

sCO₂ Brayton Cycle Layout Study on Gas-cooled Reactor for Maritime Propulsion

Chanyong Park ^a, Jeong Ik Lee ^{a*}

^aDept. Nuclear & Quantum Eng., KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon, 34141, Republic of Korea

*Corresponding author: jeongiklee@kaist.ac.kr

***Keywords :** Gas-cooled reactor, sCO₂ Brayton cycle, Heat exchanger

1. Introduction

Amid growing concerns over climate change driven by human activity, the International Maritime Organization (IMO) has been implementing continuous policies to reduce CO₂ emissions [1]. Nuclear powered vessel for civil purpose were developed and commercially operated in the late 1950s, suggesting that utilizing nuclear power as an energy source for future maritime propulsion systems aimed at carbon neutrality is technically feasible [2].

This study proposes a propulsion system consists of a small gas cooled reactor and a supercritical carbon dioxide (sCO₂) Brayton cycle. Furthermore, a gas cooled reactor (GCR) is selected for direct coupling with the power cycle, but instead of utilizing a conventional GCR concept, the Gas-cooled Pressure Tube Reactor for Marine Propulsion (GPT-Marine) is utilized [3]. Considering spatial feature of maritime vessel and relatively high core temperature of GCR, an sCO₂ Brayton cycle is chosen for a power conversion system, harnessing compactness of sCO₂ turbomachinery. [4]

The study analyzes thermodynamic performance and heat exchanger (HX) size of various layouts of sCO₂ Brayton cycle combined with a GPT-marine. A total of seven layouts are classified into three groups based on the number and arrangement of heat exchangers and turbo machinery, and the performance of each was compared using KAIST-CCD (Closed Cycle Design). Among them, three layouts with distinctive thermodynamic characteristics are chosen for further evaluating heat exchanger with KAIST-HXD (Heat eXchanger Design) code. The total heat exchanger mass and volume of three cycles are compared.

2. Methods and Results

This section presents design parameters from a novel GCR, GPT-marine, and the procedure and result of sCO₂ cycle layout modeling.

2.1 Design Parameters

The design objectives of GPT-marine reactor are employment of existing technology, improving thermal efficiency and reducing reactor dimension via removing pressurized vessels and steam generators. GPT-Marine reactor design has achieved above three goals by adopting technologies from two commercially operating reactor types: the Advanced Gas-cooled Reactor (AGR)

in the United Kingdom and Canada Deuterium Uranium (CANDU) in Canada. Here, pressurized tube concept from CANDU and high core temperature nature of AGR were combined together to remove voluminous and heavy pressurized vessels in typical reactor and accomplish superior thermal efficiency at the same time.

Basic fuel geometry of GPT-Marine is direct application of AGR's fuel pin geometry and materials. The key different feature of GPT-Marine reactor compared to AGR is a moderator. GPT-Marine reactor utilizes heavy water, D₂O, as a moderator rather than a graphite moderator in AGR, enhancing neutron shielding and neutron spectrum utilization. Especially, outstanding thermal neutron moderation characteristics of D₂O is beneficial for neutron economy owing to its lower neutron absorption rate. Figure 1 and Figure 2 are comparison between AGR core and GPT-marine core schematic and key design parameters of GPT-Marine are summarized in Table 1.

