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Preliminary Study of the Supercritical CO_2 Hybrid Cycle for the HTGR Application

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1. Introduction

A High Temperature Gas-cooled Reactor (HTGR) system is actively under developed for a variety of purposes; desalination, hydrogen generation, electricity generation, etc. In the past either steam Rankine cycle or helium Brayton cycle is the usual candidate for Power Conversion System (PCS) for the HTGR system.

However, this study was conducted to explore the potential of Supercritical Carbon Dioxide (S-CO_2) Brayton cycle for the HTGR application. The S-CO_2 cycle is being considered as a PCS due to its high thermal efficiency, simplicity, compactness and so on. Generally, the S-CO_2 Brayton cycle is characterized as a highly recuperated cycle which means that to achieve high thermal efficiency, the cycle requires a highly effective recuperator. Therefore, the S-CO_2 recompressing Brayton cycle using two recuperators is known as one of the highly efficient layouts for the S-CO_2 Brayton cycle [1]. However, highly effective recuperator can limit the temperature difference in heat receiving section and such high effective recuperator occupies nearly the whole volume of the system. Argonne National Laboratory (ANL) showed that direct application of the standard S-CO_2 recompressing Brayton cycle to the HTGR or the Very High Temperature Reactor (VHTR) is difficult to achieve high thermal efficiency due to the mismatch of the temperature difference between the temperature drop of helium as the primary reactor coolant and the temperature rise of CO_2 as the PCS coolant through an Intermediate Heat Exchanger (IHX) [2].

Therefore, our research team suggests a novel S-CO_2 cycle configuration, the S-CO_2 Brayton and Rankine hybrid cycle, to solve this limitation. This S-CO_2 hybrid concept is utilizing the waste heat of the S-CO_2 Brayton cycle as heat input to the S-CO_2 Rankine cycle. Dividing the thermal capacity of the heat source in to the Brayton cycle part and Rankine cycle part of the S-CO_2 hybrid cycle appropriately, the temperature difference at the IHX could be reduced, therefore the net system performance and operating range can be improved.

In this study, the ANL research is reviewed by the in-house cycle analysis codes developed by the Korea Advanced Institute of Science and Technology (KAIST) research team. And the S-CO_2 Brayton and Rankine hybrid cycle is studied as a PCS for the VHTR condition which was utilized by ANL research team; it was assumed that the core outlet temperature to be 850℃ and the core inlet temperature of 400℃ [2].

2. Cycle Analyses and Results

2.1 Reference Review and Validation of Cycle Design Code

As mentioned earlier, it is challenging to apply the traditional S-CO_2 recompressing Brayton cycle to the HTGR or VHTR due to the mismatch of the temperature difference between the primary and the secondary systems [2]. Generally, HTGR or VHTR needs sufficiently high temperature difference between the core inlet and the core outlet for reducing the helium flow rate; eventually decreasing core coolant velocity and pressure drop.

On the contrary, the concept of the standard S-CO_2 recompressing Brayton cycle is achieving high cycle thermal efficiency by utilizing two recuperators for reducing the waste heat and increasing the temperature of the working fluid at the IHX inlet. However, the temperature rise of the S-CO_2 recompressing Brayton cycle through the IHX is reflecting the temperature drop caused by the expansion in the turbine. In case of the traditional S-CO_2 recompressing Brayton cycle like the reference of the ANL, the CO_2 expands from 20 MPa to 7.4 MPa in the turbine that causes the CO_2 temperature rise about 150℃ in the IHX [2].

Fig. 1 shows the traditional S-CO_2 recompressing Brayton cycle applied to the VHTR under the reference condition [2]. The cycle performance calculation was carried out by the in-house code, the error between the in-house code and the reference is very low as shown in Fig. 2. As shown in Fig. 1, due to the mismatch of the temperature difference, the Turbine Inlet Temperature (T.I.T) of the S-CO_2 recompressing Brayton cycle is about 556℃ whereas the opposite side is 850℃ He entering the IHX hot side. The resulting thermal efficiency is about 47%.

