Application of Trans-Critical CO_2 power conversion system in MicroURANUS

Sungwook Choi [a], Bong Seong Oh [a], Jeong Ik Lee [a*]
[a]*Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong Yuseong-gu,Daejeon 305-701, Republic of Korea*
[*]*Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

MicroURANUS is a 60 MW_{th} lead-cooled micro modular reactor, which could be used for propulsion of ships sailing in Northern Sea Route. Because of the limited area on-board, power conversion system should only include small sized components with adequate thermal efficiencies. The power conversion system for the nuclear reactor consists of variety thermodynamic cycle designs, such as steam Rankine cycle and gas Brayton cycle. Due to the large sized components used in the steam Rankine cycle, the gas Brayton cycle was chosen for the power conversion system of MicroURANUS.

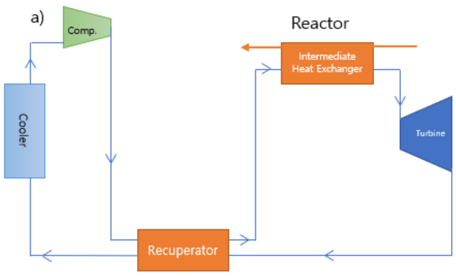
According to Dostal, supercritical carbon dioxide Brayton cycle (S-CO_2 cycle) is compact yet has suitable thermal efficiency [1]. Supercritical carbon dioxide has low compressibility near its critical point (7.38 MPa, 31°C), which causes the reduction of compressor work substantially compared to the existing gas Brayton cycle. As a result, the thermal efficiency of S-CO_2 Brayton cycle is higher than those of Brayton cycles using different gases, such as helium and nitrogen [2].

In the case of MicroURANUS, the ultimate heat sink is Northern Sea, with the average water temperature range from -2°C to 5 °C. Since the sea water temperature is far less than the critical temperature of supercritical carbon dioxide (31°C), trans-critical carbon dioxide (TC-CO_2) Rankine cycle is more suitable for the power conversion system of MicroURANUS. In this paper, application of TC-CO_2 cooled power conversion system in MicroURANUS was analyzed using GAMMA$^+$.

2. Methods and Results

2.1 Cycle Layout Selection

Among the variety of different TC-CO_2 Rankine cycle layouts, three cycle layouts were selected as the candidates: simple recuperated, recompression, and precompression-recompression. These three candidates were evaluated by their simplicity, thermal efficiency, and control variables (i.e. number of components).



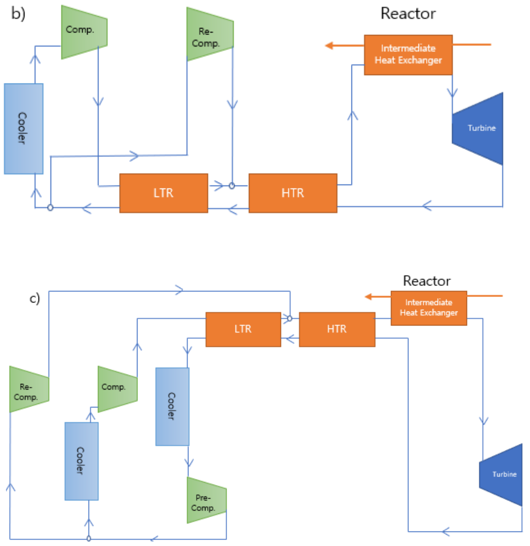


Figure 1. Layout of a) simple recuperated cycle b) recompression cycle c) Precompression-recompression cycle

In perspective of simplicity, the simple recuperated cycle is the simplest cycle among the candidates. Then, the recompression cycle and precompression-recompression cycle follow, respectively. To be used in the MicroURANUS, the simplicity of the cycle is considered to be an important factor due to the limited volume on the vessel. Therefore, the precompression-recompression cycle is not suitable.

For thermal efficiency and control variables, the recompression cycle is superior to the simple recuperated cycle, because the recompression cycle has two recuperators, while the simple recuperated cycle only has one. Thus, the recompression cycle was selected for the layout of the TC-CO_2 Rankine cycle.

2.2 Cycle Optimization

To calculate the design parameter of the recompression cycle, KAIST CCD, in-house MATLAB code for the cycle optimization, was used [3]. For the calculation, the effectiveness of the recuperators, compressors, and turbine were assumed to be 95%, 82% and 93%, respectively. The net efficiency of the cycle after the optimization process is 32.9%. The cycle efficiency seems quite low for the TC-CO_2 cycle, but considering that the reactor outlet temperature is about 350°C, which is similar to reactor outlet temperature of LWR, the cycle efficiency is reasonable. The detailed result of the cycle optimization using KAIST CCD is compared with the result from GAMMA+ in Table 1 on the later section.

