Thermal analysis on N_2 and S-CO_2 Brayton cycle for the energy conversion system of small scale ultra-long cycle fast reactor

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1. Introduction

An ultra-long cycle fast reactor (UCFR) is one of the SFR designs operating in a long cycle without refueling. The operational mechanism of long cycle fast reactor is once-through fuel cycle through breed and burn system. The benefits of long cycle fast reactor include capital/operation cost reductions, low proliferation risk, and the interim storage of light water reactor (LWR) spent fuel [1].

For the power conversion system of next generation nuclear reactor, Brayton cycle has been mainly considered. Brayton cycle not only increases overall thermal efficiency in corresponding temperature range of GenIV reactors, but also solves sodium-water reaction issues. As a working fluid in Brayton cycle, many inactive gases are selected. Among those candidates, supercritical CO_2 (S-CO_2) and nitrogen (N_2) has been focused on [2-3]. Dostal et al. [4] and Cha et al. [5] proposed S-CO_2 Brayton cycle for SFR, while CEA in France has developed nitrogen power cycle for ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) [6].

For the energy conversion system of small scale UCFR, a nitrogen Brayton cycle was introduced by author [7]. For the optimization of nitrogen Brayton cycle, sensitivity study was performed and the major factors for thermal design of the cycle were optimized.

In this study, S-CO_2 and N_2 as working fluid of Brayton power cycle for small scale UCFR were compared in terms of thermal performance. In addition, the nitrogen power cycle without intermediate loop was also analyzed.

2. Design consideration for power conversion system

2.1 Subchannel analysis data of UCFR-100

Seo et al. [8] analyzed subchannel characteristics of UCFR-100 using MATRA-LMR. The major parameters were axial fuel rod centerline temperature, axial cladding surface temperature and exit temperature of the coolant. Table 1 shows the results of coolant exit temperature from the core of UCFR-100. The average coolant exit temperature of beginning of cycle (BOC) is 485℃ on average and 529℃ as considering peaking factor, while the coolant temperature at the middle of cycle (MOC) is 485℃ on average and 526℃ in the hot channel. And the coolant exit temperature at the end of cycle (EOC) is 485℃ on average and 517℃ in the hot channel. The sodium mass flow rate of primary loop is 10.08kg/s for a single assembly and 3507.84kg/s for the core.

Table 1. Subchannel analysis results of UCFR-100 [8]

Subchannel parameters	
Coolant exit temperature from core at BOC (℃)	485
Coolant exit temperature from core at MOC (℃)	485
Coolant exit temperature from core at EOC (℃)	485
Coolant mass flow rate (kg/s)	3507.84
Maximum pressure drop (kPa)	20

2.2 Layout design of power conversion system

The reference layouts of S-CO_2 and N_2 power conversion systems for the thermodynamic evaluation were designed based on the previous studies [5-6] to evaluate their thermal performances only.

S-CO_2 power conversion system adopted a single recompression cycle shown in Fig. 1. It includes two compressors with two recuperators to minimize heat loss and regenerate exhausted heat.

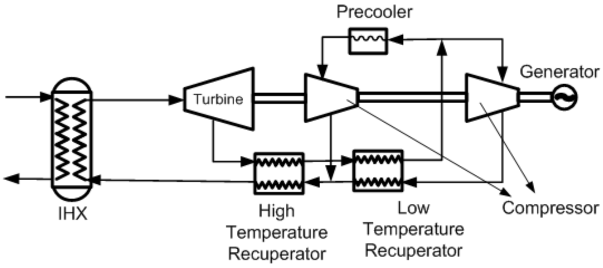

Fig. 1 BOP configuration of S-CO_2 power conversion system for UCFR-100 with intermediate loop

N_2 power conversion system includes recuperated process with single intercooler. It consists of a low pressure compressor, a high pressure compressor, a turbine, a pre-cooler, an inter-cooler, a recuperator and a generator. Fig. 2 shows the BOP configuration including intermediate loop. In addition, the BOP configuration without intermediate loop is shown in Fig. 3.

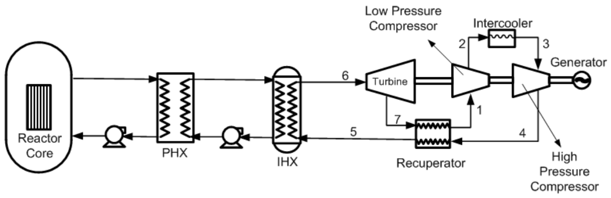

Fig. 2 BOP configuration of N_2 power conversion system for UCFR-100 with intermediate loop

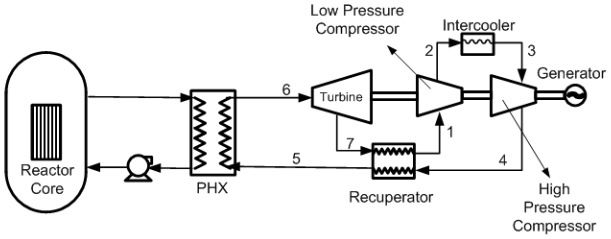

Fig. 3 BOP configuration of N_2 power conversion system for UCFR-100 without intermediate loop

