Validity study and the Configuration of the Supercritical CO_2 Brayton cycle coupled to KALIMER

Seyun Kim*, Jae-Hyuk Eoh, Myong-Whan Wi, Seong-O Kim
Fluid Sys. Eng. Div., KAERI, 150 Deokjin-Dong, Yuseong-Gu, Deajeon, Korea, 305-353, seyunkim@kaeri.re.kr

1. Introduction

A closed Brayton cycle with the use of supercritical CO_2 (S-CO_2) as the working fluid is studied. Recently, the research on the power cycle for a next generation reactor has been conducted and the S-CO_2 Brayton cycle is presented as a promising alternative for the present Rankine cycle [1]. 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 [1]. 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 KALIMER (Korean Advanced Liquid Metal Reactor) excludes the possibilities of SWR (Sodium-Water Reaction) which is the major safety-related event, so that the safety of KALIMER can be improved. The validity study and the configuration of the BOP and the optimization of the design parameters are being carried out.

2. Methodology

2.1 Configuration of the cycle

The recompression S-CO_2 Brayton cycle is adopted [1] which has two compressors, to avoid the inverse temperature difference in the inlet of the compressor due to a drastic variation of the specific heat of S-CO_2 near the critical point.

The T-s diagram of the recompression S-CO_2 Brayton cycle is depicted in Fig. 1. In the recompression Brayton cycle, the minimization of the discharged heat in the precooler is achieved with a second compressor (point 9-10). Therefore, the split fraction of the flow is a significant design parameter. Two recuperators (i.e., regenerative heat exchangers) are used for the utilization of the remaining S-CO_2 thermal energy in the cycle. The schematic of the cycle is presented in Fig. 2. The compressor inlet temperature (point 1 in Fig. 1) is set to 31 °C, near to the critical point of CO_2 (7.377 MPa, 30.97 °C) for the maximization of the cycle efficiency.

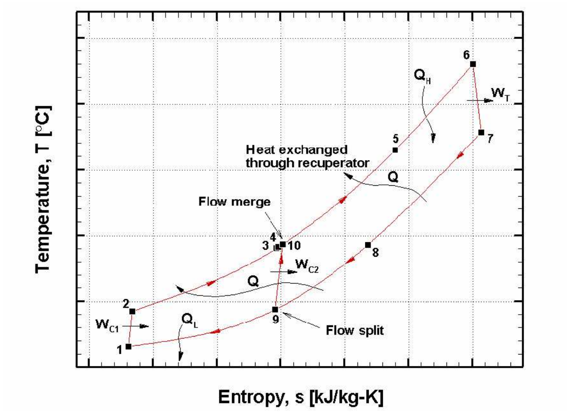

Figure 2. Diagram of the recompression S-CO_2 Brayton cycle

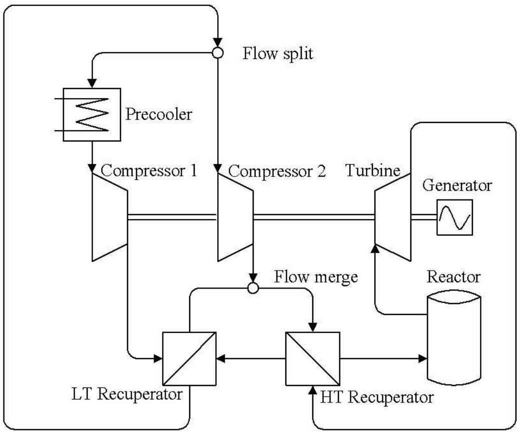

Figure 1. Schematic of the recompression S-CO_2 Brayton cycle

For the assurance of the physical appropriateness of the cycle, a computational program is developed. The equations of the mass balance and energy balance, and the isotropic efficiency of the turbine and the compressors and the effectiveness of the recuperators are formulated [3]. And the simultaneous equation is solved with the Gauss-Seidel method.

The practically achievable ranges of the component characteristics are surveyed and the pertinent value is applied. The characteristics of the main components are shown in Table 1. Despite the varying flow rate, the component efficiencies and effectiveness are regarded as constant.

Table 1. Component characteristics of the cycle

Compressor polytropic efficiency [%]	89.0
Turbine polytropic efficiency [%]	90.0
HT Recuperator effectiveness [%]	98.0
LT Recuperator effectiveness [%]	92.0

The cycle efficiency can be calculated by the definition as below.

$$\eta_{th} = \frac{Work_{out} - Work_{in}}{Heat_{in}} = \frac{W_T - W_{c1} - W_{c2}}{Q_H}$$

To validate the methodology, the comparison of the cycle configuration with a previous research is carried out. Using the system conditions of MacDonald et al [2], the cycle efficiency is calculated as 11.77 %. The cycle efficiency of MacDonald et al's calculation is 44.1%, and the difference between the results is 1.52%. The convergence criteria is set to 1.0×10^{-4}. In the same manner, for the conditions of Dostal et al [1], the deviation is 1.75%. The feasibility of the computational method is confirmed.

