can be reduced significantly [6]. Although the critical temperature of CO_2 is 31 ℃ it may not be achievable because the temperature of coolant in precooler can be limited according to the ambient temperature of the site. Therefore, the CIT, which is the minimum temperature of the cycle, was determined as 35 ℃

A Conceptual Design of Supercritical CO2 Brayton Cycle for a Small Modular Molten Salt Reactor

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1. Introduction

Research Background

- With the strengthening of greenhouse gas(GHG) emission regulations, **small modular reactors(SMR)** are attracting attention as a driving force for ships to replace fossil fuels.
- **Molten Salt Reactors (MSR)** that have advantages of high efficiency and safety are being considered as candidates for the next generation vessel power source.
- As a power conversion system for MSR, the **supercritical CO2 Brayton Cycle(SCBC)** is considered the most suitable candidate.
- Since previous studies on SCBC design with MSR are insufficient, this study is going to confirm whether MSR and SCBC are suitable for **ship power sources**.

Why MSR &SCBC for marine propulsion

- The typical operating temperature of the MSR overlaps with the maximum efficiency temperature range of the SCBC, 500 ~ 700 °C.
- The combination of MSR and SCBC can be constructed as a SMR which has much smaller size than a conventional steam turbine cycle. Thus, the cargo space of a vessel can widen enough.
- As the SCBC can further maximize the advantages of MSR, the thermal efficiency of the power conversion system is expected to reach 40-50%.

2. Cycle modeling Method

Targeted Ship Selection

- Targeted ship is a **180,000 tons of Suezmax-class oil tanker**.
- The power required to operate the ship is about **21.2MW** in total. (including Propulsion, Auxiliary, Hotel Load).

Layout of SCBC

- The layout of **re-compression Brayton cycle** is determined, which can significantly increase the cycle thermal efficiency through waste heat recovery and re-compression process as shown in Fig.1.
- The total compressing work of re-compression cycle is much less than that of simple recuperative cycle.
- The flow split ratio for the Main-Compressor (MC) side, denoted as **'a'** in Fig. 1, was analyzed by sensitivity study to find optimal value.

Cycle modeling method in DWSIM

- The cycle was designed using **Daniel Wagner Simulator (DWSIM)**, which is a program for process design and simulation.
- The properties of s-CO2, such as enthalpy, entropy, and heat capacity, are determined from **Peng-Robinson(PR)** equations of state.
- The calculation of required or generated energy at each component is based on the energy balance with the enthalpy difference as stated below. The equations on each component are described in Table 1.

$$Q = \dot{m}\,\Delta h$$

where Q is energy stream, $\dot{m}$ is the mass flow rate, Δh is enthalpy difference.