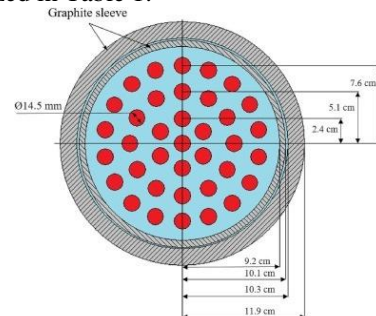


Fig. 1 Cross section of AGR fuel element

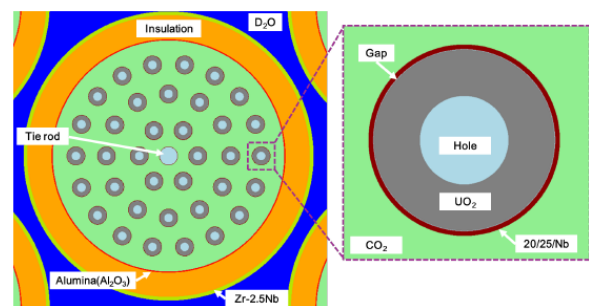


Fig. 2 Cross section of GPT-Marine fuel element

Table 1 Key design parameters of GPT-Marine

Thermal output (MW _{th})	100.0
Reactor volume (m ³)	26.2
Active core dimension	2.4 m(W) × 3.0 m(H)
Reactor dimension	3.0 m(W) × 3.7 m(H)
Number of fuel channels	37
EFPD	960

Moderator	D ₂ O
Coolant	CO ₂
Power density (MW/m ³)	3.8
Mass of uranium (ton)	4.6
Average fuel burnup (MWd/kgU)	21
Mean gas pressure (MPa)	4.1
Coolant outlet temperature (°C)	640
Moderator temperature (°C)	70

The design parameters for sCO₂ secondary side, including cycle maximum/minimum pressure and temperature, pressure drops in various HXs, and efficiency of turbomachinery, and effectiveness of HXs are summarized in Table 2.

Table 2 Design parameters of sCO₂ Brayton cycle

Reactor thermal power (MW _{th})	100.0
Maximum pressure (MPa)	20.0
Minimum pressure (MPa)	7.4
Maximum temperature (°C)	630.0
Minimum temperature (°C)	40.0
Recuperator pressure drop (kPa)	150.0
Heat exchanger pressure drop (kPa)	150.0
Precooler pressure drop (kPa)	150.0
Compressor efficiency	0.84
Turbine efficiency	0.90
Recuperator effectiveness	0.92

2.2 Cycle Layout

As aforementioned in the introduction, a total seven sCO₂ Brayton cycle layouts are designed and analyzed via KAIST-CCD. Here, layouts are classified into three groups depending on the number of heat exchanger and turbomachinery. Fig.3 to Fig.5 illustrate types of cycle compared in this research. The first group is a simple recuperated (SR) layout with one recuperator. Three layouts: simple recuperated with reheater (SRRH), simple recuperated with intercooler (SRIC) and recompression (RC) cycle is gathered into the second group since additional HX and turbomachinery are attached to SR cycle. The third group is a collection of modified recompression cycle: recompression with reheater (RCRH) and recompression with intercooler (RCIC) which are the most complex cycles with five heat exchangers and four turbomachinery.

