Application of Open-Air Brayton Cycle to sCO_2-cooled KAIST Micro Modular Reactor

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1. Introduction

Since a Micro Modular Reactor (MMR) prioritizes transportability, it requires a compact and modular design. This allows for easy transportation, scalability, and installation, making it more cost-effective than traditional large-scale nuclear plants. The KAIST-MMR combines a 36 MW_{th} gas-cooled reactor core with a closed supercritical CO_2 (sCO_2) recuperated Brayton cycle, previously. To clarify, KAIST-MMR uses two types of coolants: pressurized CO_2 and air. The air is used as an ultimate heat sink to the pressurized CO_2 in the cooling loop, which necessitates a large CO_2-air heat exchanger [1].

Westinghouse is actively developing a microreactor with an open-air Brayton cycle, called eVinci [2]. The open-air Brayton cycle draws in air from the surrounding atmosphere and subsequently exhausts it after it has been expanded in the turbine. Due to simple architecture and not needing heat exchangers to reject heat, an aerospace and power industry widely uses the open-air Brayton cycle [3].

This study proposes a conceptual layout of the open-air Brayton cycle coupled with KAIST-MMR to replace sCO_2 cycle. To explore the benefit of the proposed concept, this study evaluates the thermal efficiency of the proposed concept first. Moreover, the thermal sizing of all heat exchangers is performed, to compare the heat exchanger volume of the proposed concept to that of the original sCO_2 power cycle concept.

2. Methods and Results

2.1 Conceptual layout of open-air Brayton cycle MMR

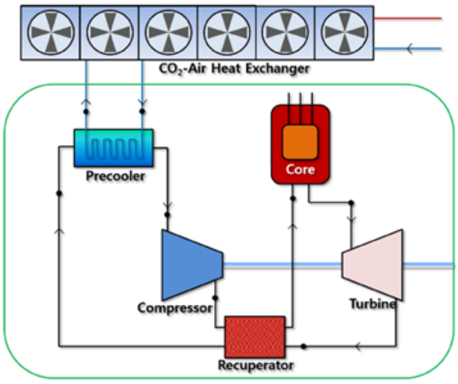

Fig. 1. Schematic diagram of the original KAIST-MMR. [1]

The original KAIST-MMR utilizes pressurized CO_2 as a coolant in the cooling loop that flows to the precooler, requiring a CO_2-air heat exchanger to cool down the pressurized CO_2, as illustrated in Figure 1. As a result of this, the size of the nuclear system is compact but the footprint of the whole system would inevitably increase.

To avoid the need for an external heat exchanger for heat rejection to an ultimate heat sink, the application of an open-air Brayton cycle is proposed in this study, and its schematic is depicted in Figure 2. In order to compare the thermal efficiency and the total volume of heat transfer equipment, it was assumed that the reactor core and other components are identical to those used in the original KAIST-MMR. Based on the cycle configuration shown in Figure 2, efficiency optimization and the design of heat exchanger were performed.

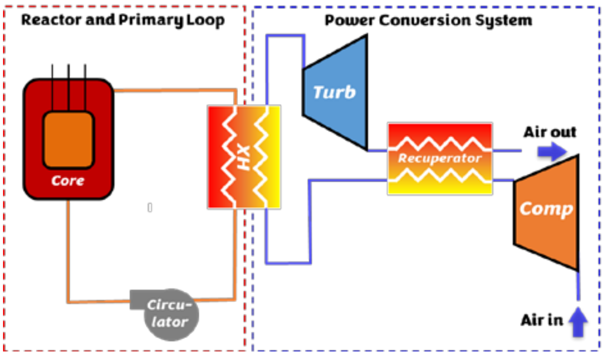

Fig. 2. Schematic of a newly proposed MMR system with an open-air Brayton cycle.

2.2 Cycle optimization

The design parameters of the power conversion system in Figure 2 were optimized using KAIST-OCD (Open Cycle Design) code. Figure 3 outlines the algorithm used in the in-house KAIST-OCD code. The design parameters listed in Table 1 were chosen and utilized to optimize the open-air Brayton cycle MMR based on the previous research works [1, 4, 5]. This included assuming a pinch point temperature difference of 10K, which represents the temperature difference between the hot side inlet and the cold side outlet of the heat exchanger. As a result, turbine inlet temperature was set at 540 ℃.

