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Study of sCO_2 System Compressor Inlet Temperature Control Strategy for Marine Propulsion

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ABSTRACT

The supercritical CO_2 (sCO_2) power generation systems can achieve high efficiencies with small machine sizes and simple cycle layout. These characteristics make them ideal candidates for marine propulsion system. From the perspective of marine propulsion, the required power system must follow the time-varying propulsion demand with high efficiency. Therefore, load-following control strategies for sCO_2 power systems have been well studied to maximize off-design efficiency. Most of the previously studied control strategies keep the compressor inlet temperature the same with the design point. However, compressor similitude models show that the optimal operating temperature of the compressor varies with compressor speed and inlet pressure. Therefore, this study is motivated to find control strategies that also adjust the compressor inlet temperature to further improve the system efficiency.

In this study, control strategies were studied for a simple recuperated Brayton cycle. The control methods are based on two widely adopted control methods, inventory control and turbine bypass control, which can achieve high efficiency, and control performance was compared by adding compressor inlet temperature control. The cycle was designed based on the heat source conditions of a reactor currently under development for marine propulsion in South Korea. Design and off-design performance predictions were made using in-house codes that have been validated through laboratory-scale experiments. System control performance comparison was performed using quasi-steady state analysis. The comparison of control performance results showed performance improvement with the addition of compressor inlet temperature control.

INTRODUCTION

To lower carbon emissions from fossil fuels, the shipping and shipbuilding industries are developing alternative energy sources for ship propulsion in response to the climate change issue. The International Maritime Organization (IMO) agreed in July 2023 to progressively cut carbon emissions to reach net-zero emissions by 2050 [1]. Despite continuous research into alternate energy sources such as hydrogen, ammonia, and biofuels [2], nuclear power remains one of the most practical options for reaching near-zero carbon emissions using current energy technologies.

Until now, most nuclear-powered ships have used small, pressurized water reactors (PWRs) equipped with steam-based power conversion systems for propulsion. However, with the advancement of Generation IV reactor technology, various reactors, including molten salt reactors (MSRs), are being re-evaluated as promising alternatives for marine propulsion [3]. MSRs offer advantages over PWRs in terms of temperature and pressure for marine applications. Nevertheless, concerns remain regarding safety, infrastructure, regulatory issues, particularly material corrosion, limited operational experience, and stringent regulations [4]. Therefore, the KAIST research team designed a reactor called the Gas-cooled Pressure Tube reactor for Marine Propulsion (GPT-Marine), based on an existing technology, which features high thermal efficiency and eliminates the need for pressure vessel and steam generator. This reactor was developed by applying technologies from the currently operating Advanced Gas-cooled Reactor (AGR) from the United Kingdom and the Canada Deuterium Uranium (CANDU) reactor from Canada. Figure 1 shows the core structure of the GPT-Marine, and Table 1 provides a summary of the major design results for the GPT-Marine reactor.

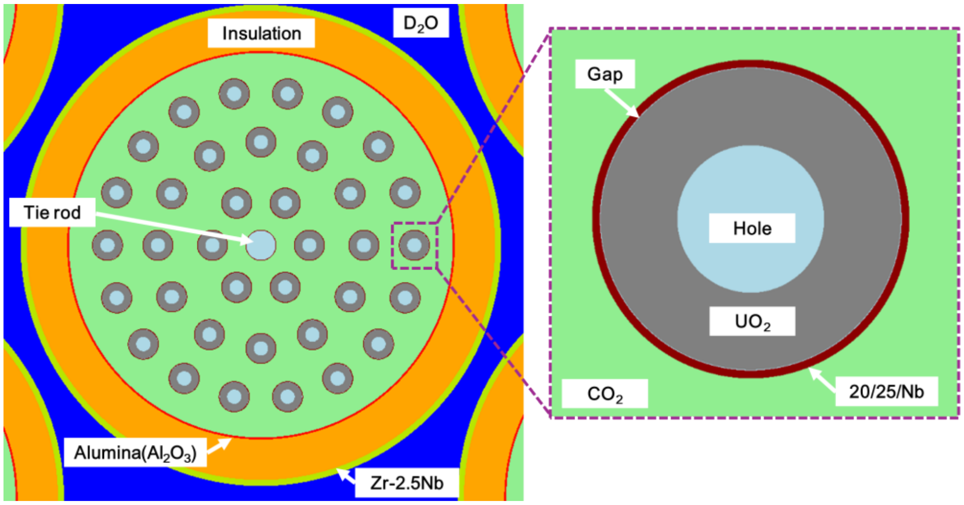

Figure 1 Cross-sectional view of single fuel channel and fuel pin of GPT-Marine reactor [5]

Table 1 Summary of major design result of GPT-Marine reactor [5]

Thermal output	100 MW_{th}	Active core dimension	2.4 m(W) × 3.0 m(H)
Reactor volume	26.2 m^3	Reactor dimension	3.0 m(W) × 3.7 m(H)
Moderator	D_2O	EFPD	960
Number of fuel channels	37	Coolant	CO_2
Power density	3.8 MW/m^3	Mean gas pressure	4.1 MPa
Mass of uranium	4.6 tonnes	Coolant outlet temperature	640 ℃
Average fuel burnup	21 MWd/kgU	Moderator temperature	70 ℃

This reactor was developed specifically with the use of an sCO_2 power system in mind. Therefore, this study optimized the sCO_2 cycle and designed the turbomachinery and heat exchanger based on the cycle design results. Furthermore, a control strategy for marine propulsion was established based on a quasi-steady state analysis. The control method was based on two widely adopted control approaches: inventory control and turbine bypass control [6]. Furthermore, since experiments have demonstrated the feasibility of compressor inlet temperature control for water-cooled precoolers [7], compressor inlet temperature control was added to further improve the control performance.

