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MUNDARIJA

PERFORMANCE ASSESSMENT OF SUPERCRITICAL CO2 BRAYTON CYCLES IN SOLAR POWER TOWER SYSTEMS

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Annotation. This study investigates the thermodynamic performance of four supercritical carbon dioxide (sCO2) Brayton cycle configurations (Simple, Regeneration, Pre-compression, and Recompression) integrated within solar power tower systems. The main objective is to evaluate their efficiency and identify the most suitable configuration for solar power tower applications operating under high-temperature conditions. All configurations were modeled under fixed operating parameters representative of typical concentrated solar power plants: a turbine inlet temperature of 700 °C, a turbine inlet pressure of 25 MPa, an ambient temperature of 20 °C, and a total heat input of 120 MWth. The results show that the Recompression cycle achieved the highest thermal efficiency of 50.7%, followed by the Pre-compression (44.5%), Regeneration (37.7%), and Simple (13%) cycles. The superior performance of the Recompression configuration is attributed to reduced compression work and enhanced heat recovery through dual recuperators. Nevertheless, cooling and compression losses remain significant, limiting further efficiency improvement. Overall, this study demonstrates that the Recompression sCO2 Brayton cycle is the most efficient and technically viable configuration for future high-temperature solar power tower systems.

Keywords: Brayton cycle, Concentrated solar power, Solar energy, Solar power tower, Supercritical CO2.

QUYOSH MINORALI ELEKTR STANSIYALARI TIZIMLARIDA SUPERKRITIK CO2 BRAYTON SIKLLARINING SAMARADORLIGINI BAHOLASH

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Annotatsiya. Ushbu tadqiqot quyosh minorali elektr stansiyalari tarkibida integratsiyalangan toʻrtta superkritik karbon dioksid (sCO2) Brayton sikli konfiguratsiyalarining (oddiy, regeneratsiyali, oldindan siqishli va qayta siqishli) termodinamik samaradorligini oʻrganishga bagʻishlangan. Tadqiqotning asosiy maqsadi ularning samaradorligini baholash va yuqori harorat sharoitida ishlovchi quyosh minorali tizimlar uchun eng maqbul konfiguratsiyani aniqlashdan iborat. Barcha konfiguratsiyalar konsentrlangan quyosh energetikasi qurilmalariga xos boʻlgan qatʼiy ish parametrlari asosida modellashtirildi: turbina kirish harorati — 700 oC, turbina kirish bosimi — 25 MPa, atrof-muhit harorati - 20 oC hamda umumiy issiqlik quvvati — 120 MWth. Natijalar shuni koʻrsatadiki, qayta siqishli sikl eng yuqori issiqlik samaradorligiga ega boʻlib, 50,7% ni tashkil etdi. Undan keyin oldindan siqishli (44,5%), regeneratsiyali (37,7%) va oddiy (13%) sikllar joylashdi. Qayta siqishli konfiguratsiyaning ustunligi siqish ishining kamayishi hamda ikki rekupirator orqali issiqlikni qayta tiklash samaradorligining oshishi bilan izohlanadi. Shunga qaramay, sovitish va siqish jarayonlaridagi yoʻqotishlar sezilarli darajada boʻlib qolmoqda va bu samaradorlikni yanada oshirishni cheklaydi. Umuman olganda, tadqiqot natijalari shuni koʻrsatadiki, qayta siqishli sCO2 Brayton sikli kelajakdagi yuqori haroratli quyosh minorali elektr stansiyalari uchun eng samarali va texnik jihatdan maqbul konfiguratsiya hisoblanadi.

Kalit so'zlar: Brayton sikli, Konsentrlangan quyosh energetikasi, Quyosh energiyasi, Quyosh minorali elektr stansiyasi, Superkritik CO2

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Introduction

Global warming remains a significant challenge for modern society. The rising energy demand necessitates continuous production, which has historically relied on fossil fuels [1]. However, due to environmental concerns and declining resource availability, a transition towards renewable energy sources has become increasingly important in power generation. Renewable energy technologies offer several advantages, including minimal or zero greenhouse gas emissions [2] and reduced dependence on fossil fuels [3].

