Application of S-CO_2 Cycle for Small Modular Reactor coupled with Desalination System

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1. Introduction

In many countries, water scarcity is deemed as one of the most serious concerns due to population expansion, economic development, severe drought caused by climate change, increasing inequalities between water demand and supply, changing consumption patterns, and so forth. To cope with these issues, KAIST research team has developed a concept of nuclear desalination and electricity co-generating plant which utilizes the energy released by nuclear fission as the heat source of both systems [2]. Also, study of application of supercritical CO_2 (S-CO_2) power cycle for a Korean large PWR, APR-1400 with desalination system has been preliminarily conducted by the KAIST research team [3-4].

The Korean small modular reactor, SMART (System-integrated Modular Advanced ReacTor, 100MW_e), is designed to achieve enhanced safety and improved economics through reliable passive safety systems, a system simplification and component modularization. SMART can generate electricity and provide water by seawater desalination. However, due to the desalination aspect of SMART, the total amount of net electricity generation is decreased from 100MW_e to 90MW_e. The authors suggest in this presentation that the reduction of electricity generation can be replenished by applying S-CO_2 power cycle technology. The S-CO_2 Brayton cycle, which is recently receiving significant attention as the next generation power conversion system, has some benefits such as high cycle efficiency, simple configuration, compactness and so on. In this study, the authors evaluate the applicability of SMART based co-generation plant producing electric power and desalination process with the S-CO_2 Brayton cycle to minimize the drop in the electricity production capacity due to the desalination process.

2. S-CO_2 layouts

In this study, to replenish the decreased power due to of the desalination in SMART, the power conversion system of SMART is replaced from a steam Rankine cycle to a S-CO_2 simple recuperated co-generation cycle. This S-CO_2 cycle has high specific power, simple layout and relatively easy to design an added extra flow split line for the desalination purpose [4]. To design an added split line for the desalination, the three revised layout of simple recuperated S-CO_2 cycle are proposed. The 1st layout is separating CO_2 flow before heat is removed by the pre-cooler after the turbine. The separated flow rate needs to be compressed before entering the desalination heat exchanger (DHX) to increase the CO_2 temperature for desalination process. The 2nd layout is splitting the CO_2 flow after the compressing process. The separated flow rate is reheated by passing through the additional re-heater to increase the CO_2 temperature for the desalination processes. The 3rd layout uses the high temperature CO_2 at the turbine outlet as a heat source for the desalination system. The separated flow joins with the main flow before entering the compressor. For cycle performance analysis, the compressor inlet condition is fixed at 31°C and 7.44MPa, which is just above the critical point of CO_2. Figures 1-3 show the proposed three S-CO_2 cycle layouts.

3. Co-generation S-CO_2 Cycle design

In this chapter, the proposed three S-CO_2 cycles are designed for the co-generation SMART system. The compressor inlet condition is fixed at 31°C and 7.44MPa, which is just above the critical point of CO_2. This cycle performance analysis is conducted to see the compatibility of the co-generation S-CO_2 cycles. Figure 1-3 and Table 1 show the design results of the three co-generation layouts. The 1st simple recuperated cycle can achieve the highest cycle efficiency. However, there are two additional components of compressor and DHX (Desalination Heat Exchanger). For the 3rd simple recuperated cycle, the cycle efficiency is not much different with the 1st simple recuperated cycle. Furthermore, there is one additional component of DHX. The inlet and the outlet temperatures of CO_2 at the DHX is high enough for the desalination. Therefore, an additional study is carried out with the 3rd simple recuperated S-CO_2 cycle layout, which is simpler than other co-generation cycles.

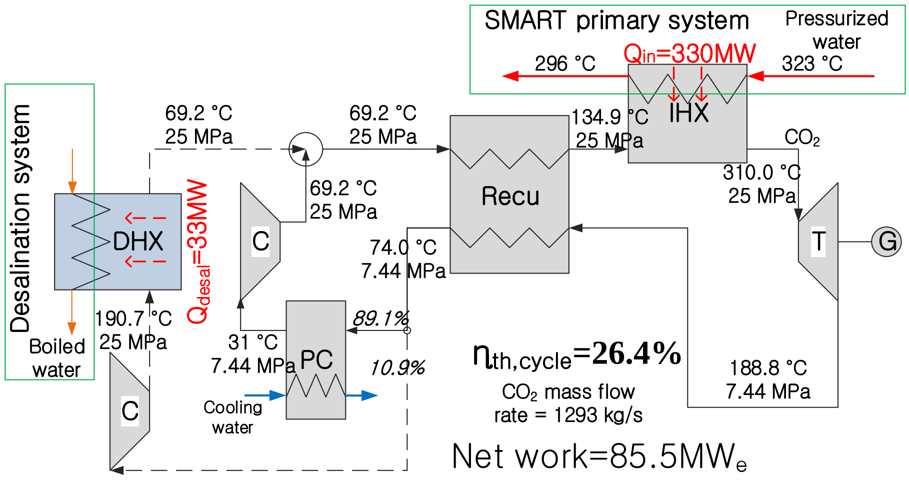

Figure 1 Results of the 1st layout for co-generation simple recuperated S-CO_2 cycle