SYSTEM AND COMPONENT DESIGN

The sCO_2 cycle was designed based on the GPT-marine reactor. The maximum temperature and pressure conditions of the cycle were determined using the design parameters of the reactor core conditions. Furthermore, the efficiency and pressure loss of the components were determined by referring to existing design cases of sCO_2 power conversion systems for ship propulsion. The design parameters of the selected sCO_2 cycle are summarized in Table 2.

Table 2 Cycle design conditions [8], [9], [10]

Condition	Value
Reactor Thermal Output	100MWth
Maximum Temperature	630°C (1166°F)
Minimum Temperature	35°C (95°F)
Compressor Efficiency	80%
Turbine Efficiency	90%
Heat Exchanger Effectiveness	95%
Heater/Pre-cooler Pressure Drop	150kPa (21.75psi)
Internal Heat Exchanger Pressure Drop	150kPa (21.75psi)
Heat Exchanger Pinch Temperature	5°C

The cycle design was performed using the in-house code KAIST-CCD (Closed Cycle Design) [11]. CO2 physical properties were obtained using the NIST REFPROP library. For the two cycle layouts shown in Figures 2 and 3, the design was optimized to maximize efficiency under the design conditions specified in Table 2. Tables 3 shows the design results that maximize the efficiency of the sCO_2 cycle in Figures 2 and 3.

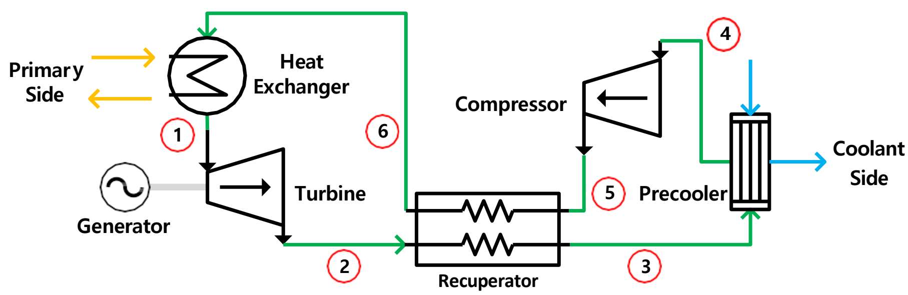

Figure 2 Simple recuperated sCO_2 cycle

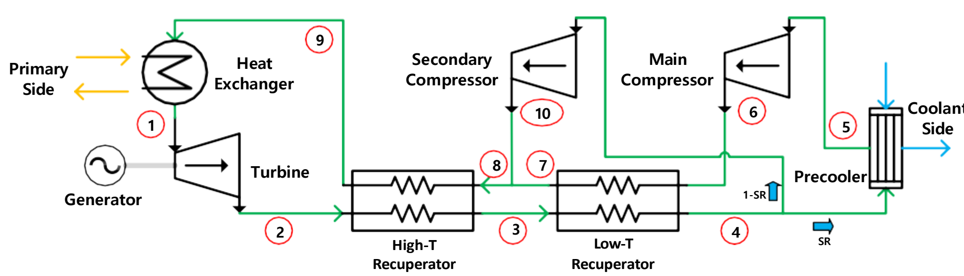

Figure 3 Recompression sCO_2 cycle

Table 3 Cycle design results

Design parameter	Recuperated cycle	Recompression cycle
Cycle thermal efficiency (%)	38.0	45.1
Cycle thermal input (MWth)	100	100
CO2 mass flowrate (kg/s)	502.28	536.44
Minimum pressure (MPa)	10.4	8.30
Main compressor pressure ratio	1.923	2.41
Secondary compressor pressure ratio	-	2.35
Main compressor work (MW)	7.948	7.892
Secondary compressor work (MW)	-	10.42
Turbine work (MW)	45.94	63.40
Turbine bypass ratio	-	0.65

Figures 4 and 5 show the temperature and pressure at each point of the two designed cycles. The efficiency difference between the recuperated cycle and the simple recompression cycle was found to be 7%p. In this study, to simplify the system installed on the vessel and to clearly observe the effect of compressor inlet temperature conditions, the recuperated cycle was selected for subsequent investigations. Using in-house codes, components for the recuperated cycle were designed conceptually.