Among renewable energy technologies, photovoltaic (PV) systems and wind power are characterized by fluctuations and variability in power output. This variability poses challenges for grid integration, making it difficult to maintain a stable and reliable power supply. As a result, energy storage systems and flexible power generation technologies play a crucial role in power grids with a high share of renewable energy. Concentrated solar power (CSP) plants equipped with cost-effective and large-scale thermal energy storage (TES) systems can mitigate the negative effects of solar irradiation variability, ensuring a more stable power output [4,5]. The dispatchable characteristic of CSP plants enables them to offset the fluctuations in power production from intermittent energy sources, thereby effectively bridging the gap between electricity generation and consumption.

Among the various CSP technologies, the solar power tower (SPT) system integrated with the supercritical CO_2 (sCO_2) Brayton cycle has gained considerable attention due to its superior performance [6]. Compared to parabolic trough and linear Fresnel collectors, SPT systems operate at higher temperatures, improving overall system efficiency [6]. Additionally, heliostat fields can be scaled up more easily, offering substantial potential for cost reduction [7]. As a result, a considerable share of recently constructed and planned CSP plants are anticipated to adopt Solar Power Tower (SPT) technology due to its capability to operate under high-temperature and high-pressure conditions [6].

A Solar Power Tower (SPT) system, as depicted in Fig. 1, operates by utilizing an array of mirrors called heliostats, which track the sun and focus its rays onto a central receiver mounted on top of a tower. The intense solar energy heats a circulating fluid, typically molten salt, to very high temperatures. This hot fluid is stored in a well-insulated tank, allowing electricity generation even during periods of low or no solar irradiation. When power is needed, the heated fluid passes through a heat exchanger, transferring its energy to another working fluid, like supercritical CO_2 or water. This secondary fluid powers a turbine that spins a generator to produce electricity. After releasing its stored thermal energy, the original fluid flows back to a cold storage tank to be reheated, allowing the process to repeat.

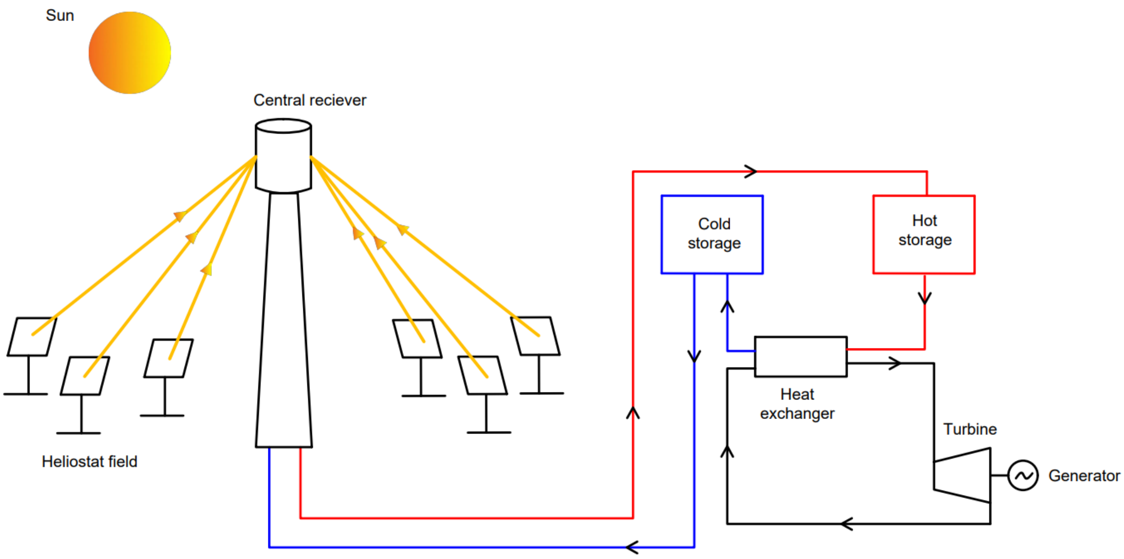

Fig. 1. Principal Scheme of the Solar Power Tower

At operating temperatures exceeding 600°C, SPT plants integrated with the sCO_2 Brayton cycle demonstrate higher thermal efficiency than traditional steam Rankine cycles [6,8]. Moreover, as the operating temperature continues to rise, the thermodynamic advantages of the sCO_2 cycle become increasingly significant. Unlike the Rankine cycle, the sCO_2 Brayton cycle features a more compact and simplified configuration with fewer components, as illustrated in Fig. 2, resulting in lower system complexity and reduced capital costs. Furthermore, the high density of sCO_2 in its supercritical state allows for significantly smaller turbomachinery, potentially up to ten times smaller than that used in steam-based Rankine cycles [9]. The appeal of supercritical CO_2 as a working fluid is attributed to its low critical point (31°C and 73.8 bar) [10], as well as its inert, abundant, non-toxic, and stable nature, ensuring safe and reliable operation [11].