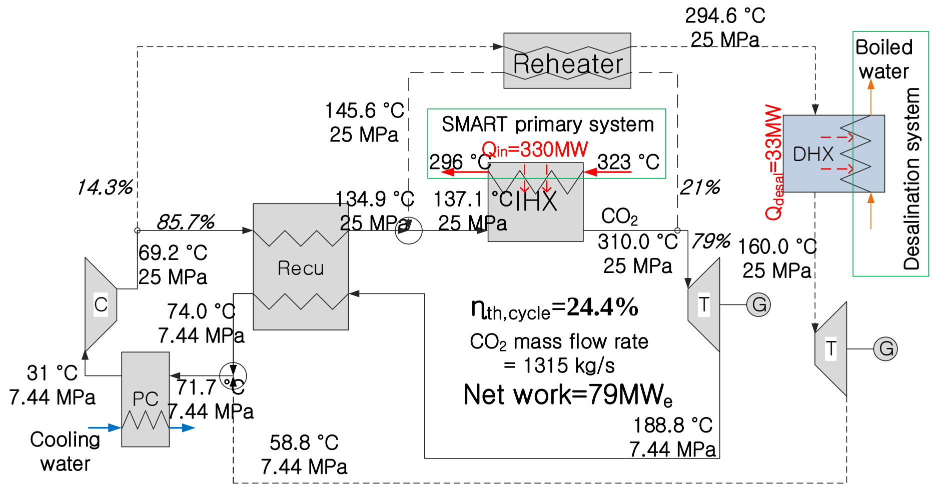

Figure 2 Results of the 2nd layout for co-generation simple recuperated S-CO_2 cycle

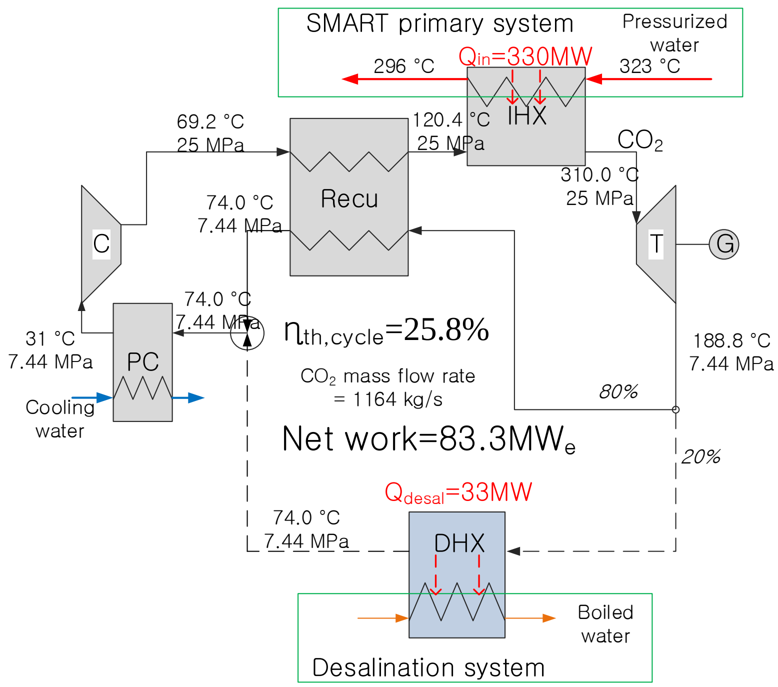

Figure 3 Results of the 3rd layout for co-generation simple recuperated S-CO_2 cycle

Table 1. The design results of the three co-generation cycles

Cycle	1st	2nd	3rd
Cycle thermal efficiency	26.4%	24.4%	25.8%
Inlet and outlet T of CO_2 at the DHX	190.7/ 69.2	294.6/ 160.0	188.8/ 74.0
Flow split ratio(s)	89.1/10.9	85.7/14.3 & 79/21 (cold side & hot side)	80/20
Additional components	Compressor DHX	Re-heater DHX Turbine	DHX
Desalination heat performance	$33MW_{th}$	$33MW_{th}$	$33MW_{th}$

To re-optimize the cycle design, the inlet pressure of the main compressor was not fixed. However, the turbine inlet temperature (310°C), the cycle minimum temperature (31°C), the target desalination heat (33MWth) and the component performances were assumed to be the same as the previous design. The revised 3rd concept cycle was designed for better cycle performance and it is shown in Figure 4. The designed cycle shows higher cycle thermal efficiency more than the above three concepts of S-CO_2 Brayton cycle and even the steam cycle of SMART. The cycle thermal efficiency is calculated to be 37.8%.

