifically the High-Pressure CDT (HPCDT) and Low-Pressure CDT (LPCDT) configurations. The single shaft setup experienced a 12-percentage-point efficiency drop with a 10% reduction in output. In contrast, the HPCDT and LPCDT configurations, which enable RPM control of the CDT-compressor set, displayed similar off-design performance trends, with the HPCDT showing a slight efficiency advantage.

The findings also suggest that the placement of the CDT does not significantly influence the off-design performance of the S-CO_2 simple recuperated cycle. Both the HPCDT layout, where the CDT is positioned on the high-pressure side, and the LPCDT layout, with the CDT on the low-pressure side, show similar performance trends. While the HPCDT configuration exhibits a minor efficiency advantage under off-design conditions, the difference is minimal.

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