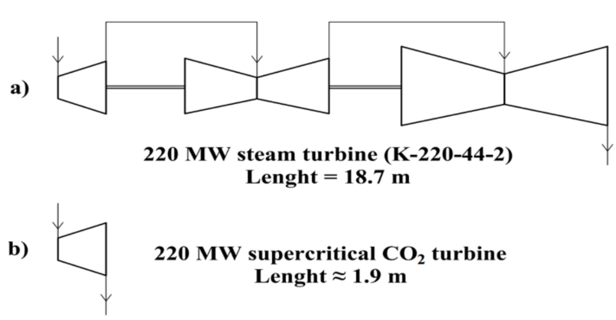

Fig. 2. A representative comparison of a) Rankine steam and b) sCO_2 Brayton turbine sizes [12]

The integration of SPT plants with sCO_2 Brayton cycles presents a promising pathway toward enhancing the efficiency and reliability of renewable energy systems. The ability of SPT systems to operate at high temperatures, coupled with the compact and efficient nature of sCO_2

cycles, makes them a viable alternative to traditional steam Rankine cycles. As research continues to highlight the advantages of various sCO_2 cycle configurations, it is essential to analyze their thermodynamic performance and suitability for SPT applications.

This study presents a comprehensive analysis of various supercritical carbon dioxide (sCO_2) Brayton cycle configurations, namely the Simple, Regeneration, Pre-compression, and Recompression cycles. These configurations offer unique thermodynamic characteristics and design considerations that influence their suitability for integration with SPT systems. By examining the operational principles, component arrangements, and thermal performance metrics of these cycle types, this analysis highlights their advantages and limitations under various operating conditions. Evaluating these factors is key to selecting the most efficient cycle layout for high-temperature SPT applications, particularly in SPT systems. Ultimately, this comparative study will support efforts to enhance overall system efficiency, reduce energy losses, and promote the development of more cost-effective and reliable SPT technologies.

Methodology

Research method. This study employs a comparative analysis to evaluate different supercritical CO_2 (sCO_2) Brayton cycle configurations within Solar Power Tower (SPT) systems. The primary goal is to optimize cycle performance and identify the most efficient configuration for concentrated solar power (CSP) applications. The thermodynamic performance of four sCO_2 Brayton cycle configurations (Simple, Regeneration, Pre-compression, and Recompression) was analyzed using thermodynamic modeling. This methodology provides a structured approach to evaluating sCO_2 Brayton cycles for CSP applications. By leveraging a comparative analysis and thermodynamic modeling, the study aims to identify the most efficient cycle configuration, with a particular focus on minimizing losses and enhancing overall performance in solar power tower systems.

sCO_2 Brayton cycles. We have selected four well-established Brayton cycle configurations for a comparative evaluation of their performance. Fig. 3 presents the four cycles' configurations analyzed in this study. The processes illustrated in Fig. 3 are numbered according to the enthalpy points used in our thermodynamic modelling. The majority of these configurations (b, c, d) incorporate a recuperator heat exchanger, while certain variations (b, d) employ a high-temperature recuperator (HTR) and a low-temperature recuperator (LTR). In contrast, the simplest configuration (a) operates without a heat recovery component.

The Simple Brayton cycle (a) represents the most basic configuration, consisting of a single compressor, turbine, and heat exchanger, without any recuperation process. In this arrangement, the working fluid expands in the turbine after being directly heated in the solar receiver and is then cooled before compression. Its simplicity offers ease of design and lower capital cost.