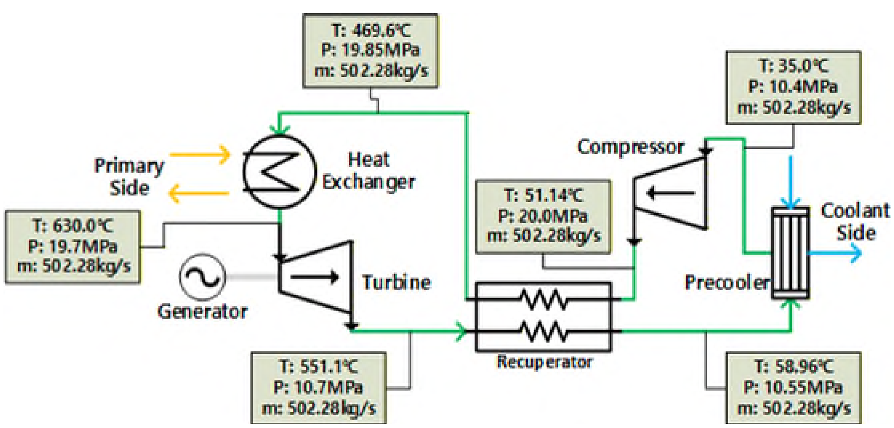

Figure 4 Recuperated sCO_2 cycle design results

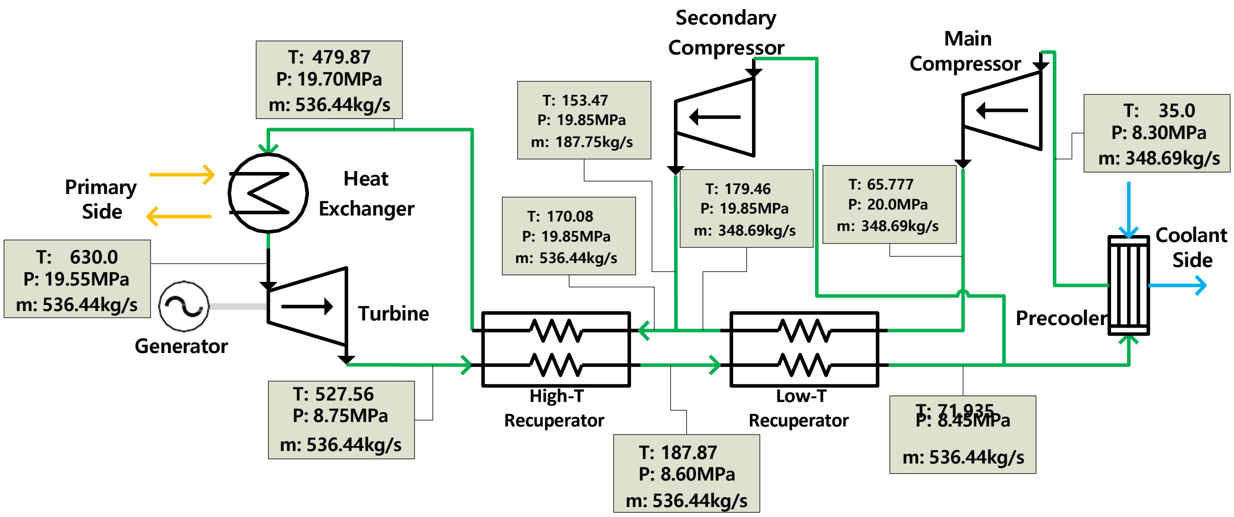

Figure 5 Recompression sCO_2 cycle design results

The recuperator was designed using the KAIST-HXD (Heat eXchanger Design) code [12]. The KAIST-HXD code employs a 1-D finite difference method, dividing the heat exchanger channel into multiple control volumes to design the exchanger and predict performance under off-design conditions. The heat transfer correlation equations used were developed based on computational fluid dynamics (CFD) and experimental data. The recuperator was designed as a counterflow printed circuit heat exchanger (PCHE) type using KAIST-HXD, incorporating the channel geometry information shown in Figure 6. The inlet and outlet conditions of the heat exchanger were selected to follow those designed using the KAIST-CCD shown in Figure 4. For pressure drop, only the core pressure drop was calculated, resulting in a value smaller than that in Figure 4. The internal temperature distribution of the designed heat exchanger is as shown in Figure 7, and the design results are as shown in Table 4.

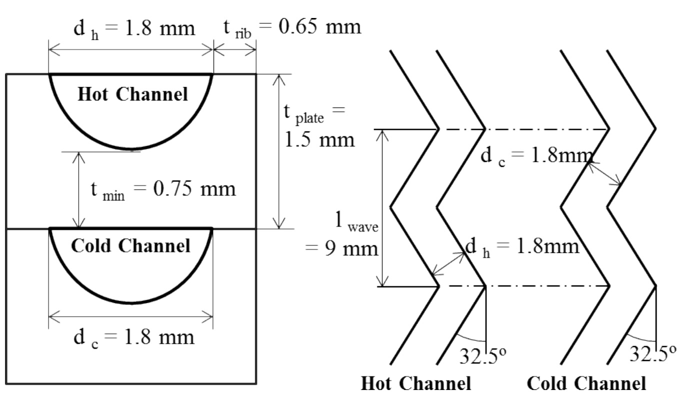

Figure 6 PCHE channel geometry [12]

