

Thermodynamic Analysis of S-CO₂ Brayton Coupled to an HTGR

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1. Introduction

The High-Temperature Gas-Cooled Reactor (HTGR) is a type of fourth-generation nuclear reactor designed to achieve a core outlet temperature of 750 to 900°C, which is significantly higher than the 280 to 320°C steam outlet temperatures of conventional Pressurized Water Reactor (PWR) based light-water reactors. From the perspective of Carnot efficiency based on the Second Law of Thermodynamics, this characteristic implies the possibility of constructing a power generation system with much higher efficiency than existing ones. However, in the Rankine cycle power generation systems widely used in current power plants, it is difficult to fully realize these benefits due to losses that occur during the phase change process of water.

To solve these issues and fully utilize the benefits of high temperatures, this paper aims to study an HTGR system integrated with a supercritical carbon dioxide (S-CO₂) cycle, which operates in a single phase without a phase change process. Due to their high efficiency at elevated temperatures, S-CO₂ cycle has been widely studied and commercially deployed as working fluids in power cycles under various high-temperature conditions beyond HTGRs. In the United States, the STEP (Supercritical Transformational Electric Power) project, led by the Southwest Research Institute (SwRI), demonstrated a 10 MW_{th} pilot plant operating under 500 °C conditions. By connecting the S-CO₂ cycle to the commercial power grid of Texas, the project verified the capability to supply 4 MW_e of electricity. And ongoing research aims to achieve a target efficiency of 50% [1]. In China, a commercial S-CO₂ cycle system led by the Nuclear Power Institute of China (NPIC) was deployed for the first time in Guizhou Province, utilizing waste heat generated from a steel plant to create a 600 °C environment. The configuration features two 15 MW generators, and it was announced that this technology achieved an 85% increase in efficiency and a 50% increase in net power generation compared to conventional systems [2].

To incorporate these research trends into the Korean HTGR design, the feasibility of applying the S-CO₂ cycle was evaluated using the performance parameters of HECTAR (HElium Cooled Thermal Application Reactor), which is currently under development by KAERI for heat supply applications.

Furthermore, if feasible, the study aims to assess cycle efficiency, compare it with existing systems, and identify the distinct advantages arising from its architectural and structural characteristics.

2. Methods and Results

In this study, the performance parameters of the HECTAR HTGR were obtained from publicly available data. A Python-based simulation was utilized to evaluate and verify the performance of each individual component.

2.1 HECTAR HTGR



Fig. 1. Drawing of HECTAR system designed by KAERI[3].

HECTAR is a HTGR currently under development by the Korea Atomic Energy Research Institute (KAERI), utilizing a graphite moderator and helium coolant. It has a thermal output of 90 MW_{th}, with helium coolant operating conditions set at an outlet temperature of 750°C [3].

Although HECTAR itself is being developed primarily for industrial heat supply, it is intended to serve as a reference model to evaluate the application of a S-CO₂ power conversion system when reactors with similar power outputs are built in the future.

2.2 KAIST – CCD

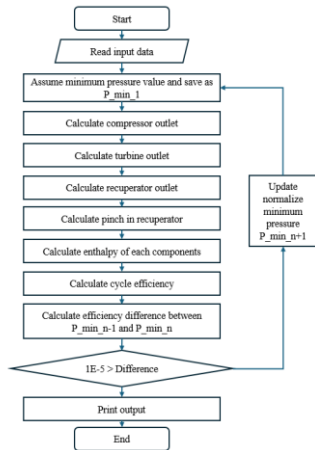


Fig 2. KAIST-CCD code algorithm

The KAIST-CCD (Closed Cycle Design) code is an in-house code designed to provide guidelines for cycle layout and design. It accepts various inputs, including the amount of external heat supplied to the cycle, the type of working fluid, the cycle layout, the maximum and minimum cycle temperatures, the maximum operating pressure, and component efficiencies. Using these inputs, the code calculates the outlet temperature and pressure of each component based on thermophysical data retrieved from the NIST REFPROP database [4].

