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Supercritical CO_2 Brayton Cycle Research at KAIST: Achieving Breakeven Conditions in the Autonomous Brayton Cycle (ABC) Test Loop

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1. Introduction

The supercritical CO_2 (S-CO_2) Brayton cycle has garnered significant attention in the energy sector due to its potential to greatly enhance power generation efficiency and reduce environmental impact compared to traditional fossil fuel-based systems. The S-CO_2 Brayton cycle offers several advantages, including higher thermal efficiency, compact component sizes, and reduced greenhouse gas emissions. These characteristics make it an attractive option for various applications, such as waste heat recovery, solar thermal power generation, and advanced nuclear reactors [1].

Currently, the experimental facility constructed at KAIST operates with an efficiency below zero, resulting in the inability to generate useful work. The ultimate goal is to achieve producing useful work from heat through the cycle. To this end, the primary objective is to achieve a breakeven state where the turbine work is enough to cover compressor work.

Precise calculations and adjustments to the current system are required while a clear identification of the necessary modifications and redesigns are needed. In this study, a modified version of an in-house cycle optimization code, KAIST-ESCA (Evaluator for S-CO_2 Cycle based on Adjoint Method), was employed to analyze such modification to KAIST facility. This code enables rapid and efficient sensitivity analysis and optimization, forming the foundation of this research [2]. It should be noted that heat loss in the piping of the ABC Test Loop is minimal and negligible, and thus was not considered in the code. The study aims to identify the optimal conditions under which the cycle can achieve breakeven condition on a laboratory scale and to design the cycle accordingly, thereby contributing to the advancement of S-CO_2 Brayton cycle research. The findings from this study are expected to provide crucial data and insights essential for improving the efficiency and reliability of S-CO_2 cycles.

2. Methods and Results

2.1 System Design and Initial Analysis

The study explores the optimal conditions required to achieve a breakeven state in the KAIST Autonomous Brayton Cycle (ABC) Test Loop. Figure 1 shows the ABC Test Loop, while Figure 2 illustrates its layout. The design parameters listed in Table I were used as input values for the in-house cycle optimization code, KAIST-ESCA. This code was used to calculate the minimum cycle maximum temperature (T_{max}) that maintains cycle efficiency at or above zero while preventing temperature inversion between the hot and cold sides within the recuperator. Additionally, the heater output required to reach this T_{max} was determined.

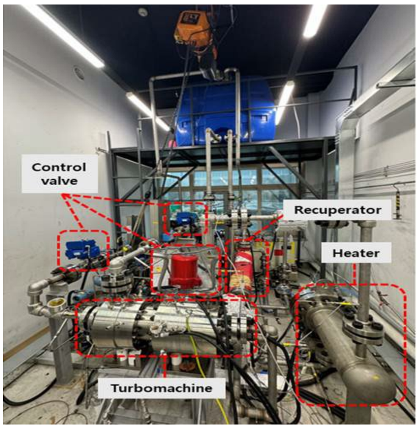

Fig. 1. ABC Test Loop

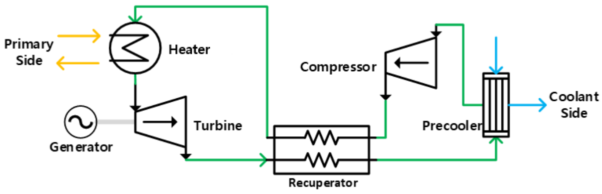

Fig. 2. Layout of ABC Test Loop.

Table I: Design and Operating Parameters of the ABC Test Loop

Parameter	Value
Compressor PR	1.2
Minimum Temperature	35.0℃
Turbine Efficiency	55%
Compressor Efficiency	55%
Recuperator Effectiveness	75%
Recuperator Pressure Drop	100 kPa
Heater Pressure Drop	50 kPa
Precooler Pressure Drop	100 kPa
Mass Flow Rate	1.5 kg/s

The thermodynamic efficiencies of the turbine and compressor were both set at 55% for this analysis. This value was selected based on the actual experimental results from the ABC Test Loop, where the measured efficiencies for both the turbine and compressor were approximately 55%. Additionally, even if the turbine and compressor were replaced with new equipment, it is unlikely that their efficiencies would drop below 55%. Therefore, the choice of 55% was deemed to be a conservative estimate for both components in this experimental setup.

The analysis indicated that a T_{max} of 363℃, with a corresponding heater output of approximately 208 kW, would be necessary to achieve breakeven condition. Given that the current heater output of the ABC Test Loop is around 26 kW, a substantial increase in heater output is evidently required to reach the breakeven operating conditions.