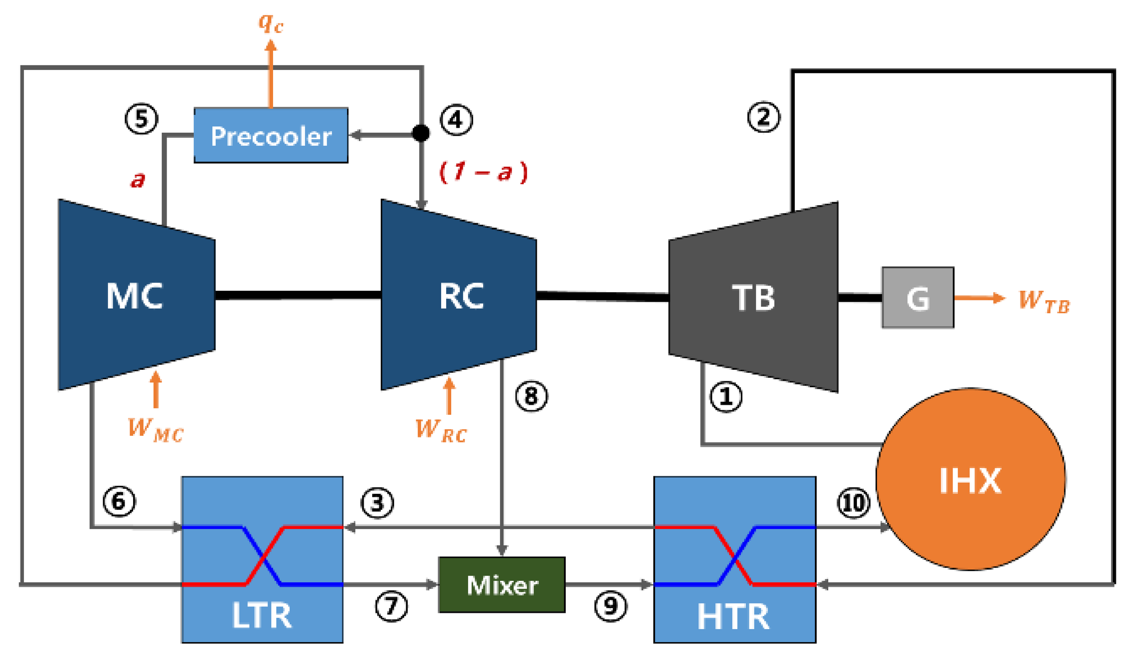

Fig. 1. Schematic drawing of the SCBC

Table 1. Energy balance equations of each component per unit mass

Component	Energy balance equation
Turbine work (w_{TB})	$w_{TB} = h_1 - h_2$
Main-Compressor work (w_{MC})	$w_{MC} = a(h_6 - h_5)$
Re-Compressor work (w_{RC})	$w_{RC} = (1-a)(h_8 - h_4)$
High-Temperature Recuperator (HTR)	$h_2 - h_3 = h_{10} - h_9$
Low-Temperature Recuperator (LTR)	$h_3 - h_4 = a(h_7 - h_6)$
Precooler heat rejected (q_c)	$q_c = a(h_4 - h_5)$
Mixer	$h_9 = ah_7 + (1-a)h_8$
Heat addition (q_{IHX}) of Intermediate Heat Exchanger (IHX)	$q_{IHX} = h_1 - h_{10}$

3. Results and Discussion

Cycle simulation

- Using DWSIM, the cycle loop was designed as shown in Fig. 2 and the input parameters are entered for each component as summarized in Table 2.
- Since the most optimal turbine inlet temperature (TIT) is 600 °C considering the core outlet temperature of MSR, the mass flow rate of s-CO2 should be maintained around 280.8 kg/s to reach the targeted thermal power of 60MWth.
- A sensitivity study with the pressure ratio of turbine within the range of 2.5 to 3.1 was conducted to maximize the cycle efficiency while the compressor outlet pressure (COP) was fixed at 25 MPa. The maximum cycle efficiency was found at compressor inlet pressure (CIP) of 8.77MPa.
- It is known that the closer the state of CO2 is to the critical point, the higher the density of CO2, which means the compressing work can be reduced significantly. Thus, the compressor inlet temperature (CIT) at MC side was determined to 35 °C, which is close to critical point.

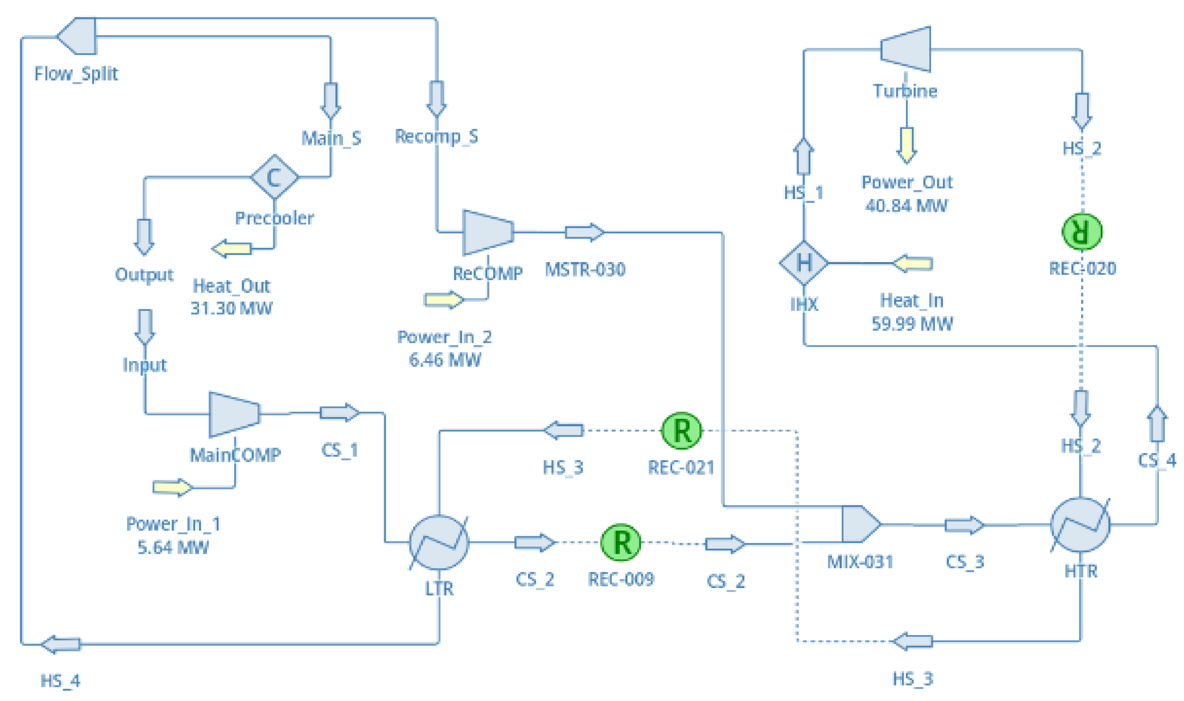

Fig. 2. Flowsheet of the SCBC in DWSIM

Simulation results analysis

- From the results of the simulation, the T-S diagram of the SCBC was depicted in Fig. 3 and the calculated cycle net power is 28.74 MWe, which satisfies the total power required for the operation of the target ship.
- The thermal efficiency of the cycle was shown to be 47.9%. Compared to the ship propulsion system designed with same oil tanker in previous study, the SCBC designed in this study has higher efficiency with even smaller thermal capacity of IHX.