To evaluate thermal performance of each power cycle, theoretical cycle efficiency was calculated using following expressions [6].

$$\eta_{cycle} = \frac{w_{cycle}}{q_{cycle}} = \frac{w_t - w_{lpc} - w_{hpc}}{q_{cycle}} \tag{1}$$

where w_{cycle} is the work received by the turbine shaft (w_t) coupled by two compressors (w_{lpc}, w_{hpc}), and q_{cycle} is the heat exchanged through the IHX.

(1) can be re-written using enthalpies *h*.

$$\eta_{cycle} = \frac{w_t - w_{lpc} - w_{hpc}}{q_{cycle}} = \frac{(h_6 - h_7) - (h_2 - h_1) - (h_4 - h_3)}{h_6 - h_5} \tag{2}$$

The efficiencies of a turbine and compressors are expressed as follows.

$$\eta_t = \frac{h_6 - h_7}{h_6 - h_{7s}} \tag{3}$$

$$\eta_{lpc} = \frac{h_{2s} - h_1}{h_2 - h_1} \tag{4}$$

$$\eta_{hpc} = \frac{h_{4s} - h_3}{h_4 - h_3} \tag{5}$$

The effectiveness of primary heat exchanger, intermediate heat exchanger and recuperator are given by next expressions.

$$\varepsilon_{PHX} = \frac{T_{Na_2,PHX,out} - T_{Na_2,PHX,in}}{T_{Na_1,PHX,in} - T_{Na_2,PHX,in}} \tag{6}$$

$$\varepsilon_{IHX} = \frac{m_{Na_2} c_{Na_2} (T_{Na_2,IHX,in} - T_{Na_2,IHX,out})}{C_{\min(Na,gas)} (T_{Na_2,IHX,in} - T_{gas,in})} \tag{7}$$

$$\varepsilon_{rcp} = \max\left[\frac{h_5 - h_4}{h_7 - h_2}, \frac{h_7 - h_1}{h_7 - h_2}\right] \tag{8}$$

A pinch point of each heat exchange is assumed to hot fluid inlet temperature minus cold fluid outlet temperature.

3. Sensitivity study on power cycle

For a comparison of power cycle designs, the major parameters including maximum pressure (P_6), efficiency of each component (η_t, η_{lpc}, η_{hpc}), pinch points of heat exchangers, and different coolant exit temperatures from the core was evaluated.

The effectiveness of heat exchangers and recuperator were 95%. The cold point of the cycle was set as 20℃. The compression ratios of low pressure compressor and high pressure compressor were optimized as 1.4 and 1.6, respectively. Pressure drop was assumed to be 40 kPa for the heat exchanger and recuperator.

3.1 Maximum pressure

The maximum pressure of the cycle is achieved at point 4, where the gas is compressed by high pressure compressor. For the sensitivity study, the efficiency of the turbine, low and high pressure compressors were fixed at 90%, 85%, 85% respectively and the pinch point was set as 15℃. Corresponding maximum mass flow rates of coolant were 4397 kg/s for intermediate sodium.

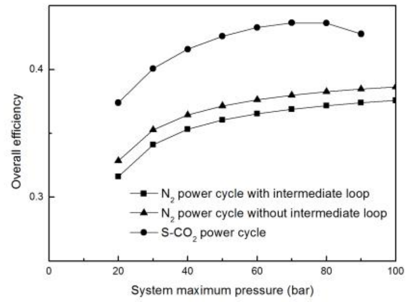

Fig. 4. The overall efficiency of three different power conversion systems as a function of maximum pressure

Figure 4 shows the overall efficiency of the cycle with increasing maximum pressure from three different designs. In the range of 20 – 100 bar of the maximum pressure, overall efficiency was varied from about 32% to 43%. The overall efficiency of S-CO_2 cycle gives the highest values for all maximum pressure points, while the difference decreases after 70 bar. And eliminating intermediate loop produces 1% enhancement of overall thermal efficiency. Although S-CO_2 cycle shows the highest thermal efficiency, its safety issue related to sodium-CO_2 reaction producing solid products [9] questions the applicability to the reactor. Instead, N_2 cycle without intermediate loop can give comparable thermal performance in high pressure region above 70 bar, which also guarantees safety of nuclear power plant.

3.2 Pinch point

The maximum pressure was fixed at 80 bar, and the efficiencies of turbine, low-pressure compressor and high-pressure compressor were set as 90%, 85%, 85%, respectively. Corresponding maximum mass flow rates of coolant were 4397 - 6473 kg/s for intermediate sodium.