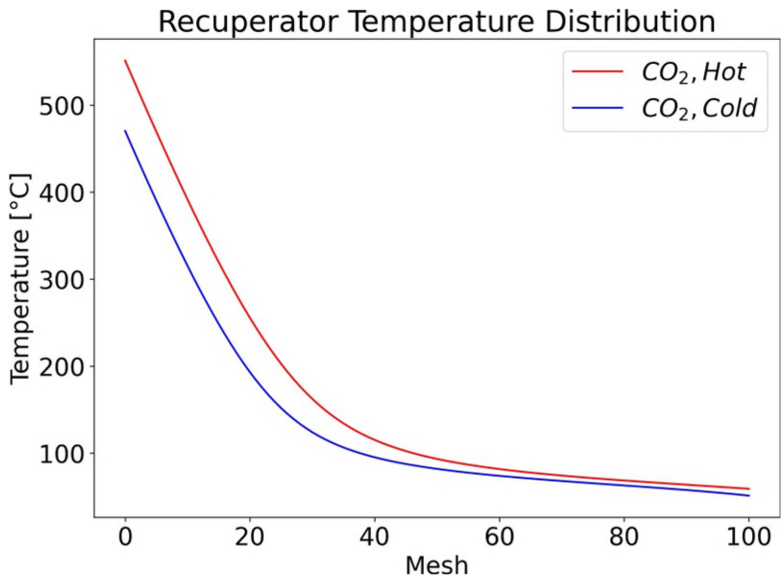

Figure 7 Recuperator temperature distribution

Table 4 Recuperator design results

Design parameter	Design results
Exchanged heat (MW)	318.38
Hot side temperature difference (K)	492.1
Cold side temperature difference (K)	419.1
Hot side pressure drops (kPa)	118.5
Cold side pressure drops (kPa)	53.18
Channel numbers	960,000
Channel length (m)	1.8

Both compressor and turbine were designed using the KAIST-TMD (TurboMachine Design) code [13]. The KAIST-TMD code employs a 1-D streamline method, utilizing velocity triangles and the continuity equation to design rotating machinery dimensions and predict performance under off-design conditions. The loss model set was selected based on the literature review, while the windage loss model applied was obtained experimentally. By considering mass flow rate and pressure ratio, the compressor was designed as two sets of double-suction centrifugal compressors, and the turbine as two sets of double-discharge radial turbines. Therefore, the turbomachinery was designed with mass flow rate and power at one-fourth of the values in Figure 4, while maintaining the same temperature and pressure conditions. The rotational speed of the turbomachine and the inlet axial velocity were selected based on Balje's n_s-d_s diagram. Furthermore, assuming the compressor is motor-driven, the rotational speeds of the compressor and turbine were designed to be different. The graphs in Figures 8 and 9 and the results in Tables 5 show the maps and design results for the designed compressor and turbine. The star marks on the graphs indicate the design points.

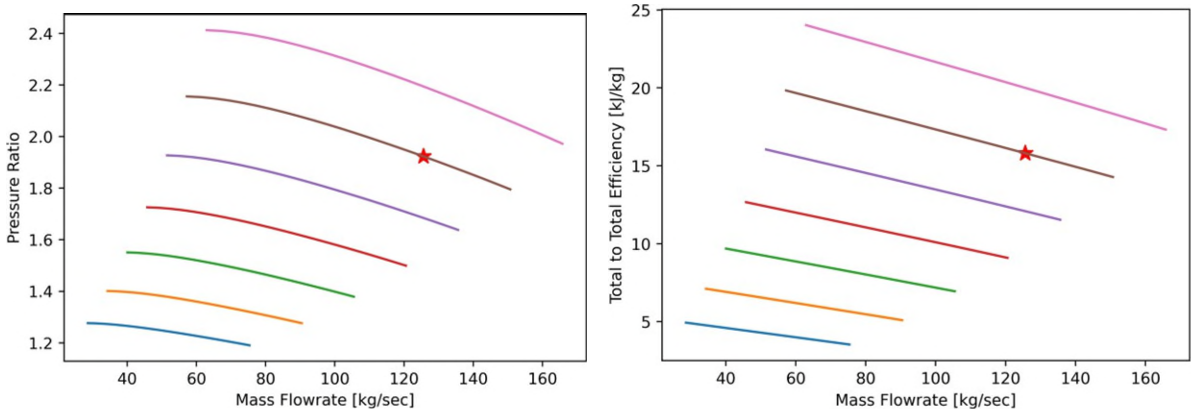

Figure 8 Compressor pressure ratio map (Left), Efficiency map (Right)

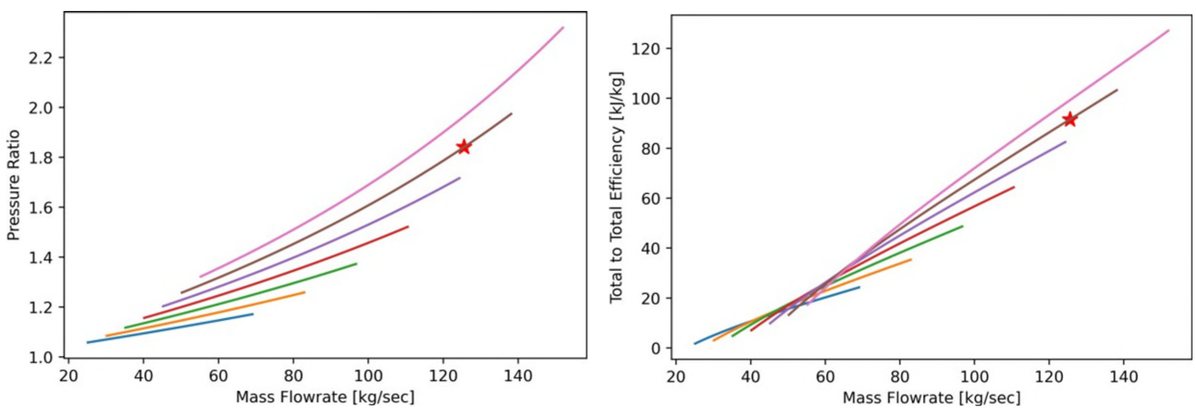

Figure 9 Turbine pressure ratio map (Left), Efficiency map (Right)

