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A Conceptual Design of Supercritical CO_2 Brayton Cycle for a Small Modular Molten Salt Reactor

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1. Introduction

Recently, as the climate change has become serious, regulations on greenhouse gas (GHG) emissions have been strengthened under various climate change agreements. In marine industry, especially, the International Maritime Organization (IMO) has announced GHG reduction strategies to limit GHG emissions from ships. Accordingly, a lot of research on nuclear energy are attracting worldwide attention as a driving force for ships to replace existing fossil fuels. Because nuclear energy is much more efficient than fossil fuels, such as heavy oil, it has advantages in economic feasibility as well as solving environmental problems. In this reason, the technology of nuclear-powered ship is in the spotlight around the world [1].

In particular, a lot of attempts are being made to apply the 4th generation reactor to ship propulsion. Among them, Molten Salt Reactors (MSR) that has advantages of high efficiency and safety is being mentioned as candidate for new power source for eco-friendly ships. In consideration of a power conversion system for MSR, a supercritical CO_2 Brayton Cycle (SCBC) is evaluated as the most suitable candidate. It is because the operating temperature of MSR is around 600°C, which is within the temperature range, 500~700°C, where the SCBC can achieve the maximum efficiency [2]. When SCBC is applied to MSR, cycle thermal efficiency is expected to reach 40-50% [3].

This paper focus on the design of SCBC, which is applicable to MSR-based nuclear propulsion ships. It is different from the existing research of nuclear propulsion ship, in that MSR is a 4th generation reactor. The characteristics of properties of supercritical CO_2 (s-CO_2) were considered to find optimal design of SCBC. Furthermore, proper sensitivity studies were conducted to get optimal process data for each component of cycle. The design results and cycle performance will be described.

2. Cycle modeling method

2.1 Cycle layout of SCBC

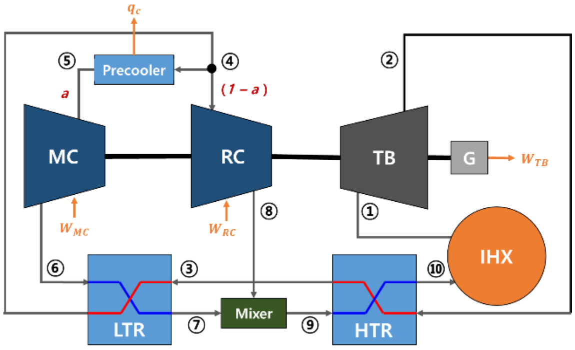

Fig. 1. Schematic drawing of SCBC

The layout of SCBC was schematically drawn with the thermodynamic state points in Fig. 1. The re-compression Brayton cycle is determined, which can significantly increase the cycle thermal efficiency through waste heat recovery and re-compression process [4]. It is because the total compressing work of re-compression cycle is much less than that of simple recuperative cycle [5]. Therefore, there are two recuperator (LTR, HTR) and two compressors (MC, RC) in the cycle layout. The flow split ratio for the Main-Compressor (MC) side, denoted as '*a*' in Fig. 1, was analyzed by sensitivity study in order to find optimal value.

2.2 Cycle modeling process in DWSIM

The cycle was designed using Daniel Wagner Simulator (DWSIM), which is an open-source program for process design and simulation. The procedure of cycle modeling in DWSIM is briefly summarized in Fig. 2.

On the flowsheet, the simulation objects, e.g. compressor, turbine, heat exchanger, are added and connected to each other, which build a layout of cycle loop as shown in Fig. 3. Then, input parameters

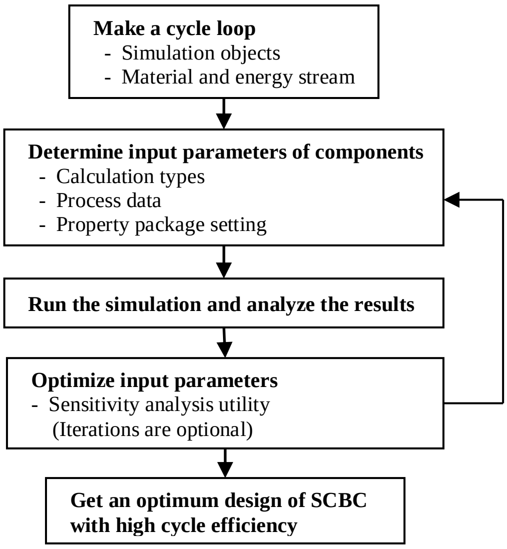

Fig. 2. Sequence of process modeling in DWSIM

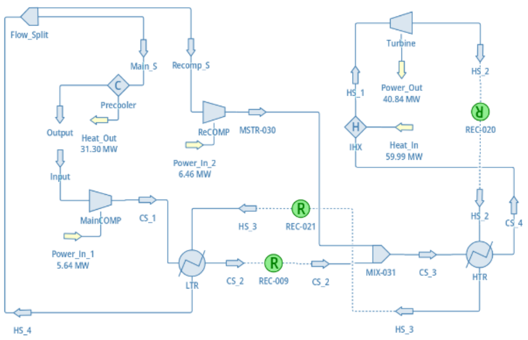

Fig. 3. Flowsheet of DWSIM

determined by user are entered for each component appropriately. Running the simulation, DWSIM starts to calculate the cycle values according to selected calculation model. The results of calculation can be summarized and analyzed by display tools. In addition, process analysis and optimization tool, such as sensitivity analysis utility, can be used to derive optimum process data to achieve maximum cycle efficiency.

In DWSIM, the properties of s-CO_2, such as enthalpy, entropy, heat capacity, are determined from Peng-Robinson(PR) equations of state, which are modified from van der Waals equations of state. These equations are today still highly relevant in process engineering.