Table 2. Cycle input parameters in DWSIM

Mass flow rate	[kg/s]	280.8
Turbine inlet temperature	[°C]	600
Compressor inlet temperature	[°C]	35.0
Compressor inlet pressure	[MPa]	8.77
Compressor outlet pressure	[MPa]	25
Recuperator hot fluid pressure drop	[MPa]	0.15
Recuperator cold fluid pressure drop	[MPa]	0.10
Cooler pressure drop	[MPa]	0.10
Turbine adiabatic efficiency	[%]	93
Compressor (MC,RC) adiabatic efficiency	[%]	85
Recuperator (HTR, LTR) heat transfer efficiency	[%]	95

Table 3. Performance of SCBC for MSR

Thermal capacity of IHX	[MWth]	59.99
Turbine generated power	[MWe]	40.84
The total required power of Two compressors(MC, RC)	[MWe]	12.10
Cycle net power	[MWe]	28.74
HTR heat exchange conductance	[kW/K]	347
LTR heat exchange conductance	[kW/K]	377
Cycle net efficiency	[%]	47.9

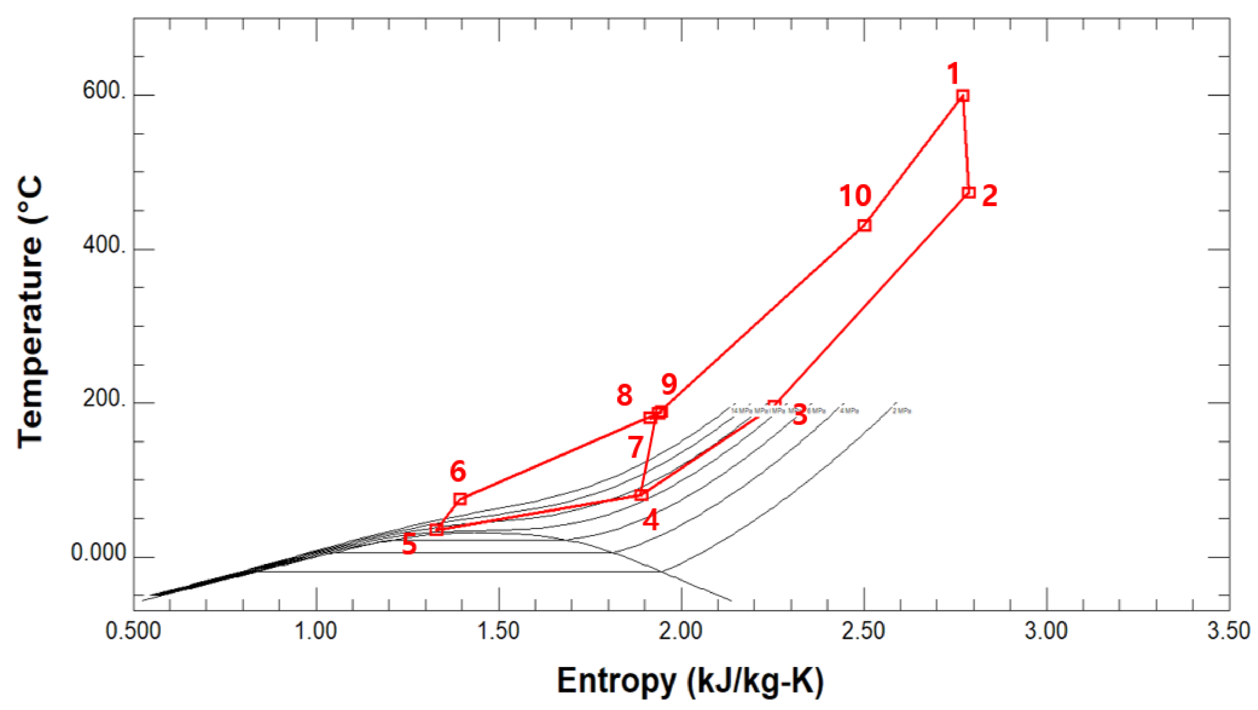

Fig. 3. Temperature-entropy diagram of the SCBC

4. Conclusion

- A conceptual design of a supercritical carbon dioxide Brayton cycle of SM-MSR was proposed as an application of marine propulsion by using the process design software, DWSIM.
- The thermal power of the IHX was targeted to 60MWth and the cycle net power was calculated in 28.74MWe, which is suitable for the power source of a 180,000-ton oil tanker.
- Thermal efficiency of the SCBC is 47.9%. Generally, thermal efficiency of the 4th generation reactor-based power generation system is expected to be around 40%. For this reason, the SCBC proposed in this paper can be considered suitable design for ship propulsion.