In the regenerative, pre-compression, and recompression sCO_2 Brayton cycles, the working fluid (supercritical CO_2) continuously circulates through a closed loop to convert solar thermal energy into mechanical work. The process begins when sCO_2 is pressurized and subsequently preheated in the recuperator using residual heat from the turbine exhaust. It is then heated further in the solar receiver, where concentrated solar radiation raises its temperature to the turbine inlet level. The high-temperature, high-pressure sCO_2 expands through the turbine, generating mechanical power that drives the generator. Upon expansion, the fluid's temperature and pressure drop, and it transfers part of its remaining heat to the incoming compressed flow through the HTR and LTR recuperators, thus recovering otherwise wasted energy. The cooled sCO_2 then passes through the cooler, where it releases excess heat to the environment before being recompressed to the initial pressure. This closed-loop process, comprising compression, heating, expansion, and heat recovery, enables the cycle to achieve high efficiency, compactness, and effective thermal integration with the SPT system.

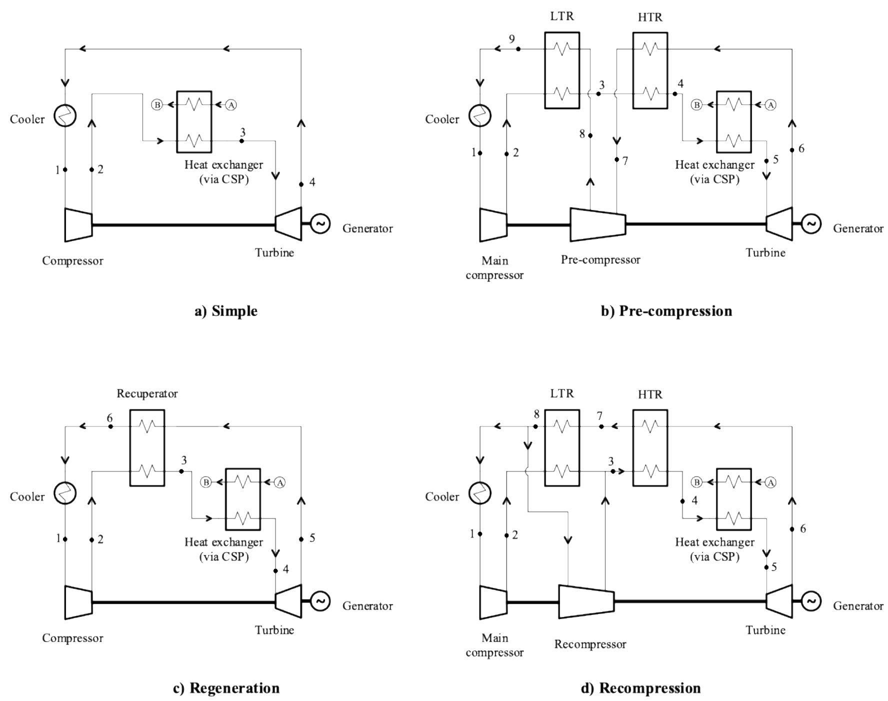

Fig. 3. Schematic representation of four Brayton cycle variants

Thermodynamic modelling. The thermal efficiency of a supercritical CO_2 Brayton cycle is a key performance indicator and is defined as the ratio of the net work output to the total heat input:

$$\eta_{sCO_2} = \frac{W_{net}}{Q_{net}} \quad (1)$$

where W_{net} is the cycle's net electrical energy, and Q_{net} is the total heat absorbed in the solar receiver or main heat exchanger. This general expression applies to all layouts (Simple, Regeneration, Pre-compression, and Recompression), where the component work and heat terms are determined from the respective enthalpy differences at each state point.

In all supercritical CO_2 Brayton cycle configurations, the turbine and compressor powers (W_t and W_c) are determined by the enthalpy differences between their inlet and outlet states. Therefore, separate equations for each layout are not required, and a general formulation can be written as follows:

$$W_t = m \cdot (h_{\text{t.in.}} - h_{t.out.}) \cdot \eta_t \qquad (2)$$

$$W_c = \frac{m \cdot (h_{\text{c.out}} - h_{c.in})}{\eta_c} \qquad (3)$$

where m is the CO_2 mass flow rate (kg/s), $h_{\text{t.in.}}$ and $h_{t.out.}$ denote the turbine inlet and outlet enthalpies, $h_{\text{c.out}}$ and $h_{c.in}$ are the compressor inlet and outlet enthalpies, and η_t and η_c represent the isentropic efficiencies of the turbine and compressor, respectively.