The KAIST-CCD code optimizes the overall cycle by adjusting the P_{min} value while keeping the input conditions fixed. It identifies the optimal P_{min} that maximizes the net work balancing the reduced compressor work against the decreased turbine work as pressure rises to determine the final design points for each component.

2.3 Components design conditions

The efficiencies and effectiveness of the components utilized in this study are summarized in the table below. These design parameters will be used as input for the KAIST-CCD code to analyze the cycle.

Table 1. Parameters for components

Parameter	Value
Thermal Load [MW _{th}]	90
Max Temperature [°C]	750
Min Temperature [°C]	35
Max Pressure [MPa]	20
Turb Efficiency [%]	88
Comp Efficiency [%]	80
Recuperator Effectiveness [%]	95

In the previous studies, the maximum cycle pressure was set to 20 MPa based on research indicating peak turbine efficiency for a 750°C HTGR, as well as the design specification established by Dostal [5]. Component efficiencies 88% for the turbine, 80% for the compressor, and 95% heat exchanger effectiveness were

adopted from literature, using the lower bound of reported ranges to ensure a conservative analysis [6]. From the literature review, it was identified that the turbine efficiency ranged from 88% to 92%, the compressor efficiency ranged from 80% to 91%, and the heat exchanger effectiveness was set at 95%. To ensure a conservative evaluation, the lowest efficiency values from these ranges were selected for this study [7, 8].

2.4 Simple Brayton cycle

In this study, two types of $S\text{-CO}_2$ cycle layouts are utilized. The first is the simple Brayton cycle.

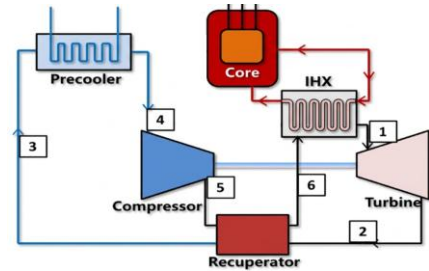


Fig. 3. A schematic diagram of simple Brayton cycle connected to core with IHx (Internal Heat eXchanger).

As shown in Figure 3, the simple Brayton cycle consists of a precooler, a recuperator, a compressor, and a turbine. An intermediate heat exchanger is implemented instead of a direct connection to the reactor core to prevent the mixing of fluids, as HECTAR utilizes helium while the power conversion system uses carbon dioxide. Due to its simple configuration, model implementation in the simulation code can be performed quickly, offering the advantages of short computational time and high reproducibility during actual implementation.

By using the KAIST-CCD code, the required mass flow rate of carbon dioxide was determined to be 568.43 kg/s. The inlet and outlet conditions for each component are presented in Table 2.

Table 2. Cycle inlet conditions for simple Brayton cycle

Component	T(°C)	P(MPa)	S(kJ/kg·K)	H(kJ/kg)
Turbine	700	19.7	2.95	1223.38
Recuperator (Cold)	634.69	12.10	2.96	1145.14
Precooler	57.44	11.95	1.53	373.81
Compressor	35.0	11.80	1.24	280.69
Recuperator (Hot)	47.28	20.0	1.25	293.72
IHX	573.99	19.85	2.78	1065.05

Based on the values in the table, a T-S diagram including isotherms was plotted to verify whether the

interconnected component parameters form a thermodynamically feasible cycle. The resulting graph is shown in figure 4.

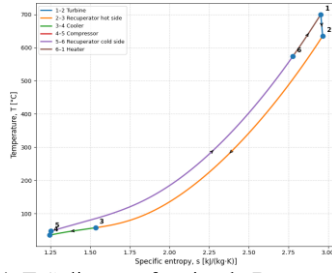


Fig 4. T-S diagram for simple Brayton cycle

Since the states observed across the individual components connect seamlessly with one another, it is confirmed that the operating conditions configured in the simulation can be practically implemented.