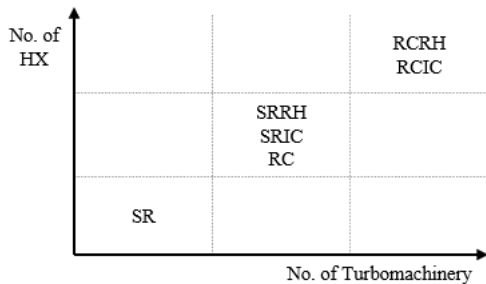


Fig. 3 Layout groups depending on complexity

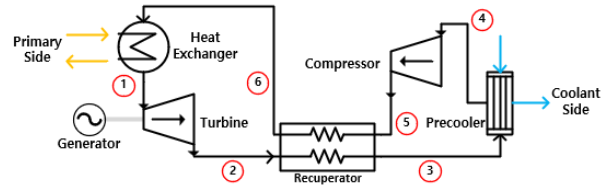


Fig. 4 Group 1: SR sCO₂ cycle

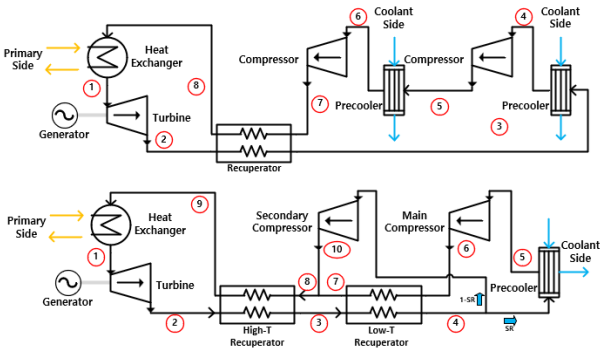
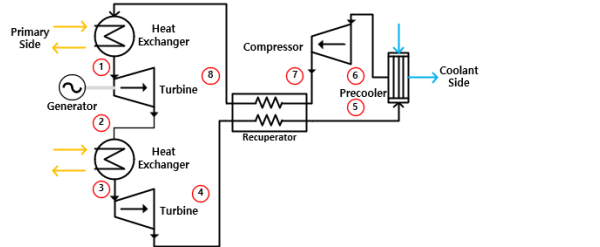


Fig. 5 Group 2: SRRH, SRIC, RC sCO₂ cycle

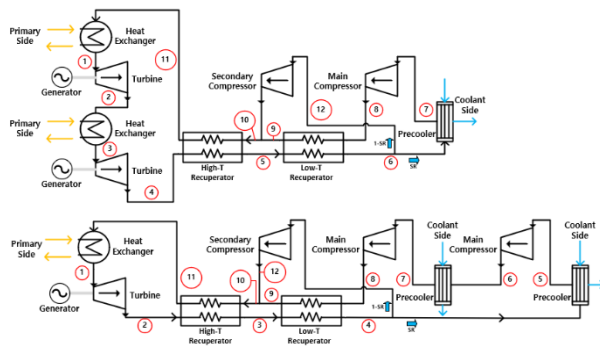


Fig. 6 Group 3: RCRH, RCIC sCO₂ cycle

2.3 Cycle Performance

KAIST-CCD is an in-house code developed for calculating the steady-state thermodynamic performance of closed cycle. Tables 3 and 4 show results of designed cycle with the maximum efficiency at the optimal point.

Table 3 SR cycle optimization result

Design parameter	SR
Cycle thermal efficiency	0.3563
CO ₂ mass flow rate (kg/s)	397.3
Specific work (kJ/kg)	89.69
Minimum pressure (MPa)	7.4
Compressor pressure ratio	2.70

Table 4 SRRH, SRIC, RC cycle optimization results

Design parameter	SRRH	SRIC	RC
Cycle thermal efficiency	0.3599	0.3575	0.4260
CO ₂ mass flow rate (kg/s)	386.37	372.57	556.64
Specific work (kJ/kg)	93.16	95.94	76.53
Minimum pressure (MPa)	7.4	7.4	8.8
Compressor pressure ratio	2.70	2.70	2.273
Split ratio	-	-	0.72

Table 5 RCRH, RCIC cycle optimization results

Design parameter	RCRH	RCIC
Cycle thermal efficiency	0.4251	0.4352
CO ₂ mass flow rate (kg/s)	544.02	492.20
Specific work (kJ/kg)	78.14	89.99
Minimum pressure (MPa)	8.6	7.4
Compressor pressure ratio	2.33	2.703
Split ratio	0.74	0.68

2.4 Cycle Mass and Volume Comparison

Table 6 SRIC, RC, RCIC cycle volume comparison

Cycle	SRIC	RC	RCIC
Precooler 1 volume (m ³)	0.484	0.670	0.316
Precooler 2 volume (m ³)	0.130	-	0.391
LT recuperator volume (m ³)	3.571	10.83	8.675
HT recuperator volume (m ³)	-	7.700	6.506
HX volume without heater (m ³)	4.185	19.20	15.498

Table 7 SRIC, RC, RCIC cycle mass comparison

	SRIC	RC	RCIC
Precooler 1 mass (kg)	2825.2	3910.8	1844.5
Precooler 2 mass (kg)	758.8	-	2282.3
LT recuperator mass (kg)	20843.9	63214.7	50636.0

HT recuperator mass (kg)	-	44944.9	37975.5
Total HX mass (kg)	24,427.9	112,070.4	92,738.3