Table 1. Design parameters of an open-air Brayton cycle MMR. [1, 4, 5]

Min temperature	15 ℃
Turbine inlet temperature	540 ℃
Thermal heat	36.18 MW_{th}
Compressor inlet pressure	101.325 kPa

Turbine efficiency	91.9 %
Compressor efficiency	84.9 %
Recuperator effectiveness	0.92
HX cold side ΔP ratio	0.03
Recuperator hot side ΔP ratio	0.01
Recuperator cold side ΔP ratio	0.01
Ratio of exhaust pressure to atmospheric pressure	0.98

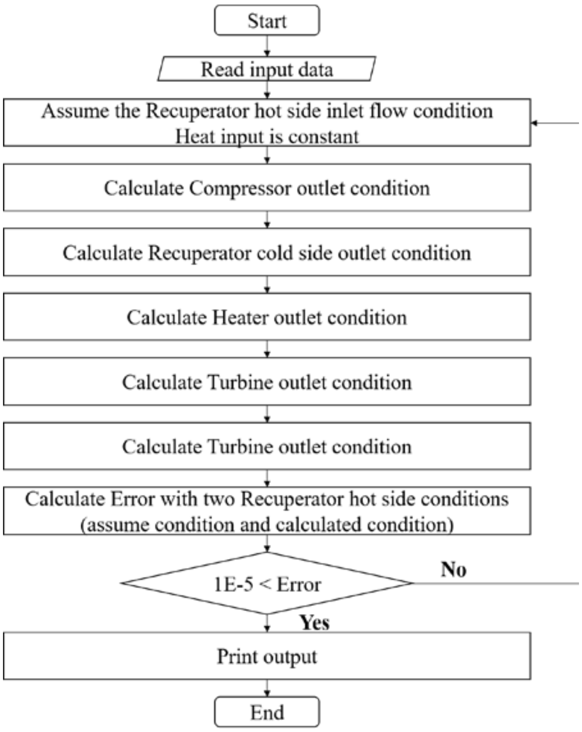

Fig. 3. Algorithms of KAIST-OCD code.

From the optimization process, the open-air Brayton cycle MMR was found to have a maximum thermal efficiency of 31.47%, as shown in Figure 4. In comparison with the KAIST-MMR system, which uses a closed sCO_2 Brayton cycle, the thermal efficiency of the open-air Brayton cycle MMR was lower by approximately 3%. The difference in efficiency is attributed to the fact that the optimal pressure ratio for the open-air Brayton cycle MMR was lower than that of the original KAIST-MMR system.

It is noteworthy that the maximum thermal efficiency of 31.47% can be achieved in an open-air Brayton cycle because the minimum temperature in the power conversion system is set to be 15℃, which is 45℃ lower than the minimum temperature of KAIST-MMR. If the minimum temperature in the open-air Brayton cycle were the same as KAIST-MMR, the maximum thermal efficiency would be 23.64%, as shown in Figure 4.

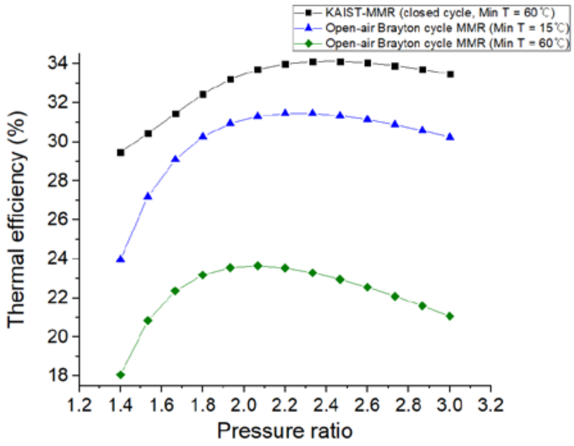

Fig. 4. Thermal efficiencies of KAIST-MMR and open-air Brayton cycle MMR with respect to pressure ratio.

The operating conditions of the power conversion system were determined based on the maximum efficiency calculation and are shown in Figure 5. Using the temperature and pressure at each point in the system, as well as the mass flowrate of air, the design of heat exchangers was conducted.

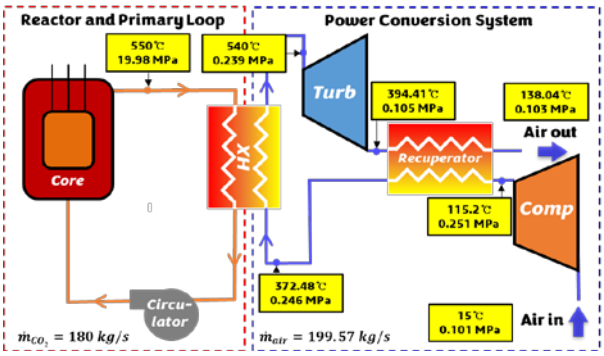

Fig. 5. Operating conduction of open-air Brayton cycle MMR.

