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Study of sCO_2 Brayton Cycle Layout for Molten Salt Reactor Applied to Marine Propulsion

Gihyeon Kim [a], Seungkyu Lee [a], Jeong Ik Lee[a*]
[a]*Dept. Nuclear & Quantum Eng., KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea*
[*]*Corresponding author: jeongiklee@kaist.ac.kr*

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1. Introduction

Maritime transportation, responsible for most international trade, heavily depends on fossil fuels. The emission of greenhouse gases from it currently accounts for 3.3% of global carbon dioxide emissions, a level that is expected to rise to 17% by 2050, which is why the International Maritime Organization working to reduce shipping's carbon emissions via greenhouse gas reduction regulations [1]. Research works for propulsion systems that replace traditional fossil fuels is gaining attraction in both academia and industry. Nuclear power is one of these options, and research on small modular reactors suitable for maritime operations is gaining attention.

This study presents a propulsion system that uses a molten salt reactor (MSR) as the heat source and couple it with a supercritical carbon dioxide (sCO_2) Brayton cycle. The high core power density of MSRs makes them ideal candidates for nuclear-based ship propulsion systems in terms of weight and volume. In addition, the high-temperature nature of MSRs allows sCO_2 cycles to achieve higher efficiencies than conventional steam Rankine cycles. Therefore, in this study, the sCO_2 Brayton cycle was chosen as the ship propulsion system due to its size and weight advantages over conventional steam Rankine cycles.

Previous study has already shown that sCO_2 power conversion systems based on MSRs [2]. However, this study focuses on land-based designs and cannot be directly applied to marine systems due to high ultimate heat sink temperature. Therefore, in this study, a lower system minimum temperature was selected to reflect cooling option with seawater. The maximum temperature and pressure of the power conversion system were selected based on MSR's previous research. In addition, to verify the system sensitivity to the heat exchanger, sCO_2 cycles were designed using KAIST-CCD (Closed Cycle Design) for 0, 1, and 2 recuperators, respectively. Finally, based on the designed cycle, KAIST-HXD (Heat eXchagner Design) was used to design the heat exchangers that account for the main volume and mass of the sCO_2 cycle to analyze how the system changes with the number of heat exchangers.

2. Methods and Results

This section describes the process and results of modeling the sCO_2 cycle, including the selection of design parameters and cycle layout to model the sCO_2 cycle and the results of optimization through KAIST-CCD.

2.1 Design Parameters

The design parameters for the sCO_2 cycle were chosen based on the Molten Salt Reactor Experiment (MSRE) which is conducted at ORNL (Oak Ridge National Laboratory). The MSRE system modified by Son et al. is chosen for ship propulsion because original MRSE does not have suitable temperature range for power generation [2]. Referring to the example of using a conventional diesel engine for ship propulsion and a small modular reactor for ship propulsion, the system design target is a net output power of 10 MWe [3,4].

Therefore, the output of the MSR core should be modified according to the efficiency of the power conversion system. In this paper, to estimate the volume and mass of the MSR core as a function of power output, the power density of the fuel salt in the core and the volume fraction of the fuel salt in the core were assumed to be constant at the value of the MSRE regardless of the core power. Depending on the core design, the fuel salt power density and volume fraction in the core can differ. However, since the relationship between fuel salt power density and core power is unclear, using the current experimentally validated MSRE is a more conservative estimate.

Table 1. Molten salt reactor core parameters [5,6,7]

Parameter	Value
Average fuel power density (MW/m^3)	14
Fuel salt density (kg/m^3)	2261.8
Fuel salt volume fraction in core	0.225

The average fuel power density and the density of the fuel salt were determined as shown in Table 1 by referring to the MSRE report [5,6]. In the case of MSRE, the fuel salt composition is designed as Table 2 [7].

