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Preliminary design of S-CO_2 Brayton cycle for APR-1400 with power generation and desalination process

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1. Introduction

To cope with the demands for the desalination considering environment 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 [1-2]. A Korean large PWR, APR-1400 has been selected as a reference plant for the desalination and electricity co-generation plant study conducted by the KAIST research team.

A supercritical CO_2 (S-CO_2) Brayton cycle is recently receiving significant attention as a promising power conversion system in wide range of energy applications due to its high efficiency and compact footprint. The main reason why the S-CO_2 Brayton cycle has these advantages is that the compressor operates near the critical point of CO_2 (30.98°C, 7.38MPa) to reduce the compression work significantly compared to the other Brayton cycles [3-8].

In this study, the concept of replacing the entire steam cycle of APR-1400 with the S-CO_2 Brayton cycle is evaluated. The power generation purpose S-CO_2 Brayton cycles are redesigned to generate power and provide heat to the desalination system at the same time. The performance of these newly suggested cycles are evaluated in this paper.

2. Co-generation S-CO_2 Cycle design

The maximum operating pressure is limited to 25MPa. It is relatively higher than the PWR steam cycle pressure but this pressure occurs in the ultra-supercritical Rankine cycle for coal power plant which operates higher than 25MPa. The other main assumptions are that the cycle maximum temperature is limited to 310°C with consideration for the APR-1400 operating condition. The compressor inlet condition is fixed at 31°C and 7.44MPa, which is just above the critical point of CO_2. Since this is a preliminary study to review the applicability of the S-CO_2 Brayton cycle instead of the existing steam Rankine cycle under the APR-1400 condition, all pressure losses like pipe loss, component loss, etc., are ignored for simplified analysis. Table I summarizes the efficiency and effectiveness of components used in the cycle analysis; turbines, compressors and heat exchangers. The component performances were assumed based on the values that are generally used for large power plants.

Table I: Component efficiency and effectiveness

Component	Value
Turbine efficiency	92 %
Compressor efficiency	88 %
Heat exchanger effectiveness	95 %
Generator efficiency	98%

In this study, the simple recuperated layout is selected as the base layout for the dual purpose APR1400. The revised S-CO_2 simple recuperated Brayton cycles are designed for the co-generation APR-1400 system.

Three concepts of the S-CO_2 simple recuperated co-generation cycle were designed. The target was to deliver 147MW heat to the desalination process. The 1st concept 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. Fig. 1 represents the 1st concept of the S-CO_2 simple recuperated co-generation cycle for APR-1400 as well as the steady-state operating conditions at each point.

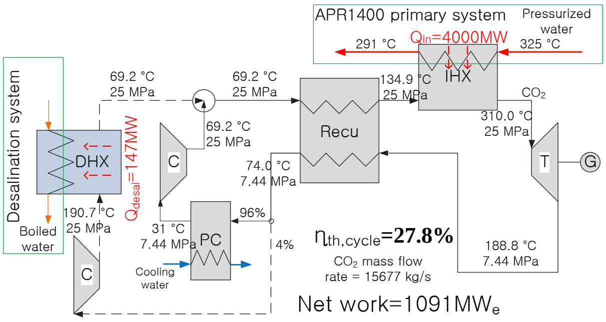

Fig. 1. The 1st concept of the S-CO_2 simple recuperated co-generation cycle for the APR-1400

The 2nd concept has two additional flow split lines to heat the separated CO_2 flow for the desalination. Fig. 2 shows the 2nd concept of the S-CO_2 simple recuperated co-generation cycle. The separated flow rate is reheated by passing through the additional re-heater to increase the CO_2 temperature for the desalination processes.

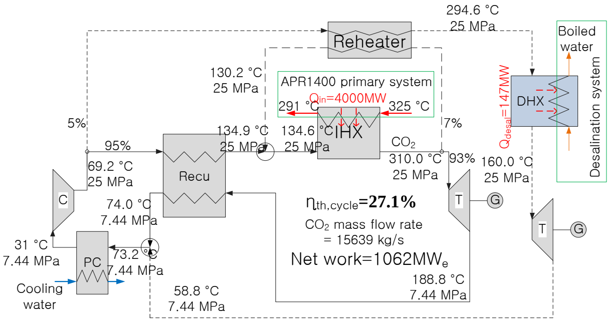

Fig. 2. The 2nd concept of the S-CO_2 simple recuperated co-generation cycle for the APR-1400

The 3rd concept uses the high temperature CO_2 at the turbine outlet as a heat source for the desalination system. Fig. 3 shows the 3rd concept of the S-CO_2 simple recuperated co-generation cycle.

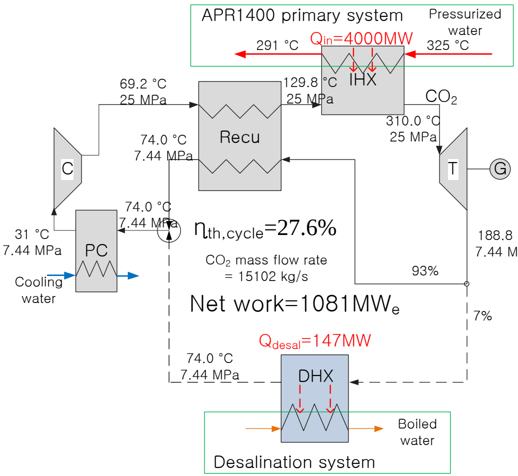

Fig. 3. The 3rd concept of the S-CO_2 simple recuperated co-generation cycle for the APR-1400

The design results of the three newly suggested co-generation cycles are summarized in Table II.

