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Design of Supercritical Carbon dioxide Integral Experiment Loop

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1. Introduction

During the next generation reactor development, a demand for the alternative power conversion cycle over the steam Rankine cycle grew as the core outlet temperature is further increased. The S-CO_2 cycle can achieve relatively higher efficiency in the moderately high turbine inlet temperature (500-750°C) condition such as Sodium-cooled Fast Reactor operating condition. The S-CO_2 cycle not only promises high efficiency but also it can improve the reactor safety by replacing violent sodium-water reaction hazard with milder sodium-CO_2 reaction. Due to this reason, Korean Atomic Energy Research Institute (KAERI) is developing Korean Advanced LIquid MEtal Reactor (KALIMER) and the S-CO_2 cycle is considered as one of the candidates for power conversion cycle. To develop and verify the characteristics of the S-CO_2 cycle, KAERI and KAIST research team is designing a Supercritical Carbon dioxide Integral Experiment Loop (SCIEL). This paper will discuss the result of preliminary study for SCIEL design.

2. SCIEL Design

2.1. Cycle layout and components

The major benefits of S-CO_2 cycle is 1) relatively high efficiency in the mild temperature range 2) competitive efficiency with a simple layout 3) compact turbo-machines. As shown in Fig. 1, the major studies settle on the S-CO_2 recompressing cycle (also known as Feher cycle) which reduces the waste heat and increases the recuperated heat by recompressing some portion of the flow without heat rejection to increase the thermodynamic efficiency of the cycle [1]. To assess the S-CO_2 recompressing cycle, an in-house code is developed by KAIST research team and the fluid properties are obtained from NIST.

Fig. 2 shows the T-S diagram of the recompressing cycle. The compressor work is effectively reduced as the inlet condition of the compressor is fairly close to the critical point. Not only compressor work is reduced but also the compact size can be attained with this characteristic. The cycle efficiency is influenced by the turbine inlet temperature, cycle pressure ratio, compressor inlet temperature, compressor inlet pressure, turbo-machine efficiency, recuperator effectiveness and heat exchanger pressure drop.

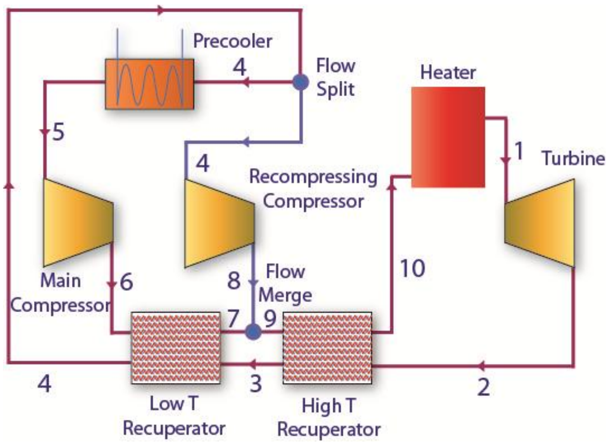

Fig. 1 S-CO_2 recompressing cycle layout

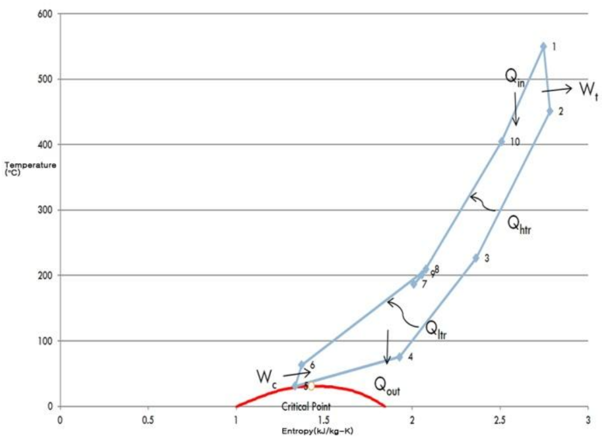

Fig. 2 T-S diagram of S-CO_2 recompressing cycle

2.2 Maximum pressure and pressure ratio study

The Brayton cycle efficiency is highly influenced by the turbine inlet temperature (TIT). Considering the SFR consideration, the TIT of the SCIEL is assumed to be 550°C. Firstly, the compressor outlet pressure has to be determined. The simple recuperated Brayton cycle efficiency gradually increases as the compressor outlet pressure increases. However, for the recompressing layout, the recompressing work also needs to be concerned and is always inefficient than the main compressor work. Therefore, the drawbacks of recompressing work and the benefits of additional recuperated heat makes the optimum point for the recompressing cycle with the compressor outlet pressure variation. Under the given condition, the optimum compressor outlet pressure is 20 MPa for the recompressing cycle.