Table 5 Turbomachinery design results

Design parameter	Compressor	Turbine
Work (MW)	1.985	11.49
Pressure ratio	1.923	1.841
Efficiency (%)	80.07	90.08
Rotating speed (RPM)	12,000	20,000
Inlet axial velocity (m/sec)	32	26
Number of vanes	18	16

Rotor hub diameter (m)	0.1	0.25

OFF-DESIGN EVALUATION

The off-design point performance of the cycle was analyzed using the in-house code KAIST-QCD. KAIST-QCD employs quasi-steady state analysis for off-design performance evaluation. Quasi-steady state analysis is a method for evaluating off-design performance using a new steady state that converges under given conditions. It has low computational complexity and minimal time requirements, making it advantageous for establishing control strategies. For the simple recuperated cycle in KAIST-QCD, the quasi-steady state of the cycle is calculated as shown in Figure 10. Additionally, the physical property changes of the fluid passing through the components under off-designed conditions are estimated using KAIST-TMD and KAIST-HXD. KAIST-HXD is used for the operations marked in red in the flowchart, while KAIST-TMD is used for the operations marked in green.

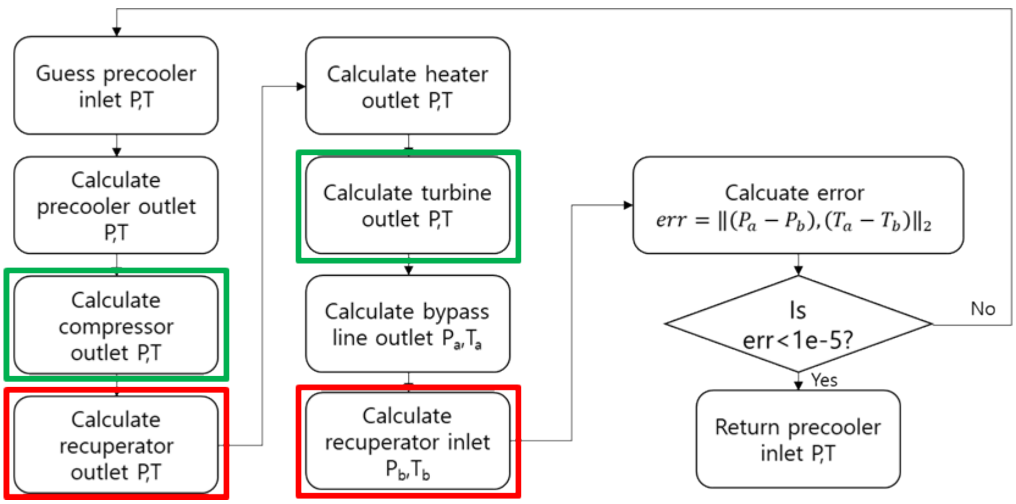

Figure 10 KAIST-QCD algorithm for recuperated cycle

In this study, among various methods used for load-following operation of the sCO_2 cycle, inventory control, turbine bypass control, heat input control, and compressor inlet temperature control were employed. First, to simulate inventory control, the system's mass flow rate was varied. Inventory control changes the total fluid mass within the system. However, due to the lack of detailed system design, such as piping, the total sCO_2 mass within the system cannot be estimated. Nevertheless, since the change in the total fluid inventory of the system due to inventory control is reflected in the form of mass flow rate, the system's on-design performance was evaluated based on the mass flow rate. Next, turbine bypass control was implemented to bypass both the intermediate heat exchanger (IHX) and the turbine simultaneously. If the turbine were bypassed alone, the CO_2 temperature entering the valve would be higher than when bypassing both the IHX and turbine, causing the valve to operate at a higher temperature. This is disadvantageous from both valve design and operational perspectives. For heat input control, simulations were performed by varying the cycle's maximum temperature. The KAIST-QCD code proceeds with the calculation while lowering the cycle maximum temperature from the design value of 630°C. Additionally, cases where the heat transfer rate at the IHX exceeded reactor design value, 100 MWth, were excluded. Finally, for compressor inlet temperature control, only cases where the temperature exceeded the design temperature of 35°C were considered, considering the distance from the CO2 critical point. Table 6 shows the conditions and ranges analyzed.

Table 6 Compressor design results

Parameter	Range
Compressor inlet temperature (°C)	35 – 55
IHX outlet temperature (°C)	550 – 630
Mass flowrate (%)	10 – 110
Turbine bypass ratio (%)	0 – 50

Figures 11 and 12 show efficiency, IHX output, and net-work results obtained through KAIST-QCD for cycle off-design conditions, varying the turbine bypass ratio, IHX outlet temperature, and mass flow rate when the CIT (Compressor Inlet Temperature) is 35°C and 40°C, respectively. Identical colors correspond to cases with the same turbine bypass ratio. Within the same color group, lines positioned lower indicate lower IHX outlet temperatures. According to the results in Figures 11 and 12, as CIT increases and the IHX outlet temperature decreases, both heater input and net-work decrease. Furthermore, increasing the turbine bypass flow rate has a greater impact on the system during off-design operation than lowering the IHX outlet temperature. Operation across the entire range from 0% to 100% output is possible without changing CIT. For each CIT, the optimal operating condition corresponds to the Pareto front, which is the set of Pareto efficient solutions, on the net-work to efficiency graph. In this case, each net-work's highest efficiency point possesses an equally excellent operating point. This is because operating efficiency is maximized by passing through the maximum efficiency point for each output.

