A Study on Supercritical CO_2 Brayton Cycle for a Molten Salt Reactor

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1. Introduction

Currently, research to apply the large supercritical carbon dioxide (s-CO_2) Brayton cycle to the 4th Generation Reactor (Gen-IV) is being carried out worldwide. Steam power generation systems used for existing power plants can cause internal safety problems as steam becomes hot and high pressure at turbine inlet temperatures above 550 ℃, On the other hand, gas turbine systems currently operating in the range of 900 ℃ or higher at the inlet of the turbine. Operating at under 900 ℃ at the inlet of the gas turbines is not competitive because the power generation efficiency is very low (35% or lower) In other words, the s-CO_2 Brayton cycle (SCBC) is attracting a lot of attention as a highly efficient and safe power generation system in the range of 500 to 900 ℃, which is the core outlet temperature range of the Gen-IV nuclear power plant. [1]

Molten Salt Reactor (MSR) is one of the Gen-IV models, and is currently being studied in many countries, including the U.S., China, and the U.K., with its high safety and excellent thermal efficiency. Currently, research on secondary systems with SFR and LFR in mind has made significant progress, but there is no complete study of large-scale s-CO_2 Brayton cycle (SCBC) for MSR. The MSR is expected to operate at higher temperatures than sodium–cooled fast reactor (SFR) and lead-cooled fast reactor (LFR) with operating temperature range of 500-750 degrees [2], with higher thermal efficiency and better cycle efficiency. The SCBC for MSR was designed by referring to the TMSR-LF1 model in China, which is currently the most advanced in MSR research.

In this study, our research team designed SCBC for MSR and confirmed its efficiency using Daniel Wagner Simulator (DWSIM), a plant design and simulation program, to evaluate whether SCBC is suitable as a secondary system of MSR.

2. Design of SCBC for MSR

2.1 Reference reactor: TMSR-LF1

TMSR-LF1 is a thorium molten salt reactor developed by Shanghai institute of Applied Physics (SINAP) in China. TMSR-LF1 is designed with thermal power of 395 MWth and electric power of 168 MWe. [3] The temperature of the molten salt released from the reactor is 700 ℃ and the turbine inlet temperature is 600 ℃. The mass flow rate of CO_2 is 1764 kg/s. However, we set the turbine inlet temperature up to 700 ℃ to improve cycle efficiency.

2.2 Design method of SCBC for MSR

Fig.1 shows the flow chart, which figure out the optimal cycle design using the DWSIM program. The initial values of cycle design are based on the TSMR-LF1. For the optimization process of the cycle, we considered heat exchanger Overall heat transfer coefficient(U), Heat exchanger area(A), and turbine inlet temperature. The other variables set to the same as the TSMR-LF1 initial values. Step3 is a variable adjustment process for turbine inlet temperature in the range of 600℃ to 700℃. Through these steps, we observe changes in the efficiency of the cycle and construct an algorithm that reaches the target efficiency of 45%.