All calculations are made from input node to output node in a module basis, according to its order of connection between the objects. Once one object has all of required properties, the data are passed to its downstream and it continues until the end node. In the single module, the calculations are based on the energy balance with enthalpy difference between the inlet and outlet of each component. It can be written by an equation below:

$$Q = \dot{m}\Delta h \qquad (1)$$

where Q is the energy stream on a component, $\dot{m}$ is mass flow rate, Δh is enthalpy difference. The energy balance equations of each component of the SCBC are given in Table I.

Table I: Energy balance equations of each component per unit mass. The notations and subscripts used in the equation are shown in Fig. 1.

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	$h_9 = ah_7 + (1-a)h_8$
Intermediate Heat Exchanger (IHX) heat addition (q_{IHX})	$q_{IHX} = h_1 - h_{10}$

The cycle thermal efficiency (η_{th}) was calculated by below:

$$\eta_{th} = \frac{W_{TB} - (W_{MC} + W_{RC})}{Q_{IHX}} \times 100 \qquad (2)$$

where Q_{IHX} is the heat added from MSR to SCBC, W_{TB} is the power generated from turbine, W_{MC} and W_{RC} are the power required on main-compressor and re-compressor, respectively.

3. Cycle Design Results and Discussion

The thermal power of the reactor was targeted to 60MWth, which is suitable as a power source for 180,000-ton oil tanker. The shaft power required to operate at a constant speed of 14 knots is about 20 MWe. In addition, approximately 4 to 5 MWe is consumed as an auxiliary load. Therefore, the power conversion system needs to generate about 25 MWe [1]. Considering the cycle efficiency, about 48%, of SCBC design proposed in this paper, 60 MWth is considered appropriate as the heat capacity of the reactor.

According to previous research on the IHX design of MSR, it is known that 600 °C is the most optimal turbine inlet temperature (TIT) considering the core outlet temperature of MSR [2]. Consequently, the mass flow rate of s-CO_2 should be maintained around 278.5 kg/s to reach the targeted thermal power of 60MWth and TIT of 600 °C.

The compressor outlet pressure (COP) was fixed at 25 MPa. Then, a sensitivity study with the pressure ratio of turbine within the range of 2.5 to 3.1 as a variable was conducted to maximize the cycle net power and cycle efficiency. From the study, The maximum cycle efficiency was found at compressor inlet pressure (CIP) of 8.77MPa.

When choosing the optimal compressor inlet temperature (CIT) at MC side, the dramatic change of CO_2 density was considered in supercritical region. The closer the state of CO_2 is to the critical point, the higher the density of CO_2, which means the compressing work

Table II: Cycle design conditions (Input to 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
Turbine outlet pressure	[MPa]	9.07
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

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 ℃.

The isentropic efficiencies of turbomachineries were selected based on the average level of the related research literatures. The isentropic efficiencies were fixed at 85% and 93% for the compressors and turbine, respectively [7,8].

Designing the power conversion system in a compact size, a Printed Circuit Heat Exchanger (PCHE) is mainly considered rather than a conventional shell and tube heat exchanger for the SCBC. PCHE, as a next-generation heat exchanger, can be manufactured on a scale of 1/10 of that of shell and tube heat exchangers. It is also applicable with working fluid of high temperature (up to 900 °C) and high pressure (up to 150 MPa). The overall heat transfer coefficient (*U*) is configured by referring to the study of Bartel et al. (2015) [9]. According to related research literature, it is assumed that the heat transfer efficiency of PCHE can reach higher than 95%. Therefore, in this study, the heat transfer efficiency of HTR and LTR was set to 95% [11, 12]. In addition, Pressure drops, occurred in the heat exchangers, was considered by referring to the study of Son et al. (2021) [10]. Including above mentioned cycle operating conditions, all other conditions are given in Table II.

Fig. 4 is a T-S diagram of the SCBC. This diagram was drawn by properties of state points that were obtained from the National Institute of Standards and Technology (NIST)'s REFPROP program. The calculation results from DWSIM were summarized in Table III.

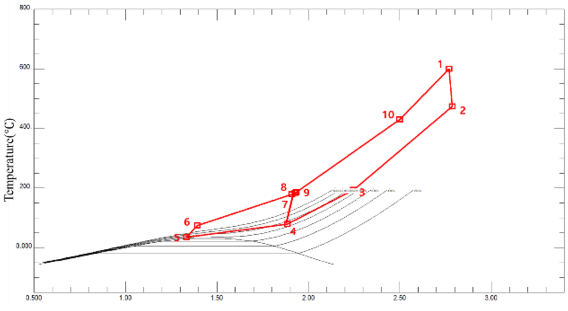

Fig. 4. Temperature-entropy (T-S) diagram of cycle

Table III: Calculation Results (Output from DWSIM)

Thermal capacity of IHX	[MWth]	59.99
Turbine generated power	[MWe]	40.84
Total required power of two compressor (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

From these design conditions, the generated power on Turbine was calculated to be 40.84MWe, while the total power required on MC, RC is 12.10MWe. Thus, the net power of the cycle is 28.74MWe. In other words, the thermal efficiency of the cycle was calculated to be 47.9%.

4. Conclusion and further works

In this study, a conceptual design of a supercritical carbon dioxide Brayton cycle of SM-MSR is proposed for marine propulsion. The cycle was designed using DWSIM, which is a process design and simulation program. The re-compression cycle was chosen as the layout of the cycle to increase the cycle efficiency. The thermal power of the reactor was targeted to 60MWth which is suitable for the power source of 180,000-ton oil tanker. Thermal efficiency of the SCBC was calculated to be 47.9% and the cycle net power of the cycle was calculated to be 28.74 MWe. 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. Safety analysis and detail design on each component of cycle, e.g. PCHE and turbomachineries, should be conducted in future research.

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