The reason the turbine inlet temperature, the carbon dioxide temperature after heat exchange with the high temperature helium, was set to 700°C is to maintain a cold end pinch temperature of 10°C while achieving a heat exchanger effectiveness of 95%. Since 90MW_{th} of heat is transferred, the carbon dioxide temperature drops to 574°C. Assuming a pinch temperature of 10°C, the helium temperature at outlet could be 584°C. Then, the effectiveness is close to 0.95, which is realizable value.

$$\varepsilon = \frac{T_{h,in} - T_{h,out}}{T_{h,in} - T_{c,in}} = \frac{750 - 584}{750 - 574} = 0.9432 \sim 0.95$$

Based on the values in Table 2, the required compressor power per unit time was calculated to be 7.41 MW, and the energy produced by the turbine was 44.47 MW, resulting in a cycle efficiency of 41.18%. To examine the fluid temperature pinch within the recuperator for this cycle, the profile is presented in figure 5.

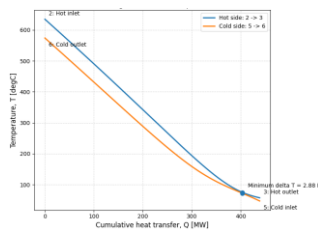


Fig 5. Temperature analysis of inside of heat exchanger

As shown in the figure, there exists a point where the internal temperature difference is 2.88 K. Although a temperature inversion does not occur, the pinch temperature between the two streams is too small. It indicates that the actual component cannot be manufactured.

2.5 Recompression cycle

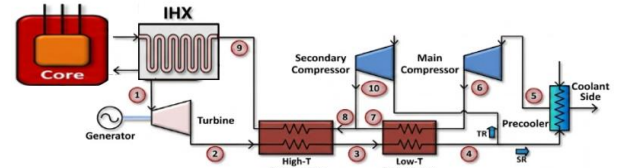


Fig. 6. Schematic diagram of recompression cycle

The second cycle layout is the recompression cycle. As shown in Figure 6, this cycle is constructed by adding one heat exchanger and one compressor to the simple Brayton cycle. It is designed to vary the heat capacity difference of the fluid entering the heat exchangers by splitting the mass flow rate distributed to the main compressor and the second compressor. This process offers the advantage of preventing a temperature pinch, which is expected to resolve the issue of the narrow temperature difference observed in the simple Brayton cycle. Furthermore, because it enhances heat recovery effectiveness, a properly configured system will result in a cycle with higher efficiency.

The difference between the simple Brayton cycle configuration and the recompression cycle is the compressor power consumption and turbine power production vary depending on the fluid flow split ratio.

Using the KAIST-CCD code to model this cycle, the required mass flow rate of carbon dioxide was determined to be 440.44 kg/s, and the inlet and outlet conditions for each component are presented in table 3.

Table 3. Cycle inlet conditions for recompression cycle

Component	T(°C)	P(MPa)	S(kJ/kg·K)	H(kJ/kg)
Turbine	700	19.55	2.96	1223.44
HTRecuperator (Cold)	591.28	8.51	2.97	1094.25
LTRecuperator (Cold)	236.00	8.36	2.36	679.34
Secondary Compressor	87.09	8.21	1.95	500.21
Main Compressor	35.0	8.06	1.46	341.16
LTRecuperator (Hot)	76.80	20.0	1.47	367.85
Number 7	216.07	19.85	2.09	620.15
HTRecuperator (Hot)	204.29	19.85	2.06	604.18
IHX	536.88	19.7	2.72	1019.09
Number 10	176.69	19.85	1.98	565.08

Once again, a T-S diagram was constructed to verify whether the cycle can operate normally, and the results are presented in Figure 7.