2.2 Identification of optimum design point

For the KALIMER normal operating condition [4], to identify the optimum design point, significant system parameters must be defined. The compression ratio of the first compressor (1-2) and the turbine inlet temperature are the important system parameters. The lower temperature of the IHX must be smaller than 339.0°C and the higher temperature of the IHX must be smaller than 511.0 °C. For varying parameters, the cycle efficiency is calculated as shown in Fig. 2. The maximum efficiency is calculated at the design point of the turbine inlet temperature of 510 °C and the compression ratio of 3.7, that is, the maximum pressure is 27.4 MPa. But, there is no experience with a component design and operating at such a condition. The maximum pressure of 20 MPa, i.e. the compression ratio of 2.7, is adopted from a previous cycle design. For the compression ratio of 2.7, the optimal design point is calculated at the turbine inlet temperature of 460 °C.

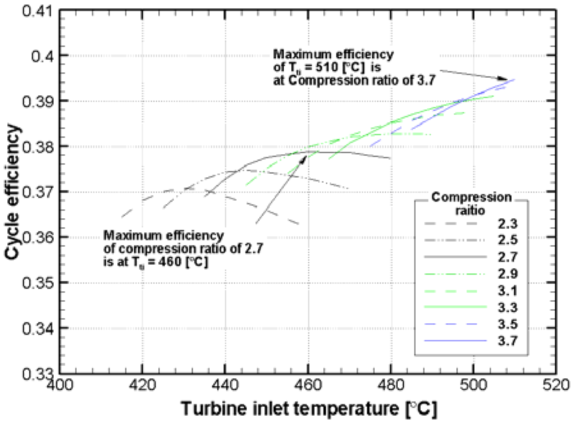

Figure 3. Calculations of Brayton cycle efficiency in various conditions

The mass flow rate of the CO_2 is calculated as 1241.69kg/s and the split mass fraction is 36.56%. For the optimal operating conditions, the cycle efficiency is about 37.91 percent. Subtracting the power for the primary coolant pumps (4.4MW) and intermediate pumps (3.4MW), a plant efficiency of 34.84 % is obtained. There are also other needs for an on-site power. For the current KALIMER design, the other on-site needs are 2.0 % of the nominal core power. However, this value also includes the power requirements of the Rankine steam cycle and, therefore, represents an overestimation for KALIMER with an S-CO_2 Brayton cycle. The details of the operating conditions are presented in Table 2.

Table 2. The properties of the optimal point of the cycle

	T[°C]	P[MPa]	H[kJ/kg]	s[kJ/kg-K]
1	31.25	7.40	359.58	1.523
2	85.30	19.98	390.07	1.536
3	176.42	19.96	564.28	1.974
4	182.72	19.96	573.47	1.995
5	330.00	19.94	764.72	2.360
6	460.00	19.62	924.47	2.603
7	355.93	7.46	817.52	2.628
8	186.25	7.43	626.24	2.275
9	93.38	7.41	515.71	2.006
10	194.09	19.96	589.68	2.030

3. Conclusion

A computational program is developed for the configuration and the analysis of the S-CO_2 recompression Brayton cycle. The physical suitability of the code is shown through a comparison with previous researches. The optimal design point of the S-CO_2 recompression Brayton cycle coupled to KALIMER is obtained with a parametric study. The cycle efficiency of 37.91 % and plant efficiency of 34.84 % are calculated. The validity of the coupling S-CO_2 recompression Brayton cycle to KALIMER is shown. In the future, a refinement of the code and a study on the components characteristics should be preformed.

Acknowledgment

This research has been performed under the International Energy-Nuclear Engineering Research Initiative (INERI) project sponsored by the Ministry of Science and Technology.

REFERENCES

[1] V. Dostal, M. J. Driscoll, P. Hejzlar and N. E. Todreas, A supercritical CO_2 gas turbine power cycle for next-generation nuclear reactors, Proceedings of ICONE 10, Arlington, 2002.

[2] P. E. MacDonald and J. Boungiorno, Design of an Actinide Burning, Lead or Laed-Bismuth Cooled Reactor That Produces Low Cost Electricity, Annual report, INEEL/EXT-01-01376, 2001.

[3] F. P. Incropera. and D. P. DeWitt, Introduction to Heat Transfer, 3rd Edition, John Wiley & Sons, 1996.

[4] D. Hahn et al, KALIMER Conceptual design report, KAERI/TR-2204/2002, KAERI, 2002.