Since the main objective of this research is to evaluate and compare the thermal efficiencies of different supercritical CO_2 Brayton cycle configurations, the efficiency of each cycle is presented separately according to its specific layout and heat recovery scheme. The thermal efficiency of the simple Brayton cycle is obtained from the net work output divided by the total heat absorbed in the heater:

$$\eta_{simple} = \frac{m\cdot\left((h_3-h_4)\cdot\eta_t-\frac{(h_2-h_1)}{\eta_c}\right)-W_{cl}}{Q_{net}} \qquad (4)$$

where h_3 and h_4 denote the turbine inlet and outlet enthalpies, respectively, while h_1 and h_2 correspond to the compressor inlet and outlet. The term W_{cl} represents the electrical power consumed by the cooling system (fans or pumps) to reject waste heat from the working fluid to the environment. In the regeneration cycle, the thermal efficiency is defined as:

$$\eta_{reg.} = \frac{m\cdot\left((h_4-h_5)\cdot\eta_t-\frac{(h_2-h_1)}{\eta_c}\right)-W_{cl}}{Q_{net}} \qquad (5)$$

where h_4 and h_5 are the turbine inlet and outlet enthalpies. The pre-compression cycle's thermal efficiency is determined by:

$$\eta_{p} = \frac{m\cdot\left((h_5-h_6)\cdot\eta_t-\frac{(h_2-h_1)+(h_8-h_7)}{\eta_c}\right)-W_{cl}}{Q_{net}} \qquad (6)$$

where h_5 and h_6 are the turbine inlet and outlet enthalpies, h_2 and h_1 corresponds to the main compressor stage, and h_6 and h_7 corresponds to the pre-compressor stage.

The recompression layout divides the mass flow at the outlet of the low-temperature recuperator into two streams: the main flow and the recompression flow defined by the mass split ratio ϕ. The thermal efficiency is evaluated as

$$\eta_{recomp.} = \\ = \frac{m\cdot\left((h_5-h_6)\cdot\eta_t-\frac{\phi\cdot(h_2-h_1)}{\eta_c}-\frac{(1-\phi)\cdot(h_8-h_3)}{\eta_c}\right)-W_{cl}}{Q_{net}} \qquad (7)$$

where h_1 and h_2 correspond to the main compressor inlet and outlet, and h_3 and h_8 represent the recompression compressor inlet and outlet, respectively.

To evaluate and compare the performance of the four supercritical CO_2 Brayton cycle configurations (Simple, Regeneration, Pre-compression, and Recompression), fixed thermodynamic parameters were assumed to represent typical operating conditions of a solar power tower system. The turbine inlet temperature was set to 700 °C, and the ambient temperature was set to 20 °C, corresponding to steady-state operation under realistic solar conditions. The total heat input (Q_{net} = 120 MW_{th}) and turbine inlet pressure (25 MPa) were kept constant across all configurations to ensure a fair comparison.

The isentropic efficiencies of the turbine (η_t = 0.93) and compressors (η_c = 0.89) were adopted from literature values commonly used in sCO_2 Brayton cycle analyses [13]. The electrical consumption of the cooler was estimated to be approximately 1% of the heat rejected to the environment [14]. These assumptions allow for a consistent thermodynamic assessment without introducing additional sensitivity effects.

Table - 1

Main assumptions of the sCO_2 Brayton cycles.

Parameter	Value
Turbine inlet pressure, P_{in}	25 MPa
Turbine inlet temperature, T_{in}	700 °C

Isentropic efficiencies of the compressors, η_c	0.89%
Isentropic efficiencies of the turbine, η_t	0.93%
Heat input, Q_{net}	120 MW_{th}
Ambient temperature, T_{amb}	20 °C
Cooler electric consumption	1% of rejected heat

Result and discussion

A performance comparison was conducted among the four supercritical CO_2 Brayton cycle layouts (Simple, Regeneration, Pre-compression, and Recompression) under the fixed assumptions outlined in Table 1. Table 2 presents the calculated performance parameters of the four supercritical CO_2 Brayton cycle configurations under nominal operating conditions (T_{in} = 700 °C, T_{amb}= 20 °C, Q_{net}= 120 MW_{th}). The results show that the Recompression cycle achieves the highest thermal efficiency of 50.7 %, producing a net power output of 60.84 MW. This enhancement is primarily due to the reduced compression work (33.08 MW) and the presence of dual recuperators, which recover a significant portion of the turbine exhaust heat. The Pre-compression cycle follows with 44.5% efficiency and a net output of 53.4 MW.

