Off-Design Performance Analysis of the Supercritical Carbon Dioxide Brayton Cycle for a Sodium-Cooled Fast Reactor

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1. Introduction

Most energy conversion systems including the LWR reactor employ the Rankine cycle to generate the electric power. Recently, research on the power cycle for a next generation reactor has been conducted, and the S-CO_2 (supercritical carbon dioxide) Brayton cycle is presented as a promising alternative for the present Rankine cycle. As an advanced power conversion system, the S-CO_2 Brayton cycle has many advantages. The principal advantage is a lower compression work compared to an ideal gas such as helium. As a result, a good efficiency at a modest temperature, a simplified compressor design, and a compact size of the heat exchangers and turbines are achieved. The S-CO_2 Brayton cycle coupled to the SFR excludes the possibilities of a SWR (Sodium-Water Reaction), which is a major safety-related event, and thus the safety of the SFR can be improved.

As a preliminary study to commercialize the S-CO_2 Brayton cycle, this work focuses on the control strategies for the off-design performance and the cycle layout to maximize the thermal efficiency by varying the thermal power from a SFR reactor. The previous works provided the thermal equilibrium conditions for the full power situation [1]. However, the actual power plants will experience the generating power variation, which should be balanced by a proper BOP cycle.

2. Methods and Results

2.1 Off-Design Control Strategy

For establishing a thermal balance of the Brayton cycle, the off-design control requires strategies both to bear the thermal power variation and minimize the induced thermodynamic imbalance. To control the thermal loading in a cycle, a CO_2 mass flow rate is changed. With changing the flow rate, temperatures and pressures in the off-design operation can keep close to the normal operating conditions. Pressure imbalance induced from turbine and compressors is compensated using throttle valves. The throttle valves are located between the compressors and recuperators to reduce the average pressure increase in the whole cycle layout. In addition, the pressure difference is also reduced by a clutch between the turbine and compressors. For the calculation stability, the inlet temperature at the main compressor is maintained to be constant. The inlet of the compressor is located close to the critical point to minimize the compressor work.

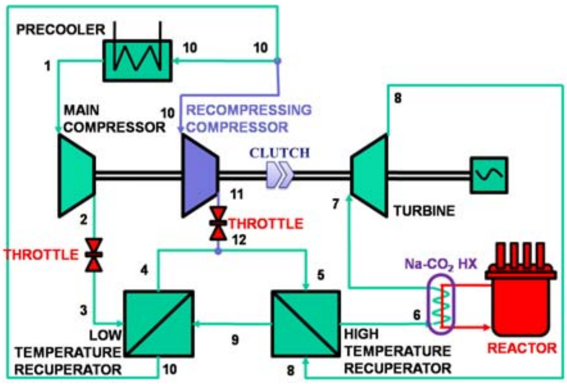

Fig. 1. Supercritical CO_2 recompression Brayton cycle

2.2 Turbomachinary Performance

The present brayton cycle involves one turbine and two compressors. The turbine and compressor are located on a common shaft with a clutch to change the ratio of rotating speed between turbine and compressors. For analyzing the off-design performance, the pressure ratio and efficiency as a function of a CO_2 flow rate is required. The performance curves for the turbine and compressors are adapted from the previous ABTR data map [2]. For illustrating the rotating speed, the pressure ratio is qualitatively reduced.

2.3 Heat Exchanger Analysis

The total heat exchanger performance can be calculated simply from a single channel result by multiplying the number of channels in the exchanger. In this work, the single channel calculations are carried out using the LMTD (log mean temperature difference) and node calculation. The LMTD calculation is applied to analyze the NA-CO_2 heat exchanger by solving the heat balance equations. From the inlet conditions, the outlet temperature and heat transfer rate can be induced. For the CO_2 recuperators, a 1-dimentional nodal calculation is applied. Starting from the initial conditions in one side of the single channel, the heat transfer rate and enthalpy calculation in each node provide the total heat transfer rate and outlet conditions of recuperators.

The detailed calculation results for heat exchanger performance are presented in Fig. 2. The significant deviation from the LMTD assumption is observed in the heat transfer rate along the node position. Therefore, the resulting heat exchanger area depicts a large difference between the Node and LMTD calculations. However, the LMTD is proven to give faster and simpler results. In this work, a NA-CO_2 heat exchanger is calculated by LMTD, and HTR and LTR are calculated by a node method.

