Performance Estimation of Supercritical CO_2 Cycle for the PG-SFR application with Heat Sink Temperature Variation

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1. Introduction

As a part of Prototype Generation IV Sodium-cooled Fast Reactor (PG-SFR) development, the Supercritical CO_2 cycle (S-CO_2) is considered as one of the promising candidate that can potentially replace the steam Rankine cycle. S-CO_2 cycle can achieve distinctively high efficiency compared to other Brayton cycles and even competitive performance to the steam Rankine cycle under the mild turbine inlet temperature region. In addition, mild sodium-CO_2 reaction can be substituted for violent sodium-water reaction to improve the reactor safety.

Previous studies explored the optimum size of the S-CO_2 cycle considering component designs including turbomachinery, heat exchangers and pipes [1-3]. Among them, 75MWe S-CO_2 cycle has been selected and the system concept and design parameters are shown in Fig. 1 and Table 1, respectively.

Based on the preliminary design, the thermal efficiency is 31.5% when CO_2 is sufficiently cooled to the design temperature [1]. However, the S-CO_2 compressor performance is highly influenced by the inlet temperature and the compressor inlet temperature can be changed when the heat sink temperature, in this case sea water temperature varies. To estimate the S-CO_2 cycle performance of PG-SFR in the various regions, a Quasi-static system analysis code for S-CO_2 cycle is developed by the KAIST research team.

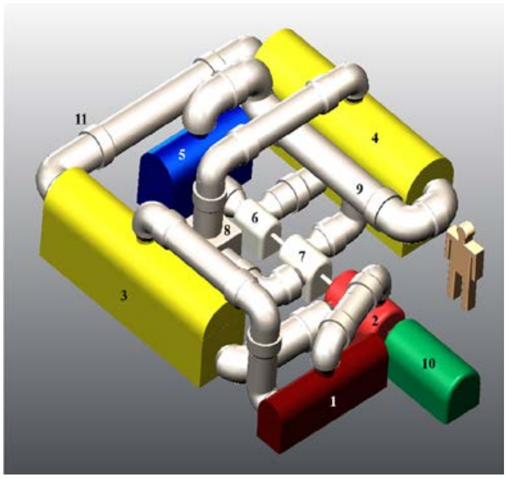

Fig. 1. The module of S-CO_2 cycle for the SFR application

Table I. The design parameters of S-CO_2 cycle for the SFR application

Thermal power, MW_{th}	76.5	Turbine inlet temperature, ^oC	508.4
CO_2 mass flow rate, kg/s	606.1	Compressor inlet temperature, ^oC	31.3
S-CO_2 cycle layout	Recompression	Turbine / MC / RC isentropic efficiency, %	92.5 / 88.2 / 91.1
Thermal efficiency, %	44.6	HTR / LTR effectiveness, %	95 / 95
Heat exchanger total pressure drops, %	5.5	Turbomachinery rotating speed, RPM	7,200
Compressor inlet / outlet pressure, MPa	7.5 / 20.2	Heat exchanger total volume, m^3	0.91

2. Off-design performance of S-CO_2 turbomachinery

To estimate the off-design performance of S-CO_2 turbomachineries, KAIST-TMD, 1-D mean line turbomachinery design code developed by KAIST research team was utilized [4]. The off-design performance of S-CO_2 turbomachineries are utilized for the Quasi-static system analysis code evaluation. Based on the design parameters of S-CO_2 turbomachinery, the off-design performance of S-CO_2 compressor and turbine is estimated as shown in Fig. 2. To utilize the off-design performance map for the system analysis, the equivalent mass flow indicates the off-design performance in various conditions. The equivalent mass flow ($\hat{m}$) is defined as below.

$$\hat{m}_{eq} = \hat{m}\frac{\sqrt{\theta}}{\delta}\varepsilon \quad (1)$$

$$\theta = \left[\frac{\frac{\gamma_a}{\gamma_a+1}T_a}{\frac{\gamma_{ref}}{\gamma_{ref}+1}T_{ref}}\right]^2 \quad (2)$$

$$\delta = \frac{P_a}{P_{ref}} \quad (3)$$

$$\varepsilon = \frac{\gamma_{ref}\left(\frac{2}{\gamma_{ref}+1}\right)^{\frac{\gamma_{ref}}{\gamma_{ref}-1}}}{\gamma_a\left(\frac{2}{\gamma_a+1}\right)^{\frac{\gamma_a}{\gamma_a-1}}} \quad (4)$$

where $\hat{m}$, γ, P, T are mass flow rate, specific heat ratio, pressure and temperature, respectively.