Table - 2

Results of sCO_2 Brayton cycles

Parameter	**Simple**	**Regeneration**	**Pre-compression**	**Recompression**
Turbine electric power, W_t, (MW)	55.45	83.6	90.1	94.5
Compressors electric power, W_c, (MW)	38.81	37.62	36.04	33.08
Cooler electric consumption, W_{cl}, (MW)	1.03	0.74	0.66	0.59
Thermal efficiency, η_{sCO_2}, (%)	13	37.7	44.5	50.7
Net power output, W_{net}, (MW)	15.6	45.24	53.4	60.84

The Regeneration layout achieves 37.7 % efficiency, benefiting from partial heat recovery in a single recuperator, though still limited by relatively high compressor work (37.62 MW). The Simple cycle, without any recuperation, shows the lowest performance, with an efficiency of only 13 % and a net output of 15.6 MW, since most of the turbine exhaust heat is rejected through the cooler (1.03 MW of electric consumption).

Overall, the results demonstrate that increasing the number of recuperation stages and splitting the mass flow between compressors substantially enhances the thermodynamic efficiency of sCO_2 Brayton systems. The recompression configuration not only maximizes energy recovery but also minimizes parasitic cooling losses, making it the most promising option for integration into high-temperature SPT plants.

Despite its superior efficiency, the Recompression sCO_2 Brayton cycle is not without limitations. While it demonstrates the highest thermal efficiency and power output among the evaluated configurations, a closer examination reveals specific sources of performance degradation that should be addressed to realize its potential in high-temperature SPT applications.

The primary source of efficiency losses in the Recompression sCO_2 Brayton cycle is the cooling system, particularly the cooler. Before entering the compressor, the working fluid undergoes cooling to reduce the work required for compression. If the flow enters the compressor at a higher temperature, the compression process demands significantly more power, increasing the overall energy consumption of the system. However, this cooling process results in the rejection of thermal energy into the atmosphere, which negatively impacts the thermal efficiency of the cycle.

Furthermore, a considerable fraction of the mechanical work generated by the turbines is required to operate the compressors, thereby reducing the overall net power output of the cycle. Approximately 33 MW of power is consumed for compressor operation, which significantly impacts system efficiency. These losses highlight the need for alternative strategies to improve cycle performance.

In summary, the comparative evaluation of the four sCO_2 Brayton cycle configurations demonstrates that the recompression layout offers the most favorable performance for integration with high-temperature SPT systems. Its dual-recuperator arrangement and optimized mass-flow distribution enable higher thermal efficiency and net power generation compared to the other layouts. Nevertheless, the analysis also reveals intrinsic inefficiencies related to the cooling process and compressor operation, which lead to substantial heat rejection and mechanical energy losses. Addressing these drawbacks through advanced closed-loop thermal management or the integration of alternative compression technologies could further enhance the overall system efficiency and reliability, promoting more sustainable and high-performance solar-driven power cycles.

Conclusion

This study analyzed and compared four supercritical CO_2 Brayton cycle configurations (Simple, Regeneration, Pre-compression, and Recompression) for use in high-temperature Solar Power Tower (SPT) systems. Under identical operating conditions (700 °C turbine inlet temperature, 25 MPa pressure, and 120 MW_{th} heat input), the Recompression cycle demonstrated the best overall performance, achieving a thermal efficiency of 50.7% and a net power output of 60.84 MW. The Pre-compression and Regeneration cycles achieved moderate efficiencies of 44.5% and 37.7%, respectively, while the Simple layout, lacking heat recovery, performed the weakest with only 13% efficiency.

Although the Recompression layout provides the highest performance, notable efficiency losses still arise from the cooling system and compressor energy consumption. Approximately one-third of the turbine's mechanical power is utilized to operate the compressors, which significantly reduces the net cycle output. To further enhance the overall efficiency, the possibility of replacing the compressor with an alternative device should be investigated as a potential approach to reduce mechanical losses and heat rejection to the environment. Further research and experimental validation are required to assess the feasibility and effectiveness of such a modification.

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