Table 2. MSRE fuel salt composition [7]

Composition	Mole Fraction (%)
^7LiF	65
BeF_2	29.2
$^{235}UF_4$, $^{238}UF_4$	0.83
ZrF_4	5

The maximum temperature and pressure conditions of the sCO_2 secondary side were determined using the design parameters of modified MSRE conditions. Furthermore, the efficiency of the components and the additional temperature and pressure conditions were determined by referencing to the previous designs of sCO_2 power conversion systems for marine propulsion [2, 8,9]. The design parameters for the chosen sCO_2 cycle are summarized in Table 3.

Table 3. Design parameters of sCO_2 power conversion system [2,8,9]

Parameter	Value
System power output (MWe)	10.0
Maximum pressure (MPa)	25.0
Minimum allowable pressure (MPa)	7.5
Maximum temperature (°C)	630.0
Minimum temperature (°C)	35.0
Turbine efficiency (%)	93%
Compressor efficiency (%)	84%
Recuperator effectiveness (%)	92%
Recuperator pressure drop (kPa)	150
Heat exchanger pressure drop (kPa)	150
Precooler pressure drop (kPa)	150

2.2 Cycle Layout

In marine propulsion systems, the total mass and volume of the cycle are the main criteria for selecting the cycle layout. In the case of the sCO_2 cycle, the heat exchangers occupy most of the weight and volume. Therefore, in this study, the cycle is optimized by varying the number of heat exchangers from 0, 1, and 2 and comparing the efficiency, volume, and weight. The layout of the sCO_2 cycle changes from Figure 1 to Figure 3 depending on the number of recuperators.

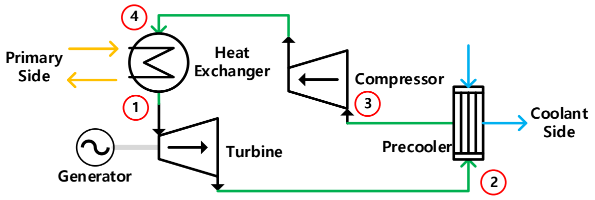

Fig. 1. Simple sCO_2 cycle

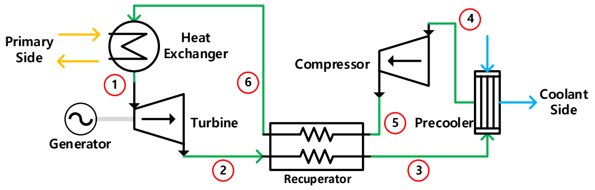

Fig. 2. Simple recuperated sCO_2 cycle

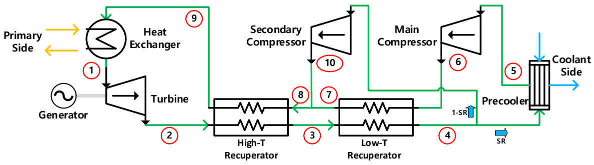

Fig. 3. Recompression sCO_2 cycle

2.3 Cycle Optimization

Using the in-house code KAIST-CCD, the cycle layouts shown in Figures 1 to 3 were optimized to satisfy the design parameters in Table 3. Tables 4 and 5 show the design results that maximize the efficiency of the sCO_2 cycle in Figures 1 and 2, respectively.

Table 4. Simple sCO_2 cycle optimization results

Design parameter	Optimization Results
Cycle thermal efficiency (%)	17.89
Cycle thermal input (MWth)	55.91
CO_2 mass flow rate (kg/s)	81.78
Compressor pressure ratio	3.33
Min. pressure (MPa)	7.5

Table 5. Simple recuperated sCO_2 cycle optimization results

Design parameter	Optimization Results
Cycle thermal efficiency (%)	42.66
Cycle thermal input (MWth)	23.44
CO_2 mass flow rate (kg/s)	123.5
Compressor pressure ratio	1.956
Min. pressure (MPa)	12.78

For the recompression cycle in Figure 3, the maximum efficiency changes with the split ratio (SR). Figure 4 shows a graph of the maximum efficiency of the cycle for different split ratio (SR). The efficiency of the cycle is maximized when SR = 0.7.

