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$_2$ ($30.98^\circ$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 ultrasupercritical Rankine cycle for coal power plant which operates higher than 25MPa. The other main assumptions are that the cycle maximum temperature is limited to $310^\circ$C with consideration for the APR-1400 operating condition. The compressor inlet condition is fixed at $31^\circ$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>
<thead>
<tr>
<th>Table I: Component efficiency and effectiveness</th>
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<tbody>
<tr>
<td>Component: Turbine, Compressor, Heat exchanger, Generator</td>
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<tr>
<td>Efficiency: 92%, 88%, 95%, 98%</td>
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</table>

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-CO2 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-CO2 simple recuperated co-generation cycle for the APR-1400](image1)

The 2nd concept has two additional flow split lines to heat the separated CO2 flow for the desalination. Fig. 2 shows the 2nd concept of the S-CO2 simple recuperated co-generation cycle. The separated flow rate is reheated by passing through the additional re-heater to increase the CO2 temperature for the desalination processes.

![Fig. 2. The 2nd concept of the S-CO2 simple recuperated co-generation cycle for the APR-1400](image2)

The 3rd concept uses the high temperature CO2 at the turbine outlet as a heat source for the desalination system. Fig. 3 shows the 3rd concept of the S-CO2 simple recuperated co-generation cycle.

![Fig. 3. The 3rd concept of the S-CO2 simple recuperated co-generation cycle for the APR-1400](image3)

As shown in the above results, the generally studied S-CO2 Brayton cycles, which are designed to operate near the critical point of CO2 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-CO2 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 (147MWth) 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-CO2 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%.

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The design results of the three newly suggested cogeneration cycles are summarized in Table II.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle thermal efficiency</td>
<td>27.8%</td>
<td>27.1%</td>
<td>27.6%</td>
</tr>
<tr>
<td>Inlet and outlet T of CO2 at the DHX</td>
<td>190.7/69.2</td>
<td>294.6/160.0</td>
<td>188.8/74.0</td>
</tr>
<tr>
<td>Flow split ratio(s)</td>
<td>96/4</td>
<td>95/5 &amp; 93/7 (cold side &amp; hot side)</td>
<td>93/7</td>
</tr>
<tr>
<td>Additional components</td>
<td>Compressor DHX Re-heater DHX Turbine</td>
<td>DHX</td>
<td>DHX</td>
</tr>
<tr>
<td>Desalination heat performance</td>
<td>147MWth</td>
<td>147MWth</td>
<td>147MWth</td>
</tr>
</tbody>
</table>

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3. Conclusions

This study was conducted to explore the capabilities of the S-CO2 Brayton cycle for a cogeneration system for APR-1400 application.

Three concepts of the S-CO2 simple recuperated cogeneration 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-CO2 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-CO2 Brayton cycles can be designed as a cogeneration cycle while producing the target desalination heat with a simple configuration. In addition, it was also found that the S-CO2 Brayton cycle can achieve higher cycle thermal efficiency than the steam power cycle under APR-1400 condition through re-optimization. The re-optimization strategy used deviated from the traditional S-CO2 Brayton cycle design approach which fixes the compressor inlet condition to approach the critical point of CO2 as near as possible for a simple cycle configuration.

This is a preliminary study of the capabilities of the S-CO2 Brayton cycle used for co-generation of APR-1400 nuclear power plant. Thus, a S-CO2 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