Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Exergy-Based Optimization of Helium Intercooling Cycle for MSR Application

Sungwook Choi [a], Jeong Ik Lee [a*]
[a]*Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 291, Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea*
[*]*Corresponding author: jeongiklee@kaist.ac.kr*

***Keywords :** Molten Salt Reactor, Intercooling Cycle, Cycle Optimization, Exergy Analysis

1. Introduction

Molten Salt Reactors (MSRs) have gained attention as advanced nuclear systems due to their inherent safety and high-temperature (~650℃) operation. A key component in MSRs is the off-gas system, which removes fission gas products from the reactor. This system typically utilizes helium bubbling, where helium is continuously supplied to the molten salt to facilitate gas removal [1]. Since the MSR already requires a dedicated helium supply system, leveraging this infrastructure for a helium-based power conversion system presents a practical and efficient approach. Among various thermodynamic cycles, the helium intercooling cycle is recognized as one of the most efficient configurations [2, 3]. The use of helium, with its high thermal conductivity and low molecular weight, further contributes to minimizing aerodynamic losses and maximizing efficiency.

Traditional cycle optimization approaches have primarily focused on maximizing thermal efficiency. Another widely used criterion in cycle optimization is maximizing specific work, which refers to the useful work output per unit mass of the working fluid. Both of these criteria are often considered independently, but each has its advantages in terms of energy utilization and system performance. However, these approaches do not fully account for exergy destruction rate, which represents irreversibility in the cycle and impacts the system's ability to effectively use the available energy. Exergy analysis provides a more comprehensive approach, as it helps identify the trade-off between efficiency, specific work, and entropy generation.

This study compares three optimization criteria for the helium intercooling cycle in MSR application:

1. Maximum cycle efficiency
2. Maximum specific work
3. Minimum exergy destruction rate

By evaluating these three criteria, the analysis aims to determine whether conventional optimization methods align with exergy minimization, or if different optimal points emerge when irreversibility is considered. The results contribute to a more refined understanding of cycle design strategies that enhance energy utilization and system sustainability in MSR applications.

2. Methods and Results

2.1 Cycle Optimization

This study targets a $100MW_{th}$ K-MSR (Korea-Molten Salt Reactor), which serves as the heat source for applying the helium intercooling cycle [4]. The molten salt used for K-MSR is $NaCl$-KCl-$MgCl_2$ (15.11-38.91-45.98 wt%). The turbine inlet temperature of the cycle was set to 635℃, considering the reactor outlet temperature and an appropriate pinch temperature between the intermediate heat exchangers [5]. The operating pressure and the minimum temperature of the helium cycle was set to 8.0 MPa and 26℃, which are the operating condition of GT-MHR [3]. Table I shows the basic input condition for the helium intercooling cycle. To perform the optimizations and compare the results, the KAIST-CCD code is utilized.

Table I. Cycle Input Condition

Parameter	Value
Thermal Load [MW_{th}]	100
Max Temperature [℃]	635
Min Temperature [℃]	26
Max Pressure [MPa]	8.0
Turb Efficiency [%]	92
Comp Efficiency [%]	90
Recuperator Effectiveness [%]	95

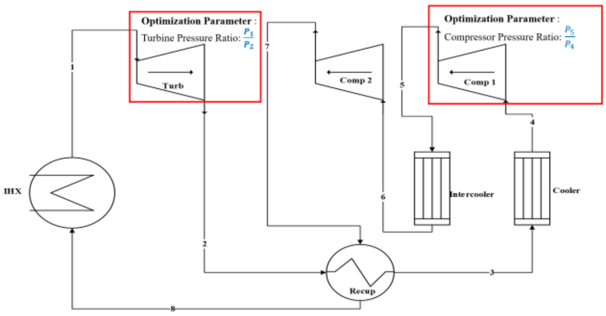

Fig. 1. Intercooling cycle layout and optimization parameter

The design parameters, as outlined in Table I are incorporated into the code input. In the cycle optimization process, the pressure ratio for both the turbine and low-pressure compressor (comp1) is varied, shown in Fig. 1. The cycle's performance parameter, such as net efficiency, turbine work, and specific work, are calculated for each combination of turbine and low-pressure compressor pressure ratios. Subsequently, by evaluating the cycle efficiency and specific work calculated at each turbine and comp1 pressure ratios, the optimal operating point, corresponding to the highest vales, can be determined [6].