2.2 Effects of Adjusting Minimum Pressure

It was found challenging to achieve the required heater output with the current experimental setup. Thus, the possibility of lowering the cycle's maximum temperature (T_{max}) by adjusting the minimum pressure (P_{min}) was explored. The goal was to identify a T_{max} lower than the calculated value when P_{min} was set at 7.6 MPa. The range of P_{min} was set from the CO_2 critical pressure of 7.38 MPa to 10.0 MPa, incrementing by 0.01 MPa, and T_{max} was recalculated for each P_{min}. The results showed that the lowest T_{max}, yielding a breakeven T_{max} of 128.278℃, could be obtained when P_{min} was 8.92 MPa. The corresponding heater output required at this T_{max} was calculated to be 136.6 kW. This indicates a significant decrease in T_{max} compared to when P_{min} was set at 7.6 MPa; however, the heater output did not decrease as much as anticipated.

Table II: T_{max} & Heater output

Parameter	P_{min} = 7.6 MPa	P_{min} = 8.9 MPa
T_{max}	363 ℃	128.3 ℃
Heater Output	208.4 kW	136.6 kW

The average specific heat capacity (Cp) at each T_{max} for all minimum pressure conditions was calculated and compared graphically. The analysis revealed a sharp increase in the average Cp at certain points, explaining why the heater output did not decrease significantly despite the reduction in T_{max}. This increase in Cp is attributed to the transition of CO_2 from the vapor-like supercritical region to the liquid-like supercritical region as P_{min} increased, crossing the pseudo-critical line [3].

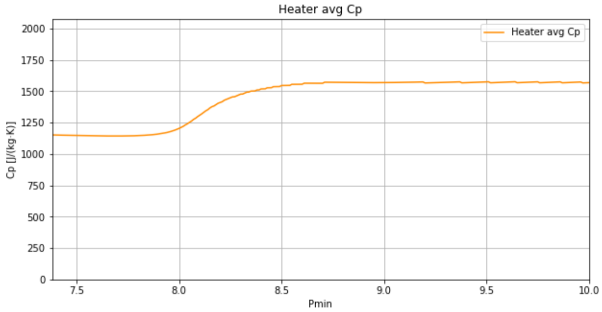

Fig. 3. Variation of Average Cp in the Heater Across the Full Ranges of P_{min}.

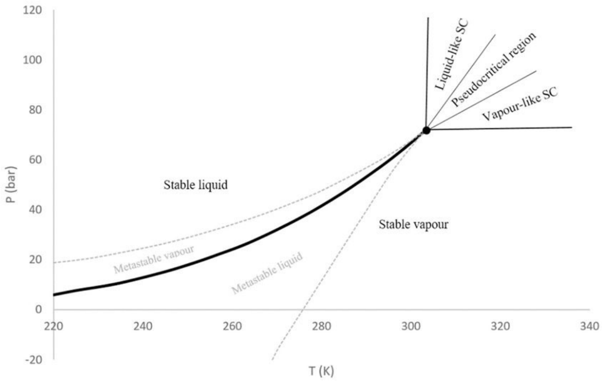

Fig. 4. Phase Diagram of CO_2.

2.3 Heater Output Variation with Adjustments to Minimum Temperature

The issue of the heater output not decreasing as expected led to consideration of raising the overall temperature of the cycle to prevent CO_2 from entering the liquid-like supercritical region, ensuring it remains in the vapor-like supercritical region. This approach was expected to lower the average Cp in the heater, thereby reducing the heater output further. To validate this approach, the minimum temperature (T_{min}) range was expanded from the original ABC Test Loop design point of 35℃ to 60℃. The P_{min} range was maintained at 7.38 MPa to 10.0 MPa. For each combination of T_{min} and P_{min}, the average Cp in the heater was recalculated using the in-house code and analyzed graphically.

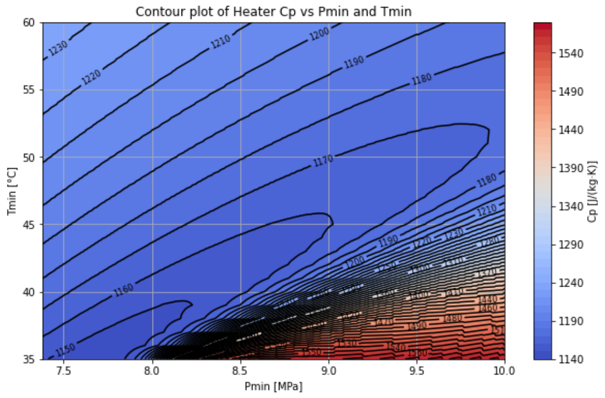

Fig. 5. Variation of Average Cp in the Heater Across the Full Ranges of P_{min} and T_{min}.