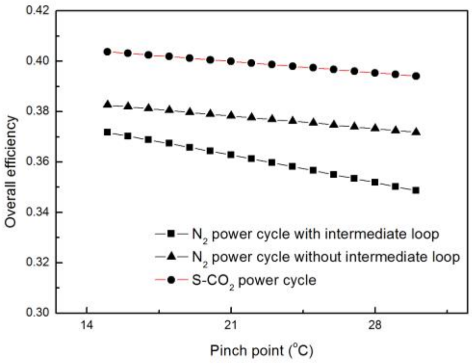

Fig. 5. The overall efficiency of three different power conversion systems as a function of pinch point

Comparing S-CO_2 cycle and N_2 cycle with intermediate loop, as the pinch point increases, the difference of thermal efficiency becomes maximum value of about 8%. However, comparing S-CO_2 cycle and N_2 cycle without intermediate loop, the difference of thermal efficiency is only about 2%. Assuming that pinch point would be maintained in minimum, S-CO_2 cycle and N_2 cycle without intermediate loop show similar thermal performance. Thus, N_2 cycle without intermediate loop gives advantages in the aspect of both thermal performance and reactor safety.

3.3 Efficiency of each component

The efficiencies of turbine and compressors slightly vary the overall efficiency of the cycle. Selected components were turbine, low-pressure compressor, and high-pressure compressor. The maximum pressure was fixed at 80 bar, and the pinch point was set as 15°C. Corresponding maximum mass flow rates of coolant were 4397 kg/s for intermediate sodium.

For all components, S-CO_2 cycle shows the highest thermal efficiency as shown in Figs 6, 7, and 8. However, as isentropic efficiency of each component increases, the difference between S-CO_2 and N_2 cycle becomes small. The minimum thermal efficiency differences between S-CO_2 cycle and N_2 cycle without intermediate loop are about 3%, which are acceptable considering the perfect safety of nitrogen cycle. Thus, if high isentropic efficiencies of compressors and turbine are maintained, N_2 cycle without intermediate loop gives more advantages than S-CO_2 cycle for small scale UCFR in the aspect of both thermal performance and safety of reactor.

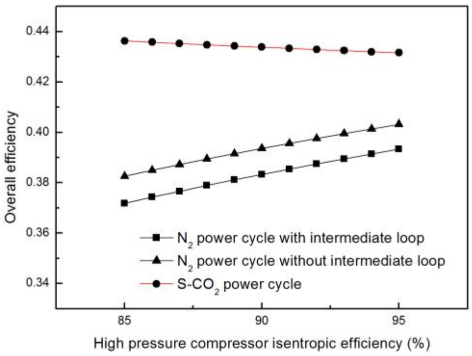

Fig. 6. The overall efficiency of three different power conversion systems as a function of high pressure compressor isentropic efficiency

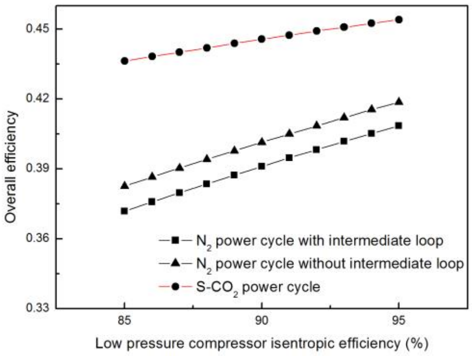

Fig. 7. The overall efficiency of three different power conversion systems as a function of low pressure compressor isentropic efficiency

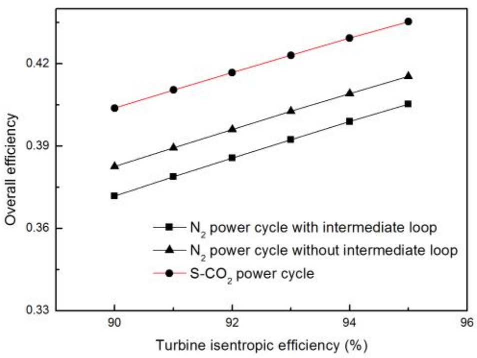

Fig. 8. The overall efficiency of three different power conversion systems as a function of turbine isentropic efficiency

4. Conclusions

For the power conversion system of next generation nuclear reactor, Brayton cycle has been mainly considered. Among the candidates for working fluid in Brayton power cycle, S-CO_2 and N_2 are analyzed in thermal aspect. For the major parameters including maximum system pressure, isentropic efficiencies of compressor and turbine, and pinch point, S-CO_2 cycle shows the highest thermal performance. However, N_2 cycle without intermediate loop gives comparable thermal performance, if high pressure around 70bar and high isentropic efficiency of each component are maintained. In addition, N_2 cycle without intermediate loop secures the safety of reactor compared to S-CO_2 cycle. Thus, N_2 cycle without intermediate loop is the most suitable for the energy conversion system of small scale UCFR. Further work will be layout optimization and turbomachinery analysis of N_2 power cycle.

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