Comparisons of the total HX volume and mass were conducted for three cycles—the SRIC, which features the smallest mass flow rate; the RC cycle, which offers high efficiency relative to the number of heat exchangers and turbomachinery; and the RCIC, the most complex and efficient among them. The results are summarized in Table 6. Former studies have pointed out that the size of turbomachinery in sCO₂ Brayton cycle is sufficiently smaller than the volume of HX [6,7], indicating that the analysis on the volume of HX could provide an insight to evaluate the system dimension of sCO₂ Brayton cycle. There is no significant difference in total precooler volume among three configurations. The total volume of SRIC cycle is 78% less than the total volume required for RC cycle. A comparison between RC and RCIC cycle reveals that the total heat exchanger volume to construct RCIC cycle is about four-fifths of the total heat exchanger volume of RC cycle.

Since the mass and volume data for the turbomachinery and reactor are not included in this study, preliminary comparison was conducted only for the heat exchanger subsystem against a commercial marine main engine. As a benchmark, the MAN B&W 8G95ME-C10.5-GI engine was selected. The power of the engine is 42.31 MW [8], the dry mass is approximately 1640 ton, and its envelope volume, estimated from overall dimensions are 1402 m³[9]. The total HX mass of RC and RCIC cycles are 6.83% and 5.65% of the benchmark engine mass. However, since this assessment is limited to a partial comparison excluding the reactor and turbomachinery, the onboard applicability of the overall propulsion system should be re-evaluated by considering the total equipment mass and volume.

3. Conclusions

GCR based GPT-marine reactor integrating with sCO₂ Brayton cycle as a power conversion system could employ technical maturity of GCR and compactness of sCO₂ turbomachinery, making it a promising candidate for marine propulsion system. Thermal performances of seven cycle layouts are investigated and heat exchanger dimension of SRIC, RC, RCIC cycles are compared. The study reveals that SRIC has the smallest total heat exchanger volume with less competitive thermal efficiency and RCIC shows the highest thermal efficiency with moderate total heat exchanger volume. The evaluation of off-design operating conditions in various sCO₂ Brayton cycles will be performed in the near future to establish robust control strategy under load following conditions.

REFERENCES

- [1] Bilgili, L., & Ölçer, A. I., IMO 2023 strategy-Where are we and what's next?, *Marine Policy*, 160, 105953, 2024
- [2] Schøyen, H., & Steger-Jensen, K., Nuclear propulsion in ocean merchant shipping: The role of historical experiments to gain insight into possible future applications. *Journal of cleaner production*, 169, 152-160, 2017
- [3] Y. Kim, G. Kim, and J. I. Lee, "Conceptual Design of Gas-cooled Pressure Tube Reactor for Marine Propulsion (GPT-Marine) with Supercritical CO₂ Power Cycle," in Proc. ICAPP 2025: Int. Congr. Advances in Nuclear Power Plants, Antibes Juan les Pins, France, Sep. 17–19, 2025
- [4] J. J. Dienhart, "Supercritical CO₂ Power Cycle Development Summary at Sandia National Laboratories," Sandia National Lab. (SNL-NM), Albuquerque, NM, USA, Tech. Rep. SAND2014-2333P, 1119778, 2014
- [5] Margulis, M., & Shwageraus, Advanced Gas-cooled reactors technology for enabling molten-salt reactors design- Estimation of coolant impact on neutronic performance. *Progress in Nuclear Energy*, 125, 103382, 2020
- [6] Baek, J. Y., Lee, J. J., & Lee, J. I., *Transient analysis of the super-critical carbon dioxide cycle coupled to pressurized water reactor for nuclear powered ships*. Universität Duisburg-Essen, 2021
- [7] V. Dostal, M.J. Driscoll, P. Hejzlar, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, MIT-ANP-TR-100, 2004
- [8] MAN Energy Solutions, "11,000 teu container vessel: An ME-GI powered vessel fitted with fuel gas supply system and boil-off gas handling," doc. no. 5510-0212-00ppr, Dec. 2018
- [9] MAN Energy Solutions, Marine engine programme 2020, doc. no. 4510-0019-00web, Apr. 2020.