The higher efficiency is obtained when the compressor inlet temperature decreases. Especially, for the S-CO_2 cycle, the drastic efficiency gain is obtained as the compressor inlet condition is close to the CO_2 critical point (30.98^{o}C, 7.48MPa).

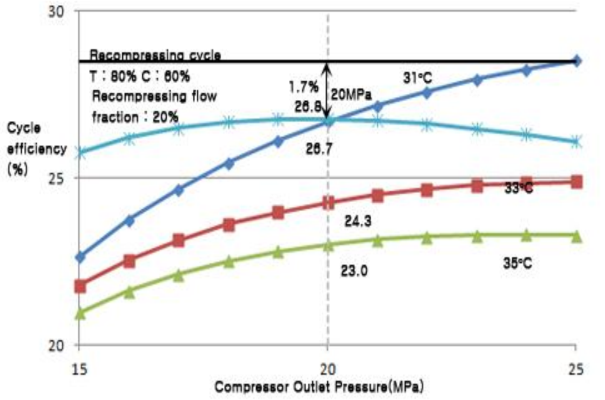

Fig. 3 The cycle efficiency of recompressing cycle and simple recuperated cycles of different compressor inlet temperature with the compressor outlet pressure variation

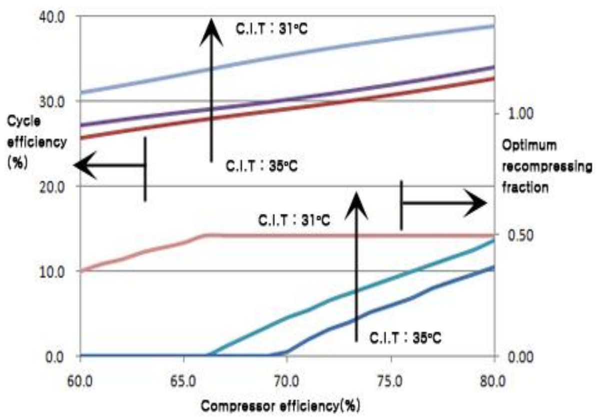

Fig. 4 The cycle efficiency and efficient recompressing flow of recompressing cycle with the compressor efficiency variation

Fig. 4 shows the cycle efficiency of recompressing cycles with the compressor efficiency variation. The optimum recompressing fraction is the value when the maximum cycle efficiency is obtained. Under the high compressor inlet condition, the recompressing process can not contribute to the cycle efficiency until the certain quality of compressor efficiency is guaranteed. However, when the compressor inlet temperature is close to the critical point, the recompressing process is always beneficial. These characteristics will be reflected for the cycle operation and control strategy of SCIEL.

2.3 Other S-CO2 internal test loops

There are three research institutes which have the S-CO_2 integral test loops as summarized in Table 1. Comparing the S-CO_2 integral test loops in other research institutes, they mainly focus on the compressor performance and analysis. TIT test loop scale is much smaller than the others[2]. SNL and KAPL thermal power is over 500 kW and they focus on the nuclear application[3][4]. SNL target temperature is above 500 ^{o}C which is comparable to the SFR operating condition and KAPL is about 300 ^{o}C more concentrating on the PWR operating condition. KAPL also adopted the conventional shell and tube heat exchangers to check the applicability of the cycle to a nuclear propulsion system [4].

		SNL(IST)	KAPL(IST)	TIT
Cycle Lay out		Double TAC Recompressing cycle	One Turbine One TAC Simple Recuperated Cycle	One TAC Simple recuperated cycle
Thermal Power(kW)		780	834.9	10
Top Temperature(°C)		537	300	277(achieved)/ 527 (target)
Top Pressure(MPa)		17.2	16.3	11.9(achieved) / 20 (target)
Heat Exchanger Type	Recuperator	PCHE	PCHE	PCHE
	Heater	Electric	Gas burning	Electric (Double pipe)
	Chiller	PCHE	Shell and tube	-

Table I: S-CO_2 integral test loops in the world

3. Summary

SCIEL is being designed for developing fundamental technologies required for the SFR power conversion system. While designing SCIEL, the compressor outlet pressure and inlet temperature were studied. The compressor efficiency is also studied and under certain conditions, the recompressing cycle can be less efficient than the simple recuperated cycle. These characteristics will be reflected to final SCIEL design.

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