2.3 Heat exchanger design

This study assumed using a straight channel PCHE heat exchanger for recuperator. The design was conducted with KAIST-HXD in-house code, which is a MATLAB-based one-dimensional Finite Difference Method (1D-FDM) code. The design parameters of the heat transfer equipment were established based on the previous work and are listed in Table 2 [1]. With the design parameters summarized in Table 2, the volumes of heat exchangers in the proposed open-air Brayton cycle MMR were decided, and the results are presented in Table 3. The total volume of the heat transfer equipment used in the proposed open-air Brayton cycle MMR is determined to be 179.51 m^3. It is noteworthy that the volume is around 45% smaller than that of the heat transfer equipment utilized in the original KAIST-MMR as shown in Table 4.

Table 2. Design parameters of heat transfer equipment in an open-air Brayton cycle MMR.[1]

Heat exchanger	
Heat load	36.18 MW_{th}
hot side mass flow rate	180 kg/s
hot side inlet Temperature	550 ℃
Effectiveness	0.95
$\Delta T_{pinch\ point}$	10 K
Recuperator	
mass flow rate	199.57 kg/s
hot side inlet Temperature	394.41 ℃
cold side inlet Temperature	115.2 ℃
Effectiveness	0.92

Table 3. The calculated values of heat transfer equipment in an open-air Brayton cycle MMR using KAIST-HXD.

Parameters	Heat exchanger	Recuperator
Number of hot side channel	608000	1520000
Number of cold side channel	1216000	1520000
Hot channel diameter (mm)	2	7
Cold channel diameter (mm)	5.3	5
Volume (m^3)	47.98	131.53

Table 4. type and volume of heat transfer equipment in the KAIST-MMR. [1, 6]

Precooler	Type	PCHE
	Volume (m^3)	0.50744
Recuperator	Type	PCHE
	Volume (m^3)	0.69265
CO_2-air HX	Type	Finned tube
	Volume (m^3)	322.7
Total volume (m^3)		323.90009

3. Conclusions and Further Works

This research proposed and optimized the cycle layout of an open-air Brayton cycle MMR. The optimized thermal efficiency was found to be 31.47%, and this value is lower than the thermal efficiency of the original KAIST-MMR using sCO_2 power cycle by approximately 3% due to the lower optimum pressure ratio. Additionally, this study evaluated and compared the total volume of heat transfer equipment used in the two systems. This effort revealed a possible reduction of volume by 45% for the proposed open-air Brayton cycle MMR concept. Therefore, the open-air Brayton cycle MMR is deemed to have better transportability than the original KAIST-MMR.

As for the future research, the study aims to explore other heat exchanger types for air recuperator such as Plate Heat Exchanger (PHX) or Plate Fin Heat Exchanger (PFHE). Furthermore, it will be assessed that the viability and the potential of using an open-air Brayton cycle for MMR if the applications are for ship propulsion and other off-grid energy supply.

ACKNOWLEDGEMENTS

This work is supported by the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant RS-2022-00143652).

REFERENCES

[1] Oh, B.W. “Safety Analysis and Development of Control Logic of KAIST Micro Modular Reactor with GAMMA+ code”, Korea Advanced Institute of Science and Technology (Thesis), 2017.

[2] Swartz, M.M.; Byers, W.A.; Lojek, J.; Blunt, R. Westinghouse eVinci™ Heat Pipe Micro Reactor Technology Development. In *International Conference on Nuclear Engineering*; American Society of Mechanical Engineers: New York, NY, USA, 2021; Volume 85246

[3] Choi, S.; Son, I.W.; Lee, J.I. Comparative Performance Evaluation of Gas Brayton Cycle for Micro–Nuclear Reactors. *Energies* 2023, *16*, x.

[4] Kays, William Morrow, and Alexander Louis London. "Compact heat exchangers." (1984).

[5] Zohuri, Bahman.; Pat McDaniel, and Cassiano de Oliveira. Advanced Nuclear Open Air-Brayton Cycles for Highly Efficient Power Conversion, *Nuclear Technology*, Volume 192 issue 1, 2015, pp. 48-60.

[6] Kim, S. G.; et al. A concept design of supercritical CO2 cooled SMR operating at isolated microgrid region. *International Journal of Energy Research* 41.4 (2017): pp. 512-525.