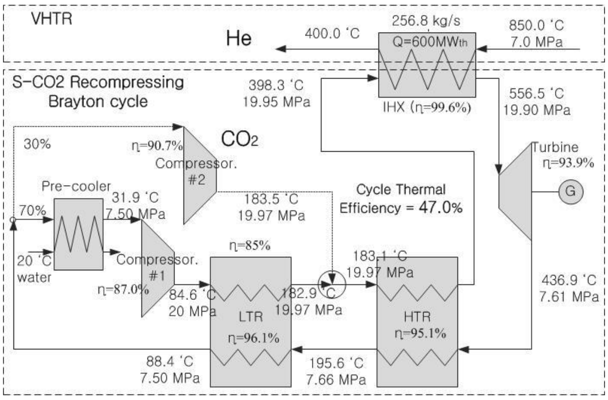

Fig. 1 Standard S-CO_2 recompressing Brayton cycle application to VHTR [2]

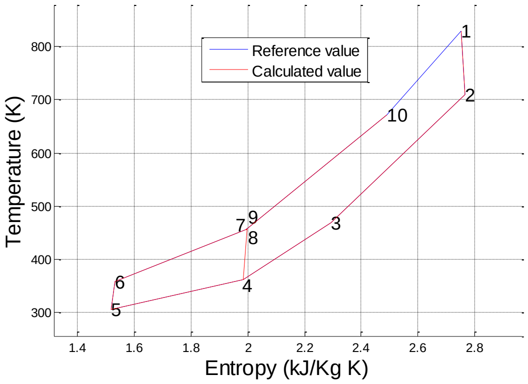

Fig. 2 T-S diagram comparison for the validation of the cycle design code

2.2 Application of the S-CO_2 hybrid cycle to the HTR

To solve this limitation of the S-CO_2 Brayton cycle using to the VHTR, authors suggest a novel S-CO_2 cycle configuration, the S-CO_2 Brayton and Rankine hybrid cycle.

The S-CO_2 Brayton and Rankine hybrid cycle is using the two cycle configurations; the simple recuperated Brayton cycle and the simple Rankine cycle. The Brayton cycle part of the S-CO_2 hybrid cycle is connected with the primary cooling system of the reactor through the IHX. The Rankine cycle part of the S-CO_2 hybrid cycle is connected with the Brayton cycle part through the pre-cooler of the Brayton cycle part to use the waste heat as the heat input. Figs. 3 and 4 show the S-CO_2 hybrid cycle's configuration and T-S diagram, respectively.

Even though each cycle part of the S-CO_2 hybrid cycle is physically independent, it is thermodynamically linked. Therefore, since each of the cycle conditions of the S-CO_2 hybrid cycle affects each cycle performance, the S-CO_2 hybrid cycle's parameters such as the pressure ratio, minimum temperature and so on should be chosen with consideration for both Brayton and Rankine cycles. In this study, the cycle minimum pressure of the Rankine cycle part of the S-CO_2 hybrid cycle is selected about 6.43MPa to get the target cycle minimum temperature, 25℃.

Fig. 3 shows that the S-CO_2 hybrid cycle is applied to the referred VHTR condition with the limitation of the Rankine cycle maximum pressure about 20MPa which results in about 49% thermal efficiency. The T.I.T of the S-CO_2 hybrid cycle is calculated about 608℃ whereas that of the S-CO_2 recompressing Brayton cycle is 556.5℃.