In addition to the conventional methods, an exergy destruction analysis has been incorporated. The exergy destruction rate is calculated using the following equations:

$$h_0 = s_0 = f(T_0, P_0)$$

$$Specific\ Exergy: \varepsilon_i = (h_i - h_0) - T_0(s_i - s_0) \tag{1}$$

$$Exergy\ flow: \dot{Ex}_i = \dot{m}\varepsilon_i \tag{2}$$

$$\dot{Ex}_{dest,\,Comp} = \dot{Ex}_4 + \dot{Ex}_6 + P_{Comp} - (\dot{Ex}_5 + \dot{Ex}_7) \tag{3}$$

$$\dot{Ex}_{dest,Turb} = \dot{Ex}_1 - (\dot{Ex}_2 + P_{turb}) \tag{4}$$

$$\dot{Ex}_{dest,Recup} = (\dot{Ex}_2 - \dot{Ex}_3) - (\dot{Ex}_8 - \dot{Ex}_7) \tag{5}$$

$$\dot{Ex}_{dest,cool} = \left(\dot{Ex}_3 - \dot{Ex}_4\right) - (\dot{Ex}_{wat,out} - \dot{Ex}_{wat,in}) \tag{6}$$

$$\dot{Ex}_{dest,intercool} = \left(\dot{Ex}_5 - \dot{Ex}_6\right) - (\dot{Ex}_{wat,out} - \dot{Ex}_{wat,in}) \tag{7}$$

$$\dot{Ex}_{dest,cycle} = \sum_{component\ i} \dot{Ex}_{dest,i} \tag{8}$$

For the reference state, the ultimate heat sink of the helium cycle is selected as water, with the reference temperature set to 17.3℃, the average sea temperature in South Korea, and the temperature difference in the cooling water is set to 30K [7]. Based on the temperature and pressure conditions at each component, the exergy destruction rate is calculated for each turbine and comp1 pressure ratio. However, for the intermediate heat exchanger, further research is required regarding the entropy of the molten salt. Therefore, exergy destruction rate for the intermediate heat exchanger was excluded from this study. Following the calculation of the respective cycle results using the aforementioned method, optimization was conducted and comparisons are made with respect to the maximum efficiency, maximum specific work, and minimum exergy destruction rate.

2.2 Results and Comparison

Table II. Cycle with maximum efficiency

Parameter	Value
Thermal Power [MW_{th}]	100.0
Net Work [MW_e]	40.276
Cycle Efficiency [%]	40.276
Mass Flow Rate [kg/s]	94.721
Turbine Pressure Ratio	1.872
Comp1 Pressure Ratio	1.409
Comp2 Pressure Ratio	1.454
Exergy Destruction Rate[MW]	20.067
Specific Work [MJ/kg]	0.425

Table III. Cycle with maximum specific work

Parameter	Value
Thermal Power [MW_{th}]	100.0
Net Work [MW_e]	33.162
Cycle Efficiency [%]	33.162
Mass Flow Rate [kg/s]	55.463
Turbine Pressure Ratio	3.692
Comp1 Pressure Ratio	2.102
Comp2 Pressure Ratio	2.030
Exergy Destruction Rate [MW]	23.665
Specific Work [MJ/kg]	0.598

Table IV. Cycle with minimum exergy destruction rate

Parameter	Value
Thermal Power [MW_{th}]	100.0
Net Work [MW_e]	39.861
Cycle Efficiency [%]	39.861
Mass Flow Rate [kg/s]	85.084
Turbine Pressure Ratio	2.068
Comp1 Pressure Ratio	1.374
Comp2 Pressure Ratio	1.658
Exergy Destruction Rate [MW]	19.716
Specific Work [MJ/kg]	0.469

Table II, Table III and Table IV present the cycle optimization results according to the methods previously described, maximum efficiency, maximum specific work, and minimum exergy destruction rate.

There is a significant difference between the optimization methods when considering maximum efficiency and specific work. The most notable distinction lies in the efficiency. The method optimized for maximum efficiency achieves an efficiency of approximately 40%, while the optimization for specific work results in an efficiency of around 33%, similar to the operating efficiency of a light-water reactor (LWR) with a lower operating temperature. However, the specific work optimization allows for a higher pressure ratio in the turbomachinery, which leads to a reduction in mass flow rate. As a result, the required size of the component can be reduced to maintain the same performance, which can contribute to a reduction in design and manufacturing costs.

Regarding the exergy destruction rate, the optimization method based on minimum exergy destruction shows the lowest exergy destruction rate compared to the other methods. The optimization based on the minimum exergy destruction rate achieves an efficiency of approximately 39.8%, which is similar to the maximum efficiency optimization. This indicates that the 100 MW_{th} from the K-MSR is effectively converted into useful work. However, the key difference between these two methods lies in the turbine and compressor pressure ratios. The exergy destruction rate minimization method results in larger pressure ratios, which consequently reduces the mass flow rate and increase the specific work.

Fig. 2, 3, and 4 illustrates the corresponding T-S diagrams and show the variations in net efficiency and specific work with respect to the turbine pressure ratio.