2.3 GAMMA+ Model

GAMMA+, General Analyzer for Multi-component and Multi-dimensional Transient Application, is a code developed by Korea Atomic Energy Research Institute to analyze the Very High Temperature Reactor (VHTR) [5]. Originally, GAMMA+ code was not capable of analyzing the S-CO_2 cycle, because it did not have corresponding fluid properties. Currently, the information required for the analysis of S-CO_2 and TC-CO_2 cycles are included in the GAMMA+ code with work of Oh [4,6]. Consequently, GAMMA+ code is now capable to analyze TC-CO_2 power conversion system in MicroURANUS.

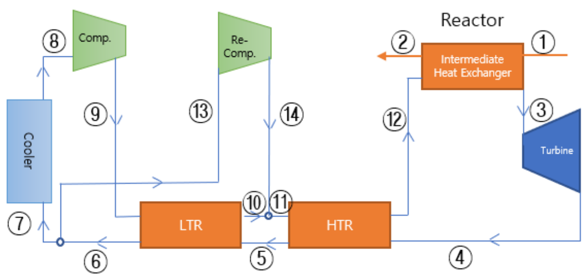


Figure 2. Design parameter check points for the recompression cycle

Table 1. Results from KAIST CCD and GAMMA+

Code / Point	KAIST CCD		GAMMA+	
	Temp (°C)	Pres (MPa)	Temp (°C)	Pres (MPa)
1	350.0	-	350.0	-
2	250.0	-	251.8	-
3	327.0	14.7	327.1	14.7
4	243.6	6.5	243.6	6.5
5	114.5	6.33	116.4	6.23
6	35.4	6.2	35.8	6.18
7	35.4	6.2	35.8	6.18
8	15.0	6.15	15.1	6.16
9	25.4	14.85	25.6	14.96
10	107.4	14.85	109.2	14.94
11	109.0	14.85	110.8	14.93
12	207.3	14.72	208.2	14.88
13	35.4	6.2	35.8	6.18
14	110.3	14.9	112.3	14.93

As shown in Figure 2, design check points 1 and 2 are in the primary side. It is given that the inlet and outlet temperature of the intermediate heat exchanger is 250°C and 350°C, respectively. Because the full analysis of primary side of MicroURANUS is out of scope for this paper, the pressure of the primary side is removed from the result. The total mass flow rate of CO_2 is 412.0 kg/s and the split ratio between points 6 and 7 is 0.48345.

Table 1 indicates that the result from the GAMMA+ corresponds to the result of KAIST CCD, which suggests the net efficiency of 32.9% for the power conversion system with TC-CO_2 recompression Rankine Cycle.

3. Summary and Future works

To analyze TC-CO_2 power conversion system of MicroURANUS, GAMMA+ code was applied. The analysis shows that the power conversion system reaches near the cycle optimization parameters, which allows the net cycle efficiency of 32.9% in MicroURANUS condition. For the future work, the primary side of MicroURANUS should be modeled using GAMMA+, so that the full transient of MicroURANUS can be simulated.

Acknowledgement

This research was supported by the National Nuclear R&D program funded by Ministry of Science and ICT and by the National Nuclear R&D program (NRF-2019M2D1A1067204) organized by the National Research Foundation (NRF) of South Korea in support of the Ministry of Science and ICT.

REFERENCES

[1] V. Dostal, M. J. Driscoll, and P. Hejzlar, "A supercritical carbon dioxide cycle for next generation nuclear reactors," USA: Massachusetts Institute of Technology, vol. MIT-ANP-TR-100, 2004.

[2] Gianfranco Angelino, "Carbon dioxide condensation cycles for power production, "Journal of Engineering for Power, vol. 90, pp. 287-295, 1968

[3] Min Seok Kim, Yoonhan Ahn, Beomjoo Kim,Jeong Ik Lee, “Study on the supercritical CO_2 power cycles for landfill gas firing gas turbine bottoming cycle” Energy, vol. 111, pp. 893-909, 2016

[4] Bong Seong Oh, Yonghee Kim, Sung Joong Kim, Jeong Ik Lee, “SMART with Trans-Critical CO2 power conversion system for maritime propulsion in Northern Sea Route, part 1: System design”, Annals of Nuclear Energy, vol 149, 2020

[5] “General Analyzer for Multi-Component and Multi-dimensional Transient Application-GAMMA+1.0 Volume 1,2: User’s and Theory manual,” Korea Atomic Energy Research Institute, 2014

[6] Bong Seong Oh, Jeong Ik Lee, Seong Gu Kim, Seong Kuk Cho, Hwanyeol Yu, “Transient analyses of S-CO2 cooled KAIST Micro Modular reactor with GAMMA+ CODE”, NUTHOS-11, 2016