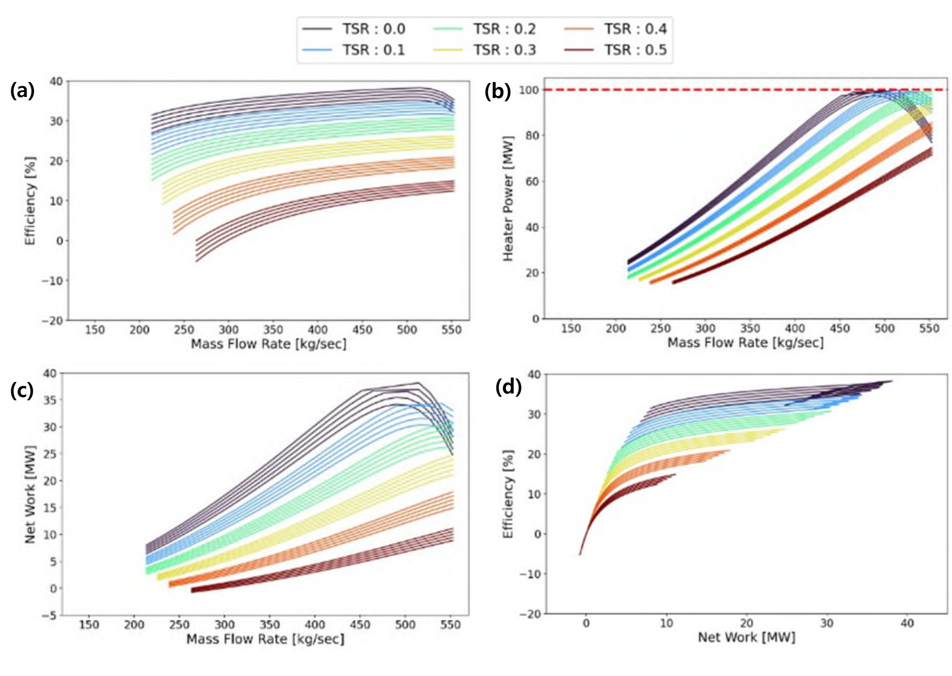

Figure 11 (a) Cycle thermal efficiency (b) Input thermal power (c) Cycle net-work (d) Cycle net-work vs cycle thermal efficiency at Compressor inlet temperature 35°C

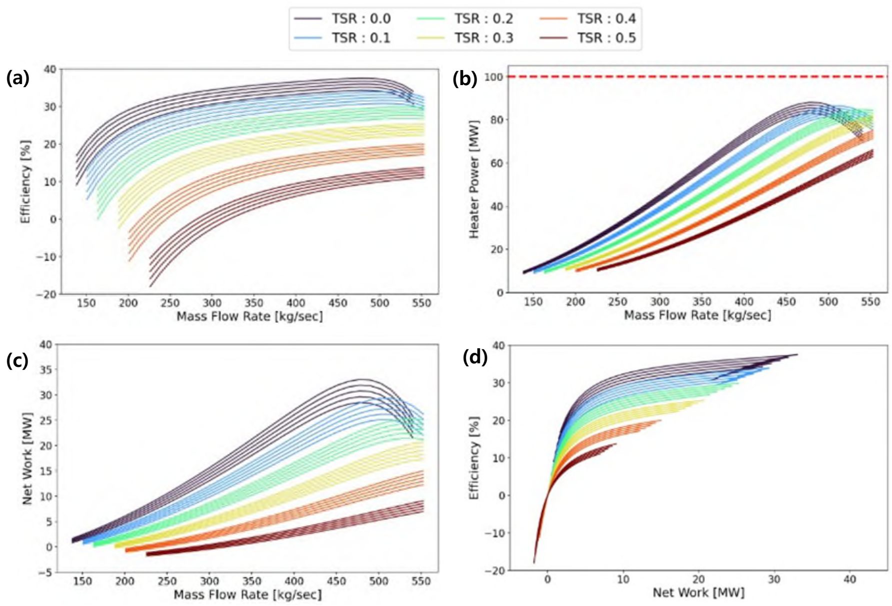

Figure 12 (a) Cycle thermal efficiency (b) Input thermal power (c) Cycle net-work (d) Cycle net-work vs cycle thermal efficiency at Compressor inlet temperature 40°C

Figure 13 shows the feasible choices and Pareto front on the net work and efficiency graph when CIT is 35°C and 40°C. The red curve represents the Pareto front for each temperature condition. Figure 14 compares these two Pareto fronts. The red solid line represents the Pareto front obtained by calculating feasible choices as CIT is increased in 1°C increments from 35°C to 40°C. The blue dashed line and black dashed line represent the Pareto fronts at CIT 35°C and 40°C, respectively. In the high-power region, it follows the case where CIT is 35°C, but in the low-power region, it follows the case where CIT is 40°C. In other words, increasing the CIT to control the system is advantageous for improving efficiency in the low-power domain.

