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Preliminary Study on Optimization for S-CO_2 Cycle coupled to ATOM Reactor

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1. Introduction

ATOM (Autonomous Transportable On-demand reactor Module) is a water-cooled autonomous small modular reactor (SMR) under development by a university consortium led by KAIST. The Supercritical Carbon Dioxide (S-CO_2) cycle that replaces the steam cycle is adopted as a power generation system, and it aims to operate under extreme environments such as desert conditions. Unlike conventional nuclear power plants that use seawater or lake waters as an ultimate heat sink, relatively high temperature air is considered to be the heat sink. As a result, an increase in the minimum temperature that may alter the optimal design points in the S-CO_2 cycle is expected.

Optimization of the S-CO_2 power cycle coupled to the water cooled SMR has been performed previously [1]. The authors performed optimization of the S-CO_2 power conversion system under the SMART reactor condition developed by KAERI. However, cycle analysis considering the rise in the minimum temperature has not yet been conducted under the light water reactor conditions.

In this paper, the cycle optimal points and performance were evaluated with the consideration of the increase of the cycle minimum temperature in ATOM reactor conditions. This study is conducted with a cycle analysis code based on MATLAB environment. The cycle maximum pressure was in the range of 15MPa to 25MPa, and the optimal design point was found for each case.

2. Methodology

In this section, the method used for cycle optimization and ATOM+S-CO_2 cycle conditions will be described.

2.1 Cycle optimization

The cycle optimization was performed with an in-house S-CO_2 cycle analysis code, named KAIST-ESCA (Evaluator for Supercritical CO_2 cycle based on Adjoint method) [2]. The optimal point is found in a given optimization variables range with fixed cycle maximum pressure, minimum temperature, and maximum temperature.

Due to the relatively high critical pressure of CO_2, the S-CO_2 cycle has a low expansion ratio and high turbine outlet temperature. Therefore, it is essential to recuperate the heat of turbine outlet side, which may cause internal pinch problem in a recuperator because the change of c_p value inside the heat exchanger is significantly larger than other gases. The KAIST-ESCA code excludes this problem by providing new effectiveness in cases where internal pinch problems occur [3].

The NIST-REFOROP 9.1 database was adopted for thermodynamic properties [4]. The iteration calculations of cycle optimization were performed with below with the error bound of 10^{-7} to obtain accurate numerical values.

2. 2 ATOM+S-CO_2 cycle

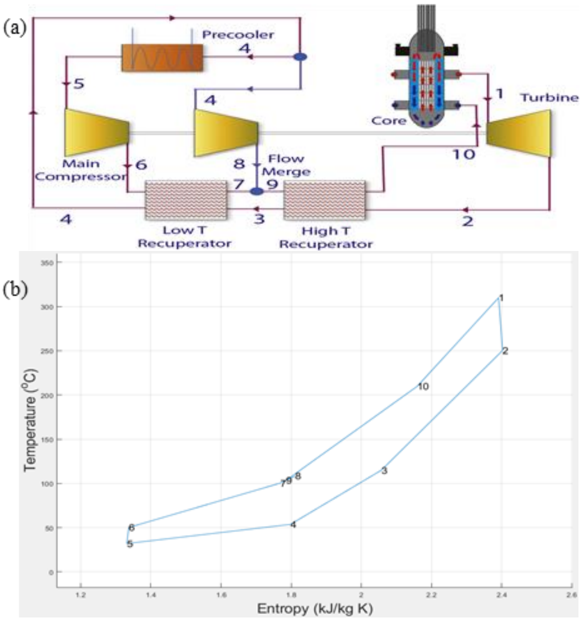

Fig. 1. S-CO_2 cycle coupled to water cooled reactor.

Fig. 1 shows schematic (a) and T-s diagram (b) of supercritical CO_2 power conversion system coupled to water-cooled nuclear reactor. In this research, SMART is adopted as a reactor side reference values because ATOM is a water-cooled reactor aiming to produce $300MW_t$ to $400MW_t$ of heat output. The TIT (Turbine Inlet Temperature) of S-CO_2 cycle is set to be 310ºC considering the core inlet and outlet temperatures.

Previously, the KAIST research team compared S-CO_2 cycle with steam cycle in the SMART reactor condition, but found that the efficiency of S-CO_2 Brayton cycle was lower than steam Rankine cycle near the TIT of the light-water reactor condition(~300℃) [5]. To maximize cycle efficiency, ATOM adopts the recompressing cycle known to exhibit the highest efficiency of various available cycle layouts.

Table I: Cycle Design Variables

Maximum Pressure [MPa]	15	20	25
Reactor Core Heat [MW$_t$]	330		
Turbine Efficiency [%]	90		
Compressor Efficiency [%]	85		
Recuperator Effectiveness [%]	95		
IHX Pressure Drop [kPa]	119		
Recuperator Pressure Drop [kPa]	100		
Precooler Pressure Drop [kPa]	80		
Turbine Inlet Temperature [°C]	310		
Minimum Temperature [°C]	25 – 60		
Flow Split Ratio [%]	30 – 99		
Expansion Ratio	1.2-2.7	1.2-3.6	1.2-4.5
Minimum Pressure [MPa]	5.2-12	5.2-16.12	5.2-20.3

The cycle design variables applied in this study are summarized in Table I. The authors compared three cases where the cycle maximum pressure was 15MPa, 20MPa, and 25MPa. Component assumed performances and turbine inlet temperature were fixed in all cases. The studied minimum temperature and minimum pressure ranges were between 25℃ and 60℃ and between 5.2 MPa and 80% of the maximum pressure, respectively, to cover both Rankine and Brayton cycles.