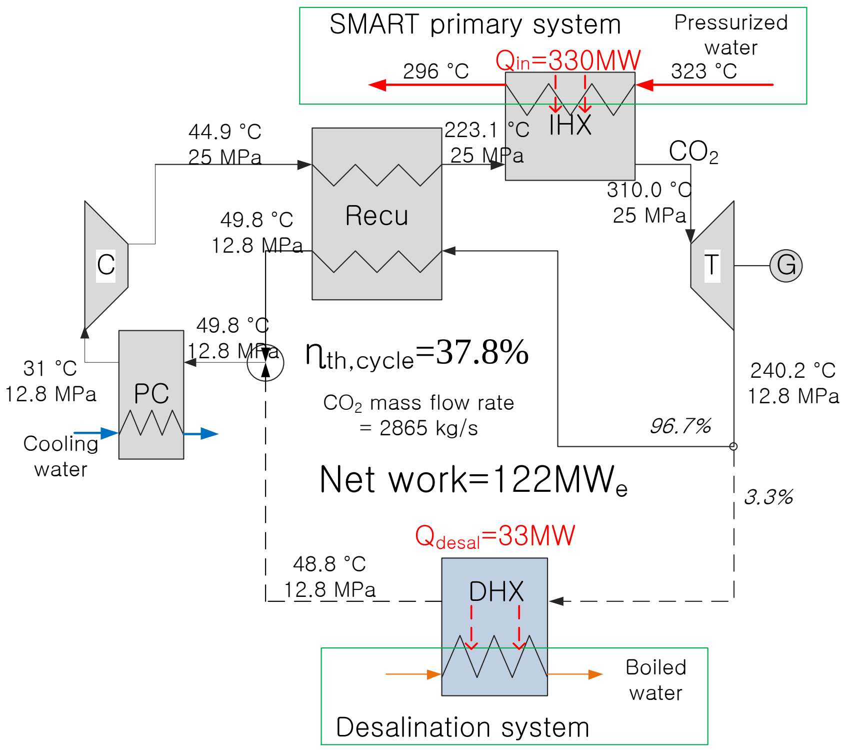

Figure 3 Cycle re-optimization results of 3rd simple recuperated S-CO_2 cycle

4. Desalination capacity analysis

MSF (Multi-Stage Flash distillation) and MSD (Multi-Effect Distillation) are mainly used for thermal desalination processes around the world. Compared to the MSF process, the MED process has advantages such as a lower top brine temperature (TBT), higher gained output ratio (GOR) and lower specific power consumption. Additionally, when coupled with vapor recovery devices, the GOR range can be increased to 16 [2]. Therefore, in APR1400 coupled with desalination system, which has been developed by Jung et al. [2], a MED process using the Thermal Vapor Compression (TVC) technology has been proposed. So, in this study, the identical thermal desalination system, which is a low-temperature horizontal tube-type MED-TVC process, is selected for the simple performance analysis. The desalination performance of the MED-TVC can be determined by thermal conditions of the source steam which is extracted from the secondary loop of SMART.

In this study, the desalination capacity analysis is simply evaluated using Table 2. Table 2 shows the desalination performance of the MED-TVC based on 400MW(th) thermal power [2].

Table 2. Effect of motive steam pressure on the MED-TVC performance based on 400MW(th) thermal power [2]

Motive steam pressure [bar]	3	9	15
Motive steam temperature [°C]	133.65	175.36	198.19
GOR [-]	12.56	13.98	14.65
Desalination capacity [m3/d]	178,451	194,784	202,760
Total pumping power [MW(e)]	10.61	9.74	9.35
Total heat transfer area [m2]	5.90E5	6.41E5	6.66E5

However, in the re-optimized 3rd simple recuperated S-CO_2 cycle, the temperature of extracted CO_2 for desalination is high enough to produce the motive steam at 15bar and 198.19°C. For simple performance comparison, it is assumed that the desalination capacity is proportional to the thermal power in the same motive steam pressure. Since the thermal power for desalination is 33MWth under SMART operating conditions, the desalination capacity is 16,727.7m^3/d. For the future work, the detailed analysis of the desalination capacity will be conducted.

4. Conclusions

In this study, the cycle performance analysis of the S-CO_2 cycles for SMART with desalination system is conducted. The simple recuperated S-CO_2 cycle is revised for coupling with desalination system. The three revised layout are proposed for the cycle performance comparison. In this results of the 3rd revised layout, the cycle efficiency reached 37.8%, which is higher than the efficiency of current SMART with the conventional power conversion system 30%. Therefore, the net electricity generation of SMART applied with the simple recuperated S-CO_2 cycle is possible to increase the electricity output 22%. Also, the layout of the power conversion system is simpler than the conventional power conversion system of SMART. Furthermore, the desalination capacity is evaluated under SMART operating conditions as well and it showed that the total amount of produced water is also reasonable.

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