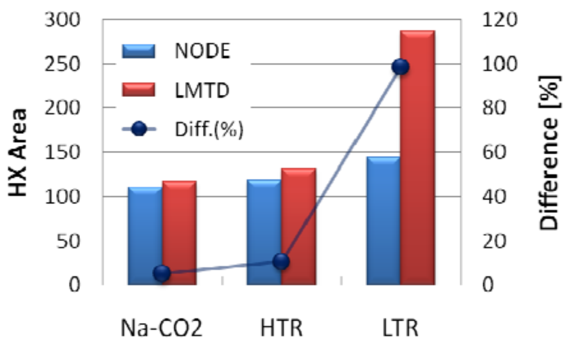

Fig. 2. Comparison of the heat transfer area between LMTD and NODE method

2.4 Off-Design Performance

The off-design performance is successfully evaluated using the present control strategies using the clutch and throttle valves. The resulting temperature entropy diagram is depicted in Fig. 3. The large difference of entropy and temperature properties is observed in the flow merging point following the outlets of the compressors. However, the off-design operating conditions are located close to the normal full power condition, which implies that each component is properly run within the achievable design range. With a reduced the flow rate, the thermal loading and efficiency in the whole cycle are deceased.

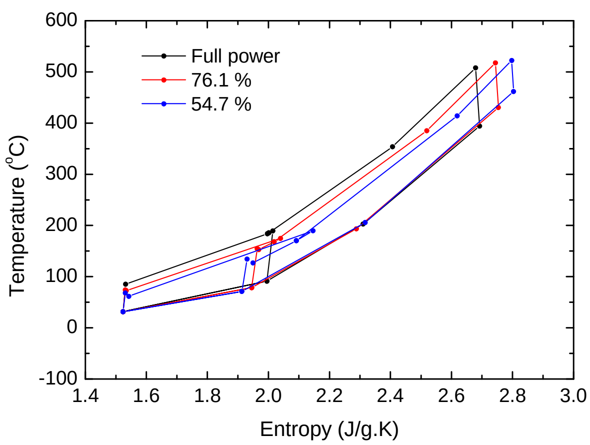

Fig. 3. T-S diagram for the different thermal powers

As the thermal loading is reduced, the sodium outlet temperature increases because we assume a constant inlet temperature for a NA-CO_2 heat exchanger. A high effectiveness of the recuperators is achieved for all the flow rate range. The effect of the compressor inlet temperature is especially important for the present Brayton cycle because the temperature is minimum in the whole cycle layout and located very close to the critical point. Therefore, the tiny deviation results in a huge change of the required heat exchanger area and the cycle efficiency, as shown in Fig. 4.

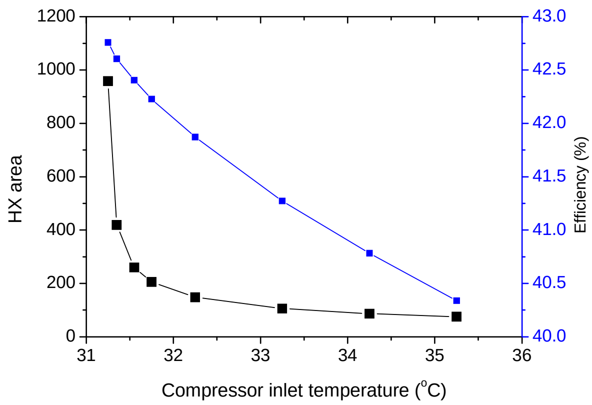

Fig. 4. Heat exchange area and efficiency variation as a function of the inlet temperature

3. Conclusions

To verity the present control scheme, a comparative study with the previous computational for a normal operating condition was conducted. The result shows that the deviations from the reference values are within 0.4%. The off-design performance is successfully evaluated using the present control strategies using the clutch and throttle valves. The large difference in the entropy and temperature properties is observed in the flow merging point following the outlets of the compressors. However, the off-design operating conditions are located close to the normal full power condition, which implies that each component is properly run within the achievable design range. The effect of the compressor inlet temperature is evaluated for the present Brayton cycle because the temperature is minimum in the whole cycle layout and located very close to the critical point. The analysis shows that the tiny deviation results in a huge change of the required heat exchanger area and the cycle efficiency. Therefore, the present compressor inlet temperature is determined to be 32.25^{o}C, which is larger than the previous value of 31.25^{o}C.

REFERENCES

[1] S. Kim, J. H. Eoh, M. W. Wi, S. O. Kim, Validity study and the Configuration of the Supercritical CO_2 Brayton cycle coupled to KALIMER, Transactions of the Korean Nuclear Society Spring Meeting, 2005.
[2] Y.I. Chang, P.J. Finck, C. Grandy, Advanced Burner Test Reactor Preconceptual Design Report, ANL-ABR-1 (ANL-AFCI-173), 2006.