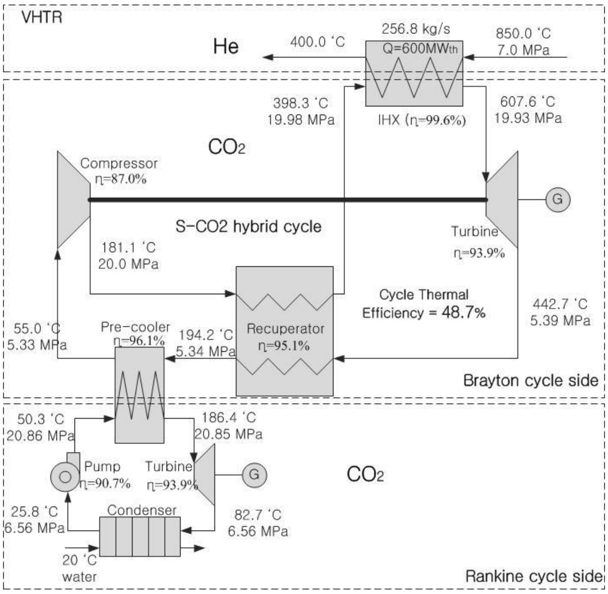

Fig. 3 Standard S-CO_2 hybrid cycle application to VHTR

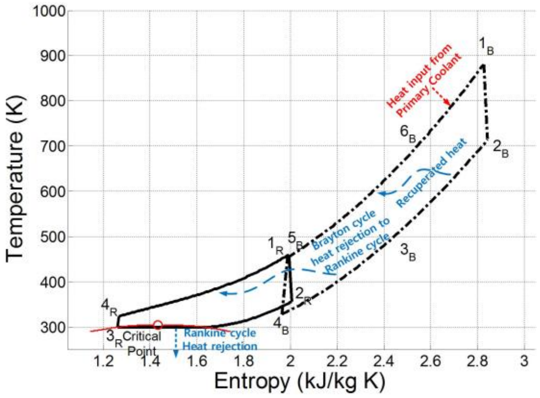

Fig. 4 T-S diagram of the S-CO_2 hybrid cycle

3. Conclusions

The S-CO_2 Brayton cycle has been receiving a lot of attention because it can achieve simple configuration and high thermal efficiency. Especially, the S-CO_2 recompressing Brayton cycle is known that high thermal efficiency could be achieved by reducing the waste heat at the pre-cooler. However, such highly recuperative cycle configuration could restrict the CO_2 temperature rise through the IHX even though the opposite coolant's temperature is sufficiently high to increase the T.I.T of CO_2 further.

Therefore, in this study, the S-CO_2 Brayton and Rankine hybrid cycle concept is suggested to overcome the temperature mismatch issue in the IHX when the S-CO_2 Brayton cycle is utilized as a PCS for the HTGR or VHTR.

As shown in the results, the application to the HTGR or VHTR, the hybrid cycle can achieve higher performance than the recompressing layout because the higher T.I.T is obtained; in this study, about 50℃ high.

The reason is because the S-CO_2 recompressing Brayton cycle's minimum pressure and temperature are decided by the critical pressure of CO_2 to reduce the main compressor work. However, the Brayton cycle part of the S-CO_2 hybrid cycle doesn't need to be near the critical point of CO_2 at compressor inlet because this cycle concept is reusing the waste heat of the Brayton cycle part as a heat input for the Rankine cycle part. Therefore, the compressor inlet condition of the Brayton cycle side of the S-CO_2 hybrid cycle could be higher than the critical temperature of CO_2 and lower than the critical pressure of CO_2 for optimal steady-state operating condition.

Therefore, the Brayton cycle side turbine of the S-CO_2 hybrid cycle is expanding from 19.9 MPa to 5.4 MPa whereas in case of the S-CO_2 recompressing Brayton cycle, from 19.9 MPa to 7.6 MPa as shown in Figs 1 and 3. As mentioned earlier, the temperature rise of CO_2 is proportional to the turbine pressure ratio.

In conclusion, to increase the thermal efficiency of system, the S-CO_2 recompressing Brayton cycle uses the way to reduce the waste heat by increasing recuperative heat, whereas the S-CO_2 hybrid cycle reuses the waste heat by connecting the Brayton cycle to the Rankine cycle. Therefore, this study shows that the S-CO_2 Brayton and Rankine hybrid cycle could be a more suitable PCS for the HTGR or VHTR than the S-CO_2 recompressing Brayton cycle.

ACKNOWLEDGEMENT

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