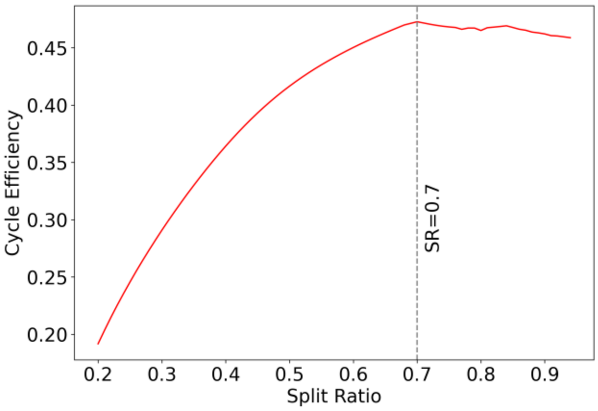

Fig. 4. Optimization of Split Ratio for Recompression sCO_2 cycle

The design results for the cycle at SR = 0.7, which is the maximum efficiency 47.28%, are shown in Table 6.

Table 6. Recompression sCO_2 cycle optimization results

Design parameter	**Optimization Results**
Cycle thermal efficiency (%)	47.28
Cycle thermal input (MWth)	21.16
CO_2 mass flow rate (kg/s)	91.10
Main compressor pressure ratio	2.936
Secondary compressor pressure ratio	2.867
Split ratio	0.7
Min. pressure (MPa)	8.516

2.4 Cycle Mass & Volume Comparison

To estimate the mass and volume based on the cycle layout, only the heat exchanger sections and reactor core were estimated from a preliminary design. The heat exchangers in the cycle are all assumed to use printed circuit type heat exchangers (PCHE), and the design was performed using the in-house code KAIST-HXD. The inlet and outlet conditions of the heat exchangers for the design were calculated via cycle optimization using KAIST-CCD. The volume of fuel salt and graphite moderator in reactor core is estimated by using design parameter of MSRE in Table 1, and cycle thermal input that meet the 10MWe power output. The calculated results are shown in Tables 7 and 8.

Table 7. Cycle volume comparison

	Simple	**Recuperated**	**Recompression**
Precooler volume (m^3)	0.166	0.155	0.185
(High-T) recuperator volume (m^3)	-	1.009	0.255
Low-T recuperator volume (m^3)	-	-	0.365
Fuel salt volume (m^3)	3.994	1.674	1.511
Graphite moderator volume (m^3)	13.76	5.766	5.205
Total volume (m^3)	17.92	8.604	7.521
Work per volume (MW/ m^3)	0.558	1.162	1.330

Table 8. Cycle volume comparison

	Simple	**Recuperated**	**Recompression**
Precooler mass (kg)	903.7	843.1	1006.9
(High-T) recuperator mass (kg)	-	5482.2	1385.4
Low-T recuperator mass (kg)	-	-	1986.4
Fuel salt mass (kg)	9033.6	3786.3	3417.6
Graphite moderator mass (kg)	28896	12108.6	10930.5
Total mass (kg)	38833.3	12108.6	18726.8
Work per mass (kW/kg)	0.2575	0.45	0.5340

The results showed that the both work per volume and work per mass were higher in the order of recompression sCO_2 cycle, recuperated sCO_2 cycle and simple sCO_2 cycle. This is because the decrease in the volume and mass of the reactor core due to the increase in efficiency had a greater impact on the overall value than the impact of the increase in the volume of the heat exchanger. From the results of both analyses, the optimal cycle for ship propulsion MSR system is the recompression sCO_2 cycle.

3. Conclusions

The molten salt reactor with sCO_2 power conversion system can be a suitable propulsion system for marine transportation. Three layouts have been investigated to be adopted by the molten salt reactor system. The layouts are compared based on the volume and mass of heat exchangers and reactor core first. The recompression sCO_2 cycle shows the best work per volume and work per mass to produce the same amount of power using MSR. Therefore, this paper recommends to utilize a recompression sCO_2 cycle for MSR marine propulsion system.

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