A Modeling of Supercritical CO2 Brayton Cycle for a Small Modular Salt Molten Reactor on Nuclear-powered Ship

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1. Introduction

As climate change impacts global warming, noticeable changes are taking places, such as increasing floods, droughts, and forest fires. To prevent this change, humanity must prevent temperatures from rising more than 1.5 degrees Celsius compared to pre-industrial times and achieve net zero by 2050. To achieve Net-Zero, many countries must make efforts to reduce fossil fuel use and use eco-friendly energy resources. In particular, a lot of attention is required in the energy transport sector which uses a lot of energy.

International Maritime Organization (IMO) stipulated MARPOL 73/78 Annex VI, an emission of air pollutants and greenhouse gases from ships are strongly regulated by nitrogen oxides below 80% of 2000 levels and sulfur oxides in ship fuels below 0.5% [1]. Accordingly, shipping and shipbuilding companies are actively developing nuclear-powered ships as eco-friendly ship because they do not emit nitrogen oxides and carbon dioxides, and can cover the growing trends of output power for ship propulsion.

Due to safety issues strongly emerging for nuclear energy, Generation IV reactor models attempt to be applied to eco-friendly ships these days. In particular, Molten Salt Reactor (MSR) is being mentioned as candidates for nuclear-powered ships for advantages of nuclear safety and compact size. Supercritical CO_2 Brayton Cycle (SCBC) was proposed as a power conversion for nuclear propulsion ships based on Small Modular Molten Salt Reactor (SM-MSR) because this layout can have advantages of high performance and compact size for ship propulsion. Therefore, this paper focus on modeling cycle layouts of SCBC, comparing powertrain's efficiency between an existing reference ship and modeled SM-MSR based on SCBC. The design results of simulation and efficiency will be described.

2. Cycle modeling method

2.1 Reference ship and reactor

The SCBC design proposed in this paper is a power conversion system for nuclear powered ship. Hirdaris *et al.* studied a conceptual design of ship propulsion system with PWR and steam turbine [2]. They selected suezmax oil tanker as a parent ship that is Energy Sprinter delivered in 2005 and operated by Enterprises Shipping and Trading S.A. The researchers replaced conventional diesel engines with the Pb-Bi cooled Small Modular Reactor (SMR) and proposed a new SMR tanker design. The SMR tanker designed by Hirdaris *et al.* was selected as a reference ship of this study because their work is a good comparison to evaluate the SCBC design proposed in this paper. The specifications of the ship are summarized in Table 1.

TMSR-LF developed in SINAP (Shanghai Institute of Applied Physics) was selected as reference reactor. TMSR-LF is a SMR with liquid-fueled thorium molten salt [3]. The schematic diagram of TMSR-LF from SINAP was shown in Figure 1 and the major information of reactor was summarized in Table 2. Fission materials of TMSR-LF are dissolved in molten salts, i.e., $LiF-BeF_2-UF_4-ThF_4$, which play two roles as both coolant and nuclear fuel in primary loop. In the event of an accident, the molten salt with a high boiling point is discharged to the drain tank in a low-pressure liquid state and solidified, so there is little possibility of leakage accidents of coolant and nuclear fuel. According to SINAP's perspective for SM-MSR, it is expected that a smaller design of TMSR-LF can be developed by scaling down the original design for merchant ship propulsion. An important point to be obtained from the reference reactor is the operating temperature condition, which is related to the turbine inlet temperature (TIT) of SCBC. The inlet and outlet temperature of the core of TMSR-LF is 600°C and 700°C, respectively.

Table 1. Specifications of reference ship (SMR tanker)

Principal particulars	Value	Unit
Length	304.25	m
Beam	48.0	m
Depth	23.1	m
Displacement volume	185,371	ton
Power at 100% MCR[1] (16.7 knots)	23,515	kW
Auxiliary load – Unloading	1,300	kW

[1] Maximum Continuous Rating

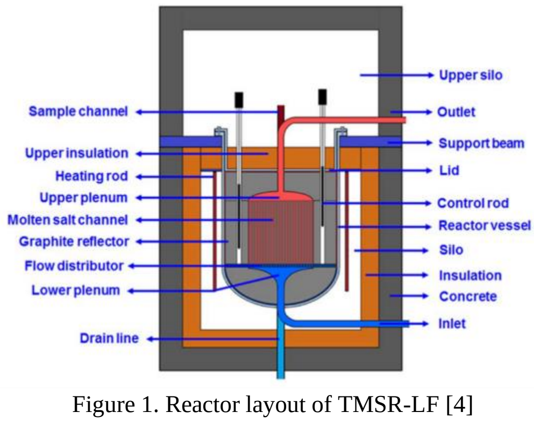

Figure 1. Reactor layout of TMSR-LF [4]

Table 2. The main features of TMSR-LF

Features	Value	Unit
Electrical capacity	168	MWe
Thermal capacity	395	MWth
Inlet/outlet temperature of primary loop	600 / 700	°C
Fuel salt of primary loop	$LiF\text{-}BeF_2\text{-}UF_4\text{-}ThF_4$	-
Salt of secondary loop	FNaBe	-

2.2 Cycle layout of SCBC

Dostal proposed the supercritical recompression Brayton cycle layout, i.e., recompression cycle, with two recuperators and two compressors [5]. In this layout, the flow of the cycle is divided into two streams on flow splitter before compression, and it also affects the input conditions of each stream to each recuperator. Therefore, an optimum flow split ratio should be determined to compensate for the specific heat difference of two side in recuperator. It can increase recuperative performance and the final thermal efficiency of the cycle. Consequently, in this study, these advantages of the recompression cycle layout are utilized to design a SCBC with high performance and compact size for ship propulsion.