The analysis revealed that as T_{min} increased at a fixed P_{min}, as CO_2 moved away from the liquid-like supercritical region toward the vapor-like supercritical region. This shift resulted in a reduction of the average Cp, aligning with the expectation that maintaining CO_2 in the vapor-like supercritical region would reduce heater output. However, while the average Cp decreased as expected, the overall temperature rise in the cycle caused the temperature difference (ΔT) across the heater to increase significantly. Although a lower average Cp would typically reduce heater output, the larger ΔT counteracted this effect, leading to an increase in heater output instead. In this scenario, the impact of the increased ΔT on heater output outweighed the benefits of a lower average Cp, resulting in an overall increase in heater output.

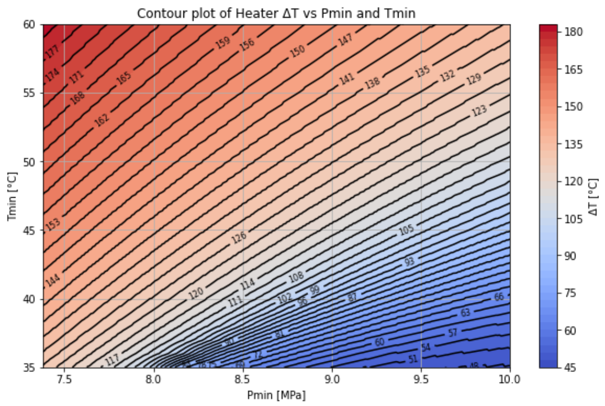

Fig. 6. Variation of ΔT in the Heater Across the Full Ranges of P_{min} and T_{min}.

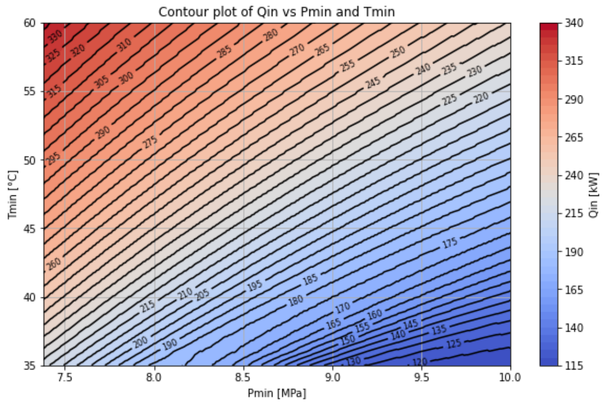

Fig. 7. Variation of Heater Output Across the Full Ranges of P_{min} and T_{min}.

These findings indicate that the increased heater output resulting from a higher T_{min} exceeds the current capabilities of the current experimental setup. Therefore, achieving breakeven at a lower heater output, within the current limitations, is more desirable. This would also help ensure that sufficient heater output capacity remains available for future power generation experiments. Based on these findings, operating the cycle within the liquid-like supercritical region, while requiring a higher average Cp, remains the more feasible approach.

3. Conclusions

The study explored the optimal conditions for achieving a breakeven state in the KAIST ABC Test Loop. It was revealed that the current experimental setup is insufficient to meet the calculated heater output requirements. To address this challenge and ultimately enable electricity generation, several critical design modifications are necessary.

First, adjusting the cycle's minimum pressure is essential. The current minimum pressure of 7.6 MPa is insufficient to achieve breakeven, so increasing the overall minimum pressure of the cycle is necessary to create the conditions needed for breakeven. By raising the minimum pressure, the cycle's performance can be optimized, and the required heater output can be maintained within more realistic limits.

Second, modifying the Turbo Alternator Compressor (TAC) to reduce work loss is crucial. Introducing a magnetic coupling to the existing TAC can minimize friction between the CO_2 and the shaft, thereby reducing work loss. This modification will alleviate the burden on the heater and help reduce the additional energy required to achieve breakeven.

Third, increasing the heater output is a key measure for achieving breakeven conditions. By expanding the heater's capacity, the system can reach higher T_{max} required for breakeven conditions, laying the foundation for future power generation. It is worth noting that the current heater installed in the ABC Test

Loop has a capacity of 26 kW but was designed to support up to 50 kW of output. The size of this heater has been calculated to be approximately 46,500 cm^3. Given the current design, it is reasonable to assume that the heater size is proportional to output. Therefore, even if the heater output were increased to 150 kW, approximately three times the current level, there would still be sufficient space within the loop to accommodate larger heater. Additionally, the current heater is a cartridge type, with linear and uniform fluid flow inside the heater. Therefore, even if the heater size increases with higher output, the associated pressure drop is not expected to be significantly greater than the current level.

Finally, based on the findings of this study, modifications to the experimental setup are planned to enable the achievement of breakeven conditions.

By implementing the necessary design changes and modifications, the commercial viability of the S-CO_2 Brayton cycle is aimed to be further enhanced. These improvements will ultimately increase the cycle's efficiency and reliability, contributing to the establishment of an optimal environment for power generation.

Acknowledgement

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