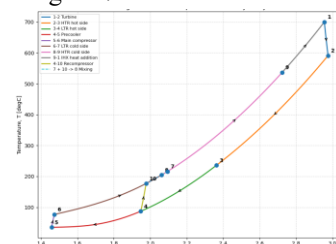


Fig 7. T-S diagram for recompression cycle

As observed in Figure 7, the continuous and seamless connections between the component states indicate that the cycle will operate successfully in an actual configuration.

In this process as well, the compressor efficiency calculated for a turbine inlet temperature of 700 °C is approximately 0.95, as formulated in the equation below.

$$\varepsilon = \frac{T_{h,in} - T_{h,out}}{T_{h,in} - T_{c,in}} = \frac{750 - 546.88}{750 - 536.88} = 0.9531 \sim 0.95$$

Based on Table 3, the calculated turbomachinery work was 8.34 MW for the main compressor and 8.28 MW for the second compressor, while the turbine produced 56.90 MW of work. This corresponds to an efficiency of 44.75%, confirming that it achieves higher efficiency than the simple Brayton cycle.

The values calculated above are based on a split ratio of 0.7, as this ratio yielded the highest efficiency, as shown in figure 8.

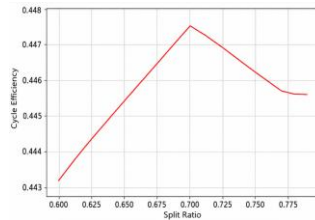


Fig 8. Cycle efficiency difference by split ratio

To verify that a temperature pinch does not occur in either of the two heat exchangers in the recompression cycle, the internal temperature profiles were tracked. The results, presented in Figure 9, confirm a more generous pinch point compared to the simple Brayton cycle, with the temperature differences in both heat exchangers remaining above 10 K.

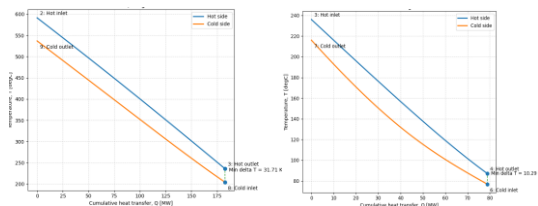


Fig 9. Temperature analysis for high temperature heat exchanger(right) and low temperature heat exchanger(left)

2.6 Compare with Rankine cycle

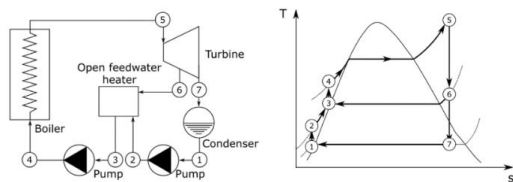


Fig 10. Equipment of regenerative Rankine cycle and T-S diagram[9]

Since the efficiency of each cycle layout has been calculated, a quantitative comparison with the Rankine

cycle, which is currently widely used in nuclear power generation, is conducted to evaluate the performance level. The Peach Bottom Unit 1 and HTR50S HTGRs were selected for this comparison, as both reactors possess thermal outputs and outlet temperatures like those of the HECTAR HTGR.

Peach Bottom Unit 1 is a 115 MW_{th} HTGR designed and operated with a design temperature of 750°C, which utilizes a non-reheat, 5-stage regenerative Rankine cycle for power generation. Under design operating conditions, its thermal efficiency was approximately 39%, while the average efficiency recorded during actual operation was 37.2% [10].

The HTR50S, presented in research by the Japan Atomic Energy Agency (JAEA), operates at a thermal output of 50 MW_{th} and is designed with an outlet temperature of 750°C, identical to that of HECTAR. Utilizing a non-reheat, three-stage regenerative Rankine cycle for power generation, its thermal efficiency was evaluated to be 34.5% [11].