The energy stream of each component in and out of the cycle boundary are also denoted in yellow in Figure 2. Heat transfer in the recuperators and mixer also occurs between two flows, but it is not marked in the Figure. In thermodynamic analysis, the energy stream of each component is calculated by the enthalpy difference between the input and output as written below:

$$Q = \dot{m}\Delta h \tag{1}$$

, where $\dot{m}$ is the mass flow rate of the stream and Δh is enthalpy difference. By the equation of (1), the energy balance equations of SCBC components are derived and summarized in Table 3. The notations and subscripts used in the equation are shown in Figure 2.

An important criterion in the cycle design process is the cycle thermal efficiency to evaluate the performance of the SCBC. The cycle thermal efficiency (η_{th}) was calculated as below:

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

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

Equation (2) can be rewritten by enthalpy difference term as shown in equation (3):

$$\eta_{th} = \frac{(h_1 - h_2) - \big(a(h_6 - h_5) + (1-a)(h_8 - h_4)\big)}{h_1 - h_{10}} \tag{3}$$

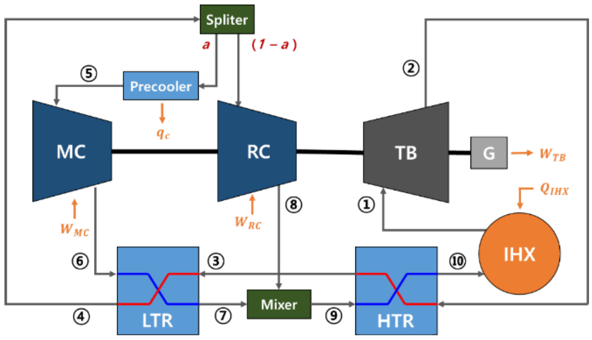

Figure 2. Recompression cycle layout of SCBC

Table 3. Energy balance equations of the cycle per unit mass

Component	Energy stream	Energy balance equations
Turbine	Generated power (w_{TB})	$w_{TB} = h_1 - h_2$
Main-compressor	Required power (w_{MC})	$w_{MC} = a(h_6 - h_5)$
Re-compressor	Required power (w_{RC})	$w_{RC} = (1-a)(h_8 - h_4)$
HTR	Heat exchanged	$h_2 - h_3 = h_{10} - h_9$
LTR	Heat exchanged	$h_3 - h_4 = a(h_7 - h_6)$
Precooler	Heat rejected (q_c)	$q_c = a(h_4 - h_5)$
Mixer	Heat exchanged	$h_9 = ah_7 + (1-a)h_8$

3. Cycle Simulation and Discussion

3.1 Cycle modeling process in DWSIM

SCBC was modeled and simulated by Daniel Wagner Simulator (DWSIM), which is open-source analysis program for process design and simulation. The thermodynamic properties of CO_2 were obtained from Peng-Robinson equations of state [6].

To verify whether this program is suitable as a tool for SCBC design, the SCBC design for ABTR (Advanced Burner Test Reactor), which was studied by Argonne National Laboratory (ANL), was set as a reference model to verify DWSIM. The design results of both DWSIM and ANL report are compared in Table 4. Although, there are some differences between the two results due to the difference in property of CO_2, it is not large enough to doubt that DWSIM program and ABTR design report do not specify the reference of the property. Therefore, it is considered that the validity of DWSIM as a SCBC design tool was verified.

The SCBC simulation was conducted according to the flowchart in Figure 3. First, each of components in recompression cycle was added on a flowsheet of DWSIM and connected to each other as shown in Figure 4. Secondly, the design parameters of SCBC were put in setting page of each component, which are determined properly to meet basic requirements of reference ship and reactor. One of important requirement of SCBC is to produce cycle net power of 25MWe or more, which is the required power consumption to operate the target ship. The cycle net power is defined as production power of a turbine generator minus the total power consumption of two compressors. As shown in flowchart, the cycle net power was calculated twice in the middle of design process to ensure whether the requirements are met or not. And then, sensitivity studies on cycle thermal efficiency were conducted with two major independent variables to derive optimum design that maximizes cycle thermal efficiency. Finally, the cycle thermal efficiency of the cases was calculated and the optimal cycle design was determined by comparing the efficiency.