In the case of recompressing cycle, the optimized variables are the flow split ratio (main compressor to recompressing compressor) and the turbine expansion ratio when the maximum temperature, the maximum pressure and the minimum temperature are prescribed. For each maximum pressure, the lowest temperature was increased by 1°C and the cycle optimal design points and performance corresponding to each minimum temperature were evaluated.

3. Results

The cycle optimization results are shown in Fig. 2. As shown in the figure, cycle efficiency and cycle minimum temperature tend to be inversely proportional. The optimum design point at the maximum efficiency is also changed. Specifically, the cycle minimum pressure, flow split ratio and mass flow rate are increasing.

Within the analysis range, the cycle maximum efficiency was 31.75% at the maximum pressure of 20MPa and the lowest temperature at 25℃. The minimum efficiency was 20.4% when the maximum pressure was 15MPa and the minimum temperature was 60℃.

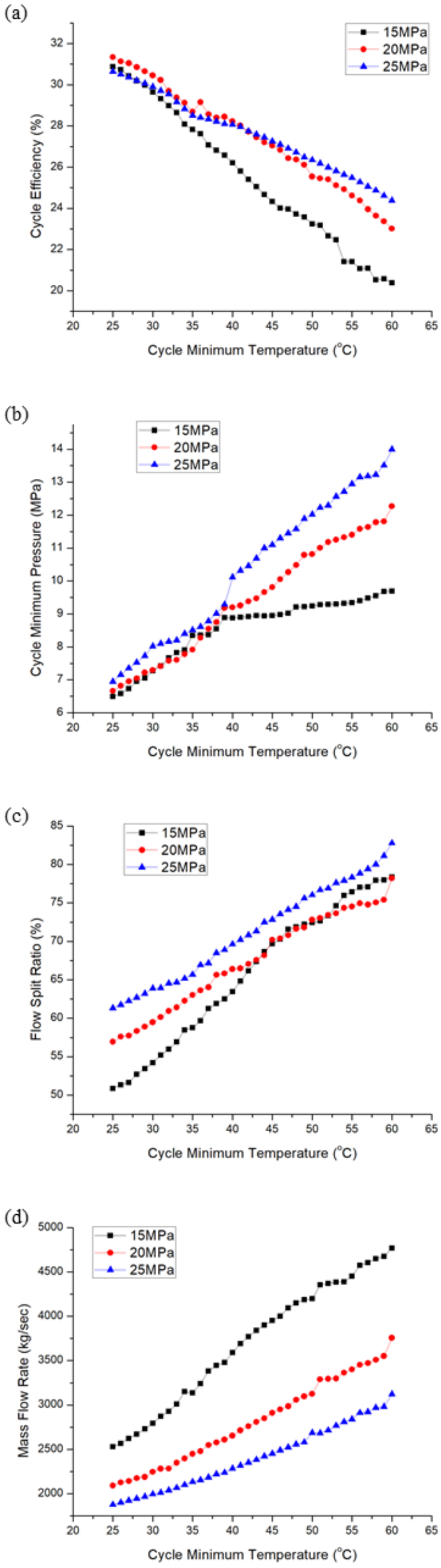

Fig. 2. Change of Cycle Maximum Efficiency and Optimal Points According to Increase of Cycle Minimum Temperature.

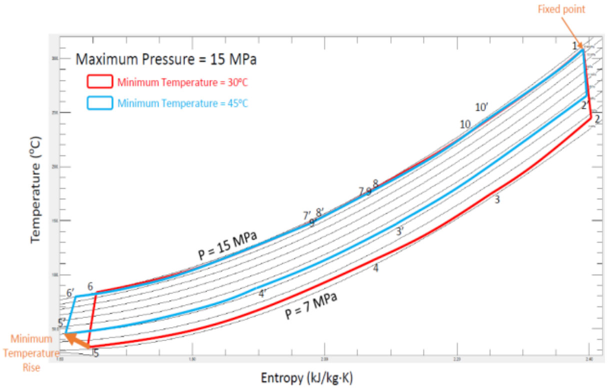

Fig. 3. Change in T-s Diagram Due to rise in Cycle Minimum Temperature (Maximum Pressure = 15MPa).

For cases with maximum pressure of 15 MPa, the T-s diagrams of the optimized cycles at the lowest temperature of 30℃ and at 45℃ are shown in Fig. 3. Fixing the cycle maximum pressure means that the point 1 is fixed, so that the expansion ratio (point 1 to point 2) in the turbine decreases as the cycle minimum temperature increases. As the cycle minimum pressure increases, the temperature profile within the recuperator moves away from the critical point and the abrupt change in the c_p value is reduced, resulting in a cycle becoming more like a simple recuperated cycle (increase in flow split ratio). Also, when the core outlet temperature (the turbine inlet temperature) is fixed, the enthalpy difference decreases as the core inlet temperature rises, so the system mass flow rate increases to eliminate the same amount of heat from the core.

4. Conclusions

In this study, cycle optimization considering the rise in cycle minimum temperature of ATOM+SCO_2 system was performed. An in-house cycle analysis code, KAIST-ESCA, was used for optimization calculation. Under water cooled reactor conditions. Under the water cooled reactor conditions, the studied maximum pressure was 15-25Mpa, and the flow split ratio was 30-99%. The minimum temperature and pressure ratio ranges included both Rankine cycle and Brayton cycle.

It was confirmed that the cycle efficiency decreased as the cycle minimum temperature was increased, and the mass flow rate, flow rate and cycle minimum pressure were found to increase. When the cycle minimum temperature increased from 25 ℃ to 60 ℃, the cycle efficiency decreased from a maximum of 31.75% (20 MPa) to a minimum of 20.4% (15 MPa).

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