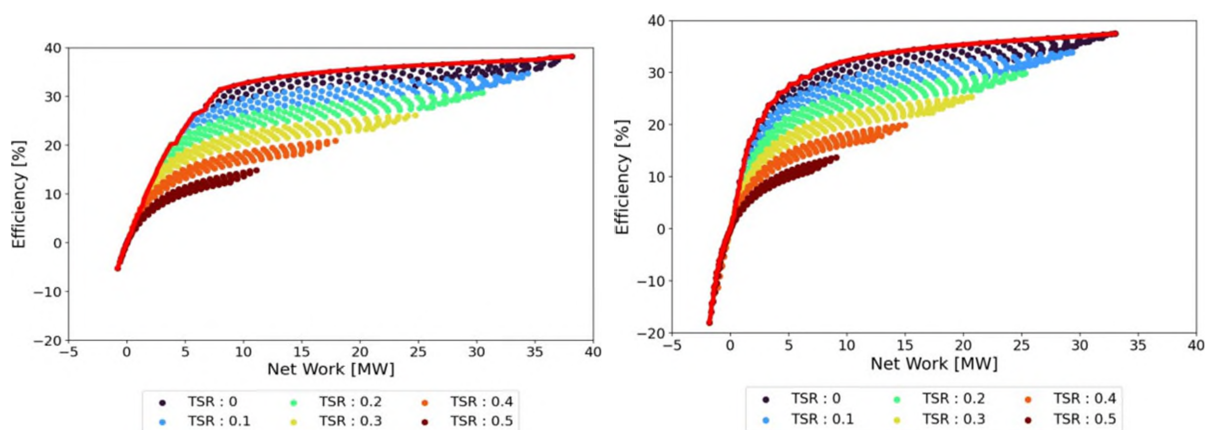

Figure 13 Feasible operation point at CIT 35°C (Left), CIT 40°C (Right)

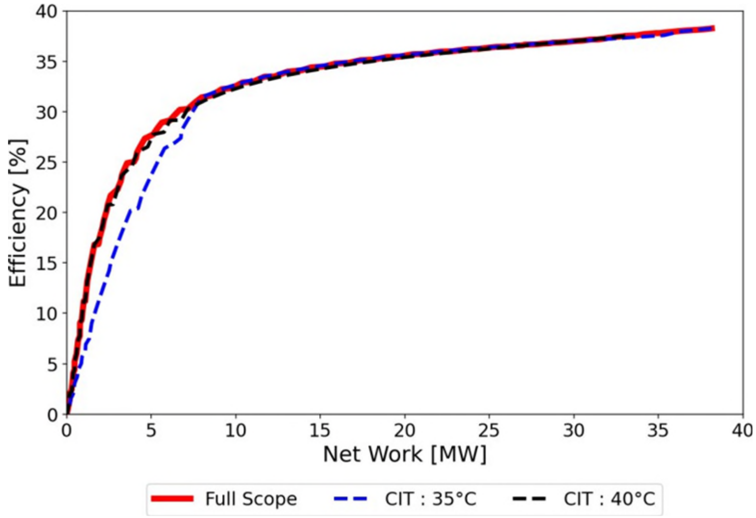

Figure 14 Compare of Pareto front at CIT 35°C and 40°C

As shown in the results of Figures 11 and 12, the efficiency decreases significantly when turbine bypass is engaged. Furthermore, even without turbine bypass, net work decreases as compressor inlet temperature (CIT) rises. Therefore, from an efficiency perspective, increasing the CIT is more advantageous than using turbine bypass alone. Accordingly, it was further examined whether overall system power control is possible with only compressor inlet control and inventory control without turbine bypass, and the required maximum CIT was confirmed. Figure 15 shows the Pareto front between net work and efficiency obtained by raising the CIT to 55°C. When the CIT reached 55°C, the net work became zero. The red line represents the Pareto front obtained across the temperature range incrementally raised from 35°C to 55°C. Like the results up to 40°C, increasing the CIT control becomes more advantageous in terms of efficiency as the operating point moves from high to low power. Therefore, by raising the CIT to 55°C, full-range operation at higher efficiency becomes possible using only compressor inlet temperature control, inventory control, and IHX temperature control without a turbine bypass valve.

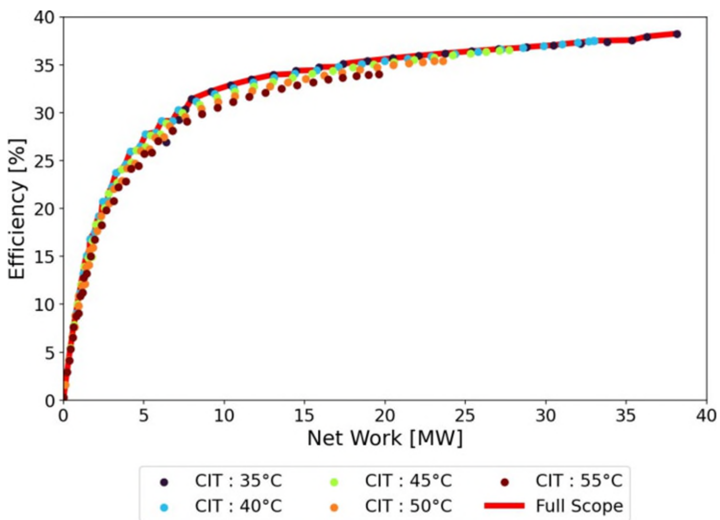

Figure 15 Overall pareto front by changing CIT

SUMMARY AND CONCLUSIONS

This study addresses a full-range operation method for a marine propulsion sCO_2 system based on compressor inlet temperature control, utilizing the design of the GPT-Marine reactor; a gas-cooled pressure-tube reactor for marine propulsion that integrates proven technologies from AGR and CANDU reactors. The primary objective of this study was to develop a full-range operation method for the power conversion system, incorporating compressor inlet temperature control, based on a reactor designed for marine applications and assuming the use of sCO_2.