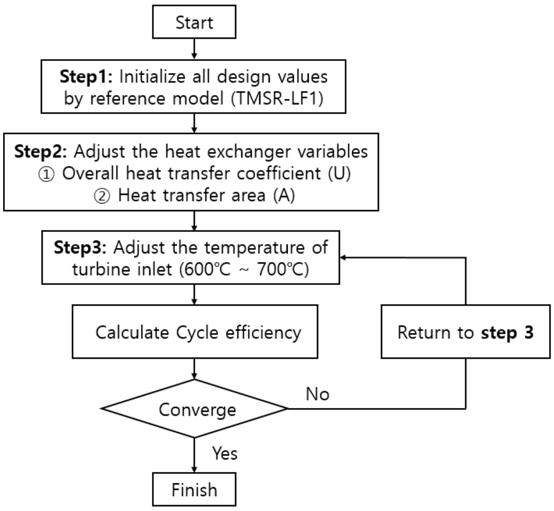

Fig. 1. Flow chart to design of SCBC for MSR

2.3 Design result of SCBC for MSR

Fig. 2 is a block diagram of SCBC for MSR. Fig. 3 is a schematic diagram of the cycle implemented by the DWSIM based on Fig 1. To achieve high cycle efficiency, it was designed as a Brayton cycle power conversion system with a recuperative and recompression cycle. There are two recuperators and one main compressor and one recompression compressor. [3] The recuperators were divided into low-temperature recuperator (LTR) and high-temperature recuperator (HTR) depending on the temperature to efficiently preheat or precool the CO_2. The recompression cycle forms a flow rate that can transfer high-temperature heat from low-pressure to high-pressure low-temperature side through flow distribution at the entrance of the recuperator. It can solve the problem of pinch points caused by the thermophysical properties of supercritical carbon dioxide and reducing the loss of heat emitted to the outside. These factors contribute to the rise in efficiency.

The process by which SCBC for MSR operates is as follows: CO_2 heated by the core at point 1 is decompressed by the turbine at point 2. CO_2 emitted from the turbine is cooled through a HTR and a LTR (points 3-4). After that, CO_2 is divided into half, some are cooled (point 5) before entering the main compressor (point 6), others are compressed again by re-compressor(point 10), then merged with CO_2 compressed by the main compressor (point 8), and re-entered into the HTR.

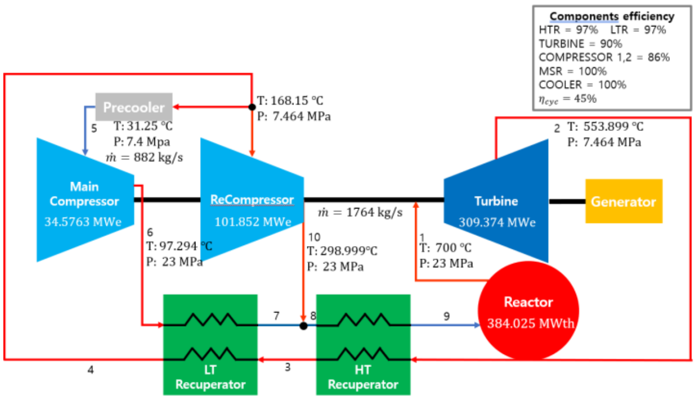

Fig. 2. Layout of SCBC for MSR

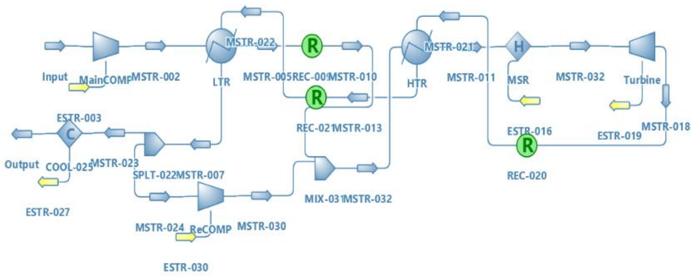

Fig. 3. Schematic diagram of design of SCBC for MSR using DWSIM

3. Simulation Results and Performance Evaluation of SCBC for MSR

Design conditions input in DWSIM for cycle design are summarized in this Table 1. Table 2 shows the design results and cycle performance calculated on DWSIM. The design parameters about the turbomachinary components and heat exchangers are established by referring to studies on the design of power conversion systems based on SFR and LFR. [4, 5] The basic assumption of this study is that all simulation measurements are in the steady state conditions, and that there are no heat or pressure losses in the pipe and heat exchanger.

Simulation results from Table 2 show that designed SCBC for MSR has a thermal power of 386.648 MWth and produce electric net power of 173.7 MWe and the cycle net efficiency is 45%. This is almost identical to the conceptual design content of the reference model TMSR-LF1, 395 MWth of thermal power and 168 MWe of electric power output. And the efficiency also showed better results than the expected efficiency of 42–43%.