Since these reported values account for actual net electricity generation, whereas the efficiencies determined in this study are through the cycle layout analysis only considering the turbine, compressor, and external heat input, this disparity needs to be addressed. According to the previous works, the turbine-generator efficiency is typically assumed to be 0.98, indicating a negligible difference. Applying this generator efficiency, the net efficiencies of the simple Brayton cycle and the recompression cycle are adjusted to 40.36% and 43.86%, respectively. Because both values remain higher than those of the Rankine cycles, the proposed systems demonstrate strong competitiveness compared to existing systems.

Furthermore, $S\text{-}CO_2$ enables smaller system sizes compared to Rankine cycles, thanks to its unique property variations near the critical point, low viscosity, and high density. In terms of size, it allows for the construction of a more compact system, which is expected to offer geographical and economic advantages for overall power plant design and operation.

2.6 Tritium transport barrier

In addition to efficiency, economic viability, and system footprint, the $S\text{-}CO_2$ power conversion system also holds potential for enhancing radiological safety management compared to conventional systems. When tritium is produced within a nuclear reactor, it can permeate into the secondary system due to the high temperature conditions and expansive surface area of the heat exchangers. If subsequently released into the environment, it induces radioactive contamination and poses radiation exposure risks to individuals, making it imperative to mitigate the environmental release of tritium.

According to a study by the Idaho National Laboratory (INL) research, HTGRs exhibit a significantly higher tritium production rate compared to conventional reactors. Specifically, for a power plant with an identical

thermal output of $1,000\text{ MW}_{th}$, a PWR generates approximately 2 Ci/day of tritium, whereas an HTGR is evaluated to produce around 50 Ci/day [12].

In KAERI's analysis report, tritium can also be generated within the HECTAR reactor through ternary fission, impurities contained inside the graphite blocks, and neutron activation reactions with helium [3]. In other words, HTGRs greater preparation is required for tritium generation, safety, and separation issues compared to conventional systems.

This issue also occurs in MSR (Molten Salt Reactor) utilizing lithium and beryllium. In conventional Rankine systems, when tritium enters the system, it can react with the hydrogen in water, forming tritiated water molecules. Since the molecular weight difference between tritiated and non-tritiated molecules is at most 2, separating tritium from the working fluid is inherently difficult and often leads to imprecise results. Research on MSR concludes that the $S\text{-CO}_2$ system helps address these issues [13].

The core argument is that since carbon dioxide does not significantly react with hydrogen, the generated tritium remains within the power conversion system. Due to the large difference in molecular weight, the difficulty of separating tritium from carbon dioxide during fluid management is much lower, enabling stable and effective separation. The potential for tritium generation applies equally to HECTAR, and the necessity for its separation is identical to that of MSRs. Under these circumstances, implementing an $S\text{-CO}_2$ cycle in HECTAR utilizes the power conversion system itself as a final defense barrier against tritium release. Thereby, enhancing radiological safety management without requiring additional safety measures.

3. Conclusions

The $S\text{-CO}_2$ cycle has garnered significant attention due to its capability to make power conversion systems compact and highly efficient. However, under the core outlet temperature conditions of conventional light-water reactors, it faced limitations as its efficiency did not differ substantially from that of the Rankine cycle. This study confirmed that the HTGR provides high outlet temperature conditions that maximize the distinct characteristics of the $S\text{-CO}_2$ cycle, thereby widening the efficiency gap with the conventional Rankine cycle. Furthermore, the $S\text{-CO}_2$ system facilitates more manageable control over tritium generation and release within the HTGR compared to existing systems. Based on these various findings, compelling reasons have been verified to seriously consider the implementation of the $S\text{-CO}_2$ cycle as the primary power conversion system for fourth-generation HTGR nuclear power plants.

In future work, design points will be identified and implemented to ensure that the performance of turbomachinery and heat exchangers aligns with the predictions of this study. Furthermore, detailed design of the overall power conversion system will be conducted by examining the cycle's feasibility and durability

through transient analysis and thermal stress evaluations in the system.

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