Table 4. Comparison of design parameters of ABTR from ANL report and DWSIM simulation

Parameters	ABTR report	DWSIM simulation	Unit
CO_2 mass flow rate	1377	1377	kg/s
Thermal power	250	247.7	MWth
TB generated power	156.4	158.6	MWe
MC required power	27.9	30.0	MWe
RC required power	27.1	30.1	MWe
Cycle net power	101.4	98.5	MWe
Cycle efficiency	39.1	39.8	%

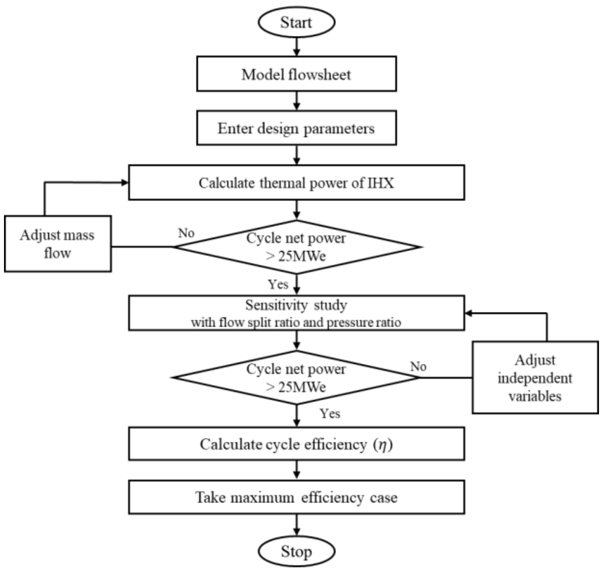

Figure 3. Modeling and Simulation flowchart

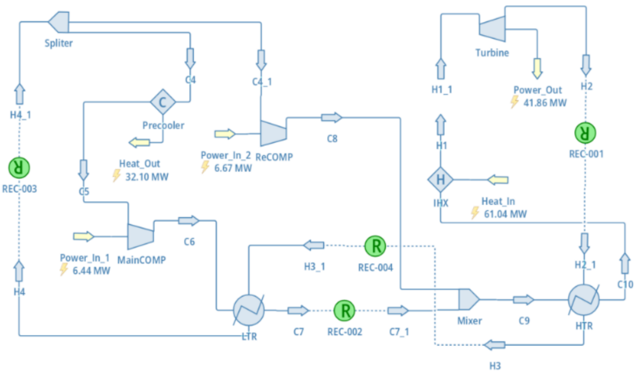

Figure 4. DWSIM flowsheet of the SCBC

The sensitivity study for flow split ratio ('a') was conducted by increasing from 0.5 to 0.9 by 0.02. As the flow split ratio is increased, the sum of compressor power consumption is gradually decreased. However, the cycle thermal efficiency does not keep increasing with the flow split ratio and picks the highest point at 0.7 and then decreases again. It is because when the flow split ratio exceeds 0.7, the heat load of IHX should be larger to maintain the basic constraint of TIT at 600°C.

As a results of the sensitivity studies above, the top 5 cases were organized in the order of high cycle thermal efficiency in Table 4. The optimal cycle design was determined by calculating and comparing changes in cycle thermal efficiency for the variables above. It was the case of pressure ratio 2.94 with 8.5 MPa of cycle minimum pressure and flow split ratio 0.7 as seen in first line of Table 4. From these design conditions, the generated power on turbine was calculated to be 41.49 MWe, while the required power of MC and RC is 6.07 and 6.29 MWe, respectively. Thus, the net power of the cycle is 29.13 MWe. The IHX should have the capacity to supply 60.97 MWth heat into SCBC, and the cycle thermal efficiency of the cycle was calculated to be 47.78%.

Table 5. Top 5 cases in order of cycle thermal efficiency

MC inlet pressure [MPa]	Pressure ratio	Flow split ratio ('a')	Cycle net power [MWe]	Cycle thermal efficiency [%]
8.5	2.94	0.7	29.13	47.78
8.6	2.91	0.7	29.03	47.75
8.4	2.98	0.7	29.17	47.74
8.7	2.87	0.7	28.91	47.71
8.3	3.01	0.7	29.17	47.70

4. Conclusion

In this study, SCBC for nuclear-powered ship using SMR as an energy source, the cycle was modeled and simulated using DWSIM, a process designing program. The basic model was carried out with the design requirement to stably produce 25MWe of power required for operating the reference ship and to obtain optimal efficiency. The layout of SCBC was designed as a recompression cycle that can maximize the efficiency of the recuperator. When the flow split ratio was 0.7 and the pressure ratio was 2.94, the optimal efficiency of 47.78% was obtained. It was about 12% higher than the efficiency of PWR-based SRC design of Hirdaris *et al.* [7]. It is also expected to enlarge the cargo space for the ship by utilizing SMR and SCBC as a powertrain of SMR tanker. Estimating the volume for the entire cycle to evaluate the cycle in terms of sizing requirements, transient analysis of SCBC considering load variation of nuclear-powered ships on sailing, detailed design of turbomachineries, e.g compressor, turbine) and heat exchanger e.g IHX recuperators, precoolers should be conducted in future work.

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