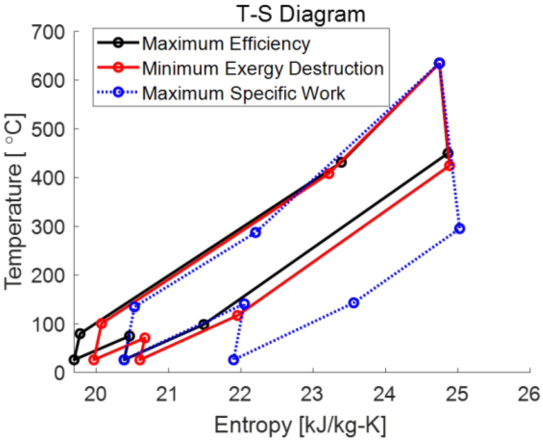

Fig. 2. T-s Diagram for each optimization method

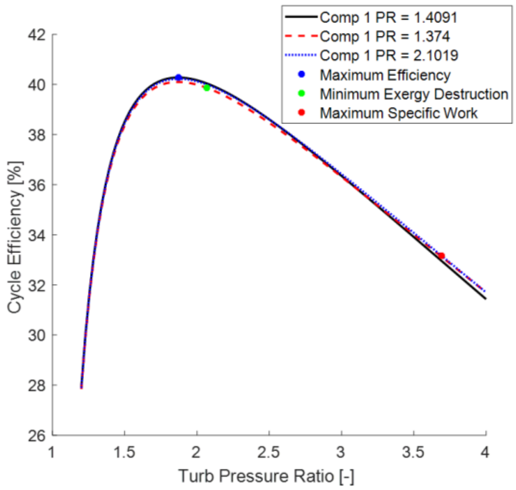

Fig. 3. Cycle efficiency for each optimization method

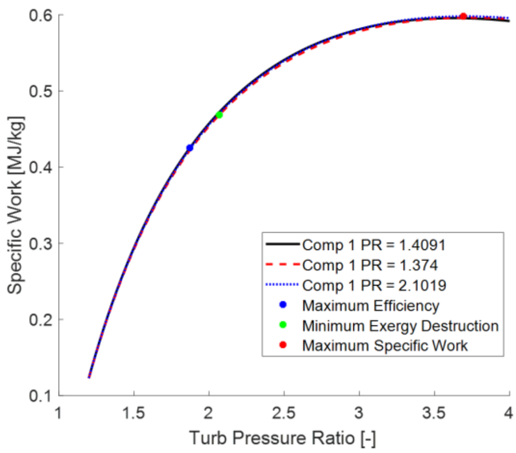

Fig. 4. Specific work for each optimization method

3. Summary and Conclusions

This study compares three optimization criteria for the helium intercooling cycle in MSRs: maximum cycle efficiency, maximum specific work, and minimum exergy destruction rate.

The results show that the maximum efficiency method yields an efficiency of approximately 40% while optimizing for specific work results in around 33%. Exergy destruction rate minimization achieves a similar efficiency but requires larger turbine and compressor pressure ratios, leading to reduced mass flow rate. Higher pressure ratios for turbomachinery are more challenging in design due to the need for more stages in the turbomachinery. Thus, the study concludes that although both maximum efficiency and minimum exergy destruction rate optimization methods yield similar efficiencies, maximizing cycle efficiency provides a more practical and cost-effective solution for K-MSR application. Therefore, the maximum efficiency optimization is recommended for practical applications.

NOMENCLATURE

Symbol [Unit]	Definition
$\varepsilon\ [\frac{J}{kg}]$	Specific Exergy
$h\ \left[\frac{J}{kg}\right]$	Enthalpy
$T\ [K]$	Temperature
$S\ \left[\frac{J}{kg-K}\right]$	Entropy
$\dot{Ex}\ [W]$	Exergy Rate
$\dot{m}\ \left[\frac{kg}{s}\right]$	Mass Flow Rate
$\dot{Ex}_{Dest}\ [W]$	Exergy Destruction Rate
Subfix	
i	Cycle point
Wat,in/out	Water inlet/outlet

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government (MSIT) (No. RS-2024-00457356)

REFERENCE

[1] W. J. Choi, J. H. Park, J. Lee, J. In, Y. Cho, Y. Kim and S. J. Kim, "Experimental and Numerical Assessment of Helium Bubble Lift During Natural Circulation for Passive Molten Salt Fast Reactor," *Nuclear Engineering and Technology*, vol. 56, no. 3, pp. 1002-1012, 2024.

[2] C. Sánchez, R. Juárez, J. Sanz and M. Perlado, "Design and analysis of helium Brayton power cycles for HiPER reactor," *Fusion Engineering and Design*, vol. 88, no. 9-10, pp. 2679-2683, 2013.

[3] Rolls-Royce plc., "Preliminary Assessment of the GT-MHR Power Conversion System," Rolls-Royce plc, 2007.

[4] D. Yeo, C. Lee and G.-H. Koo, "Parametric study of the fuel salt drain system design of K-MSR," in *Transactions of the Korean Nuclear Society Spring Meeting*, Jeju, Korea, 2024.

[5] I. W. Son, S. Choi, Y. Jeong and J. I. Lee, "Design study of heat transport and power conversion," *International Journal of Energy Research,* vol. 46, pp. 15441-15462, 2022.

[6] S. Choi, I. W. Son and J. I. Lee, "Comparative Performance Evaluation of Gas Brayton Cycle for Micro–Nuclear Reactors," *Energies,* vol. 16, no. 4, p. 2065, 2023.

[7] The Korea Times, 10 January 2025. [Online]. Available: https://www.koreatimes.co.kr/www/nation/2025/02/113_390039.html. [Accessed 9 March 2025].