Table 1. Cycle design conditions of SCBC for MSR(Input data to DWSIM)

Mass flow rate of CO_2	[kg/s]	1764
Initial pressure of CO_2	[MPa]	7.4
Initial temperature of CO_2	[℃]	31.25
Turbine inlet temperature	[℃]	700
Turbine outlet pressure	[MPa]	7.4
Compressor outlet pressure	[MPa]	23
HTR overall heat transfer coefficient	[W/$m^2\cdot$K]	1341
LTR overall heat transfer coefficient	[W/$m^2\cdot$K]	1241
TB adiabatic efficiency	[%]	90
Main compressor adiabatic efficiency	[%]	85
Recompressor adiabatic efficiency	[%]	85
HTR heat transfer efficiency	[%]	97
LTR heat transfer efficiency	[%]	97

Table 2. Performance of SCBC for MSR

Thermal input power	[MWth]	386
Turbine generated power	[MWe]	311.5
Main compressor required power	[MWe]	34.6
Recompressor required power	[MWe]	103.2
Cycle net power	[MWe]	173.7
HTR heat exchange area	[m^2]	25587.8
LTR heat exchange area	[m^2]	7712.55
Cycle net efficiency	[%]	45

To reduce the size of the power generation system, it was designed to consider printed circuit heat exchanger (PCHE) rather than conventional shell and tube heat exchangers. As a next-generation heat exchanger, PCHE can be manufactured on a scale of 1/10 of that of shell and tube heat exchangers and can be applied to fluids in ultra-high temperatures (900 °C) and ultra-high pressures (150 MPa). Overall heat transfer coefficient (*U*) and Heat exchange area (*A*) is configured by referring to the study of Bartel, N. et al. (2015). [6]

Generally, PCHE has a *U* of 300-700 [W/$m^2\cdot$K], but according to Bartel, N. et al. (2015), if the flow path in the heat exchanger is shaped like a zigzag rather than a straight line, it will improve to approximately 1,300 [W/$m^2\cdot$K]. Based on these research facts, the flow paths of heat exchanger were designed assuming a zigzag channel PCHE for cycle design at DWSIM.

Fig. 4 is a T-S diagram of the SCBC for MSR and Table 3 represents the material properties of CO_2 in each point of the designed SCBC for MSR. Both the CO_2 material properties in Table 3 and the T-S diagram in Fig. 3 are obtained from the National Institute of Standards and Technology (NIST)'s MINI-REFPROP program.

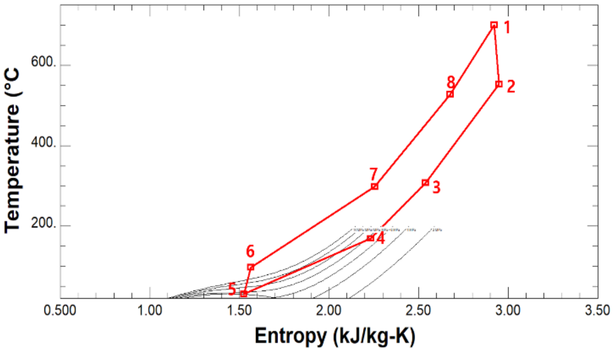

Fig. 4. Temperature-entropy diagram of designed SCBC for MSR

Table 3. Specified state point of CO_2 in SCBC for MSR

	Temperature (℃)	Pressure (MPa)	Density (kg/m^3)	Entropy (kJ/kg-K)
1	700.00	23.000	118.91	2.9222
2	552.86	7.4000	46.948	2.9489
3	307.80	7.4000	68.811	2.5394
4	169.37	7.4000	96.977	2.2331
5	31.250	7.4000	368.61	1.5247
6	97.294	23.000	563.52	1.5637
7	298.10	23.000	221.46	2.2562
8	527.83	23.000	146.43	2.6771

4. Conclusion and further works

This work shows the evaluation results of the performance and suitability of whether the s-CO_2 Brayton cycle is applicable to the MSR model. To verify the feasibility of MSR application of the s-CO2 Brayton cycle, we figure out MSR secondary system simulation results with DWSIM, a plant design and simulation program. For cycle design, we refer to TMSR-LF1, one of MSR prototype models in China. TMSR-LF1 is designed with thermal power of 395 MWth and electrical power of 168 MWe. Simulation results show that the designed cycle has a thermal power of 386.648 MWth, with 174.4 MWe generating electric power. The net efficiency of the cycle is 45% when the turbine inlet temperature is 700°C. This is similar to the conceptual design of the reference model, 395 MWth of thermal power and 168 MWe of electric power output. The efficiency was also better than 42-43% expected to TMSR-LF1. These experimental results show that the SCBC cycle is suitable as a secondary system of MSR.

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