Table II: The design results of the three S-CO_2 simple recuperated co-generation cycles

Cycle	1st	2nd	3rd
Cycle thermal efficiency	27.8%	27.1%	27.6%
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)	96/4	95/5 & 93/7 (cold side & hot side)	93/7
Additional components	Compressor DHX	Re-heater DHX Turbine	DHX
Desalination heat performance	147MW$_{th}$	147MW$_{th}$	147MW$_{th}$

As shown in the above results, the generally studied S-CO_2 Brayton cycles, which are designed to operate near the critical point of CO_2 at the main compressor inlet, are not easy to outperform the steam cycle with very simple layout under APR-1400 operating condition. For designing the S-CO_2 Brayton cycle that can outperform the steam cycle in terms of a power generation capability under APR-1400 condition, an additional study was carried out with the layout of the 3rd concept relatively simpler than other cogeneration cycles. 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 (147MW$_{th}$) and the component performances were assumed to be the same as previous design. The revised 3rd concept cycle was designed for a high cycle performance as shown in Fig. 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 APR-1400 with lower cycle pressure compared above. The cycle thermal efficiency is calculated to be 40.3%.

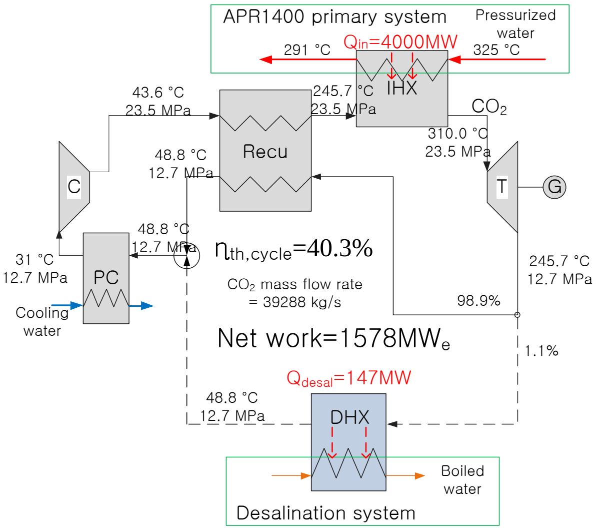

Fig. 4. The revised 3rd concept of the S-CO_2 simple recuperated co-generation cycle for the APR-1400

3. Conclusions

This study was conducted to explore the capabilities of the S-CO_2 Brayton cycle for a cogeneration system for APR-1400 application.

Three concepts of the S-CO_2 simple recuperated co-generation cycle were designed. The target was to deliver 147MW heat to the desalination process. The thermal efficiencies of the three concepts are not significantly different, but the 3rd concept is relatively simpler than other cycles because only an additional heat exchanger is required. Although the 2nd concept is relatively complicated in comparison to other concepts, the temperatures at the inlet and outlet of the DHX are higher than that of the others. Since the operating temperature and pressure of motive steam in desalination systems are related with the fresh water cost, the 2nd concept can be a better option in this respect.

As shown in the results, the S-CO_2 Brayton cycles are not easy to outperform the steam cycle with very simple layout and general design points under APR-1400 operating condition. However, this study shows that the S-CO_2 Brayton cycles can be designed as a co-generation cycle while producing the target desalination heat with a simple configuration. In addition, it was also found that the S-CO_2 Brayton cycle can achieve higher cycle thermal efficiency than the steam power cycle under APR-1400 condition through re-optimization. The re-optimization strategy deviated from the traditional S-CO_2 Brayton cycle design approach which fixes the compressor inlet condition to approach the critical point of CO_2 as near as possible for a simple cycle configuration.

This is a preliminary study of the capabilities of the S-CO_2 Brayton cycle used for co-generation of APR-1400 nuclear power plant. Thus, a S-CO_2 Brayton cycle with better performance that can outperform the steam cycle in every aspect will be continuously investigated in the future.

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REFERENCES

[1] Y. H. Jung, Y. H. Jeong, J. Choi, A. F. Wibisono, J. I. Lee, H. C. No, Feasibility study of a small-sized nuclear heat-only plant dedicated to desalination in the UAE, Desalination, Vol.337, pp. 83-97, 2014.
[2] W. W Lee, Y. H. Jung, J. I. Lee, Studies of S-CO_2 power cycle application for a large PWR with a desalination capability, ICAPP 2015, ANS, Nice, France, 2015.
[3] V. Dostal, P. Hejzlar, M.J. Driscoll, The supercritical carbon dioxide power cycle: comparison to other advanced power cycles, Nuclear Technology, Vol.154, pp. 283–301, 2006.
[4] V. Dostal, M.J. Driscoll, P. Hejzlar, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, Thesis, MIT-ANP-TR-100, 2004.
[5] H. J. Yoon, Y. Ahn, J. I. Lee, Y. Addad, Potential advantages of coupling supercritical CO_2 Brayton cycle to water cooled small and medium size reactor, Nuclear Engineering and Designing, Vol. 245, pp. 223-232, 2012.
[6] S. J. Bae, J. Lee, Y. Ahn, J. I. Lee, Preliminary studies of compact Brayton cycle performance for Small Modular High Temperature Gas-cooled Reactor system, Annals of Nuclear Energy, Vol. 75, pp. 11–19, 2015.
[7] S. J. Bae, Y. Ahn, J. Lee, J. I. Lee, Various supercritical carbon dioxide cycle layouts study for molten carbonate fuel cell application, Journal of Power Sources, Vol. 207, pp. 608-618, 2014.
[8] Y. H. Ahn, J. I. Lee, Study of various Brayton Cycle Designs for Small Modular Sodium-Cooled Fast Reactor, Nuclear Engineering And Design, Vol.276, pp. 128-141, 2014.