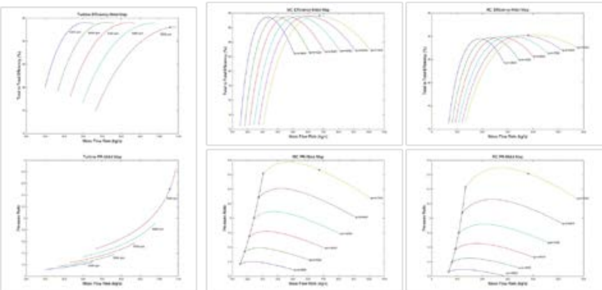

Fig. 2. Off-design performance of S-CO_2 turbomachinery

3. Quasi-static system analysis code

With the preliminary component design and performance parameters, a quasi-static system code is developed and its algorithm is shown in Fig. 3. The thermal efficiencies are predicted for the heat sink temperature variation as shown in Fig. 4. From the annual database of sea water temperature in East sea region, the maximum and minimum temperatures are 23.8 and 7.4, respectively. As the compressor inlet temperature increases, the net power decreases due to pumping power increase to maintain the compressor inlet temperature. An abrupt decrease in thermal efficiency is shown when the heat sink temperature is 23.8°C.

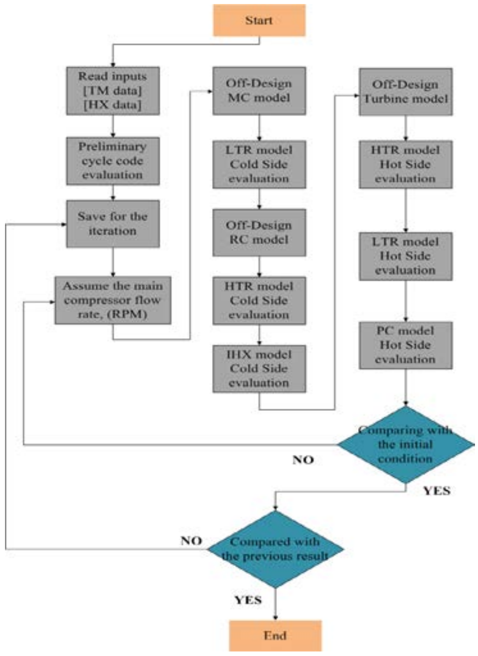

Fig. 3. a quasi-static analysis code algorithm

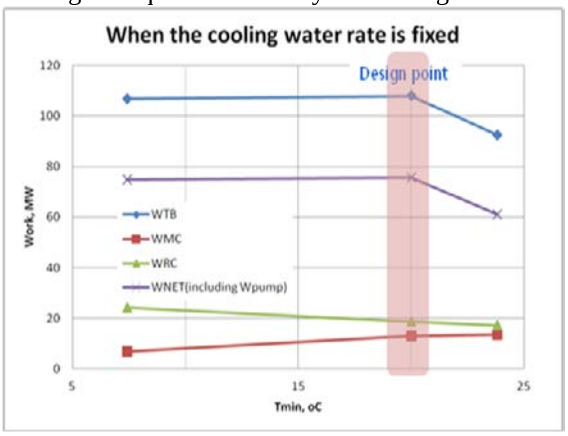

Fig. 4. Thermal efficiency of S-CO_2 cycle with the compressor inlet temperature variation

4. Summary and further works

A S-CO_2 cycle for PG-SFR is designed and assessed for off-design performance with the heat sink temperature variation. The heat sink temperature conditions are referred from the annual database of sea water temperature in East sea. When the heat sink temperature increases, the compressor inlet temperature can be influenced and the sudden power decrease can happen due to the large water pumping power. When designing the water pump, the pumping margin should be considered as well.

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