To achieve this goal, two sCO_2 cycles were optimized using KAIST-CCD based on reactor temperature conditions and existing studies. Among the designed cycles, the simple recuperated Brayton cycle was selected to maximize the effect of CIT control. Among the cycle's key components, the heat exchanger was selected as a PCHE type and designed using KAIST-HXD. The compressor was selected as a double-suction centrifugal compressor, and the turbine as a double-discharge radial turbine, both designed using KAIST-TMD. Quasi-steady state analysis was performed using KAIST-QCD with the designed components. The effects of four control strategies—turbine bypass control, inventory control, heat input control, and compressor input temperature control—on off-design system performance were investigated.

Quasi-steady state analysis results showed full-range operation was possible without CIT control. However, for the simple recuperated cycle, efficiency could be increased by raising the CIT temperature for low-power operation. Furthermore, when turbine bypass control was engaged for off-design operation, the system's off-design efficiency was lower compared to when CIT and heat input were adjusted. Therefore, an analysis was conducted to determine if full-range operation was possible without turbine bypass control. For this system, output could be reduced to zero when the CIT reached 55°C, operating solely using compressor inlet temperature control, inventory control, and maximum system temperature control. This allows removal of the turbine bypass valve, enabling a simpler system. It also reduces the number of control variables, enabling easier operation. For marine systems, using a water-cooled precooler makes compressor inlet temperature control significantly easier. Consequently, employing a precooler water flow rate valve instead of a turbine bypass valve operating at high temperature and pressure is more advantageous.

In conclusion, compressor inlet temperature control is a key control method for enhancing efficiency in the low-power range of sCO_2 systems for marine propulsion. Furthermore, it enables operation across the entire range without turbine bypass control, allowing for a simpler and easier-to-control system layout. However, it is necessary to verify whether compressor inlet temperature control can track real ship operation scenarios through time-dependent transient analysis to determine if its use is a viable option.

REFERENCES

[1] L. Bilgili and A. I. Ölçer, “IMO 2023 strategy-Where are we and what’s next?,” *Mar Policy*, vol. 160, p. 105953, 2024.
[2] H. Schøyen and K. Steger-Jensen, “Nuclear propulsion in ocean merchant shipping: The role of historical experiments to gain insight into possible future applications,” *J Clean Prod*, vol. 169, pp. 152–160, 2017.

[3] S. Park, S. Kim, G. A. K. M. R. Bari, and J.-H. Jeong, “Fundamental Understanding of Marine Applications of Molten Salt Reactors: Progress, Case Studies, and Safety,” *J Mar Sci Eng*, vol. 12, no. 10, p. 1835, 2024.
[4] M. Dunn, “Molten Salt Reactors: Current technology status and the challenges for maritime applications,” in *Conference Proceedings of INEC*, 2024.
[5] Yeongchan Kim, Gihyeon Kim, and Jeong Ik Lee, “Conceptual Design of Gas-cooled Pressure Tube Reactor for Ma-rine Propulsion (GPT-Marine) with Supercritical CO2 Power Cycle,” *International Congress on Advances in Nuclear Power Plants*, 2025.
[6] N. Carstens, “Control strategies for supercritical carbon dioxide power conversion systems,” Massachusetts Institute of Technology, 2007.
[7] G. Kim, S. Lee, I. W. Son, and J. I. Lee, “Optimal controller for S–CO2 compressor inlet conditioning,” *Case Studies in Thermal Engineering*, vol. 59, p. 104528, 2024.
[8] S. Son and J. I. Lee, “Application of adjoint sensitivity analysis method to supercritical CO2 power cycle optimization,” *Energy*, vol. 147, pp. 1153–1164, 2018.
[9] B. S. Oh, Y. Kim, S. J. Kim, and J. I. Lee, “SMART with Trans-Critical CO2 power conversion system for maritime propulsion in Northern Sea Route, part 1: System design,” *Ann Nucl Energy*, vol. 149, p. 107792, 2020.
[10] I. W. Son, S. Choi, S. J. Kimb, and J. I. Leea, “Thermal-sizing of the molten salt reactor system with gas Brayton cycle,” *System*, vol. 12, p. 14, 2021.
[11] Y. Ahn, J. Lee, S. G. Kim, and J. I. Lee, “Studies of supercritical carbon dioxide Brayton cycle performance coupled to various heat sources,” in *ASME Power Conference*, American Society of Mechanical Engineers, 2013, p. V002T09A002.
[12] S. Baik, S. G. Kim, J. Lee, and J. I. Lee, “Study on CO2–water printed circuit heat exchanger performance operating under various CO_2 phases for S-CO_2 power cycle application,” *Appl Therm Eng*, vol. 113, pp. 1536–1546, 2017.
[13] S. K. Cho, S. J. Bae, Y. Jeong, J. Lee, and J. I. Lee, “Direction for high-performance supercritical CO2 centrifugal compressor design for dry cooled supercritical CO2 Brayton cycle,” *Applied Sciences*, vol. 9, no. 19, p. 4057, 2019.

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