Sensitivity study on nitrogen Brayton cycle coupled with a small ultra-long cycle fast reactor

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1. Introduction

Among Gen IV nuclear reactors, a sodium fast reactor (SFR) is the most promising type of reactors. The ultra-long cycle fast reactor (UCFR) is one of the SFR designs, which is operated in a long cycle without refueling. The concept of UCFR is based on the breed and burn system which is a once-through fuel cycle. The main characteristics of UCFR are constant neutron flux and power density. They move their positions every moment at constant speed along with axial position of fuel rod for 60 years [1].

Simultaneously with the development of the reactors, a new power conversion system has been considered. To solve existing issues of vigorous sodium-water reaction in SFR with steam power cycle, many researchers suggested a closed Brayton cycle as an alternative technique for SFR power conversion system. Many inactive gases are selected as a working fluid in Brayton power cycle, mainly supercritical CO_2 (S-CO_2) [2,3,4]. However, S-CO_2 still has potential for reaction with sodium. CO_2-sodium reaction produces solid product, which has possibility to have an auto ignition reaction around 600℃ [5]. Thus, instead of S-CO_2, CEA in France has developed nitrogen power cycle for ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) [7,8,9]. In addition to inactive characteristic of nitrogen with sodium, its thermal and physical similarity with air enables to easily adopt to existing air Brayton cycle technology [5].

In this study, for an optimized power conversion system for UCFR, a nitrogen Brayton cycle was analyzed in thermodynamic aspect. Based on subchannel analysis data of UCFR-100 [6], a parametric study for thermal performance of nitrogen Brayton cycle was achieved.

2. Subchannel analysis on UCFR-100

Seo et al. [6] analyzed subchannel characteristics of UCFR-100 using MATRA-LMR. The major parameters analyzed were axial fuel rod centerline temperature, axial cladding surface temperature and exit temperature of coolant.

2.1 Design parameters of UCFR-100

The UCFR-100 has hexagonal core layout. There are 348 drivers in an inner region of 10 radial rings, 13 control rods, and 234 reflectors in an outer region of radial 3 rings in the UCFR-100 core. The major design parameters of UCFR-100 are shown in table 1.

Table 1. Major design parameters of UCFR-100 [6]

	Parameters	*UCFR-100*
Core	Core thermal output (MWth)	260
	Core electric power (MWe)	100
	Core inlet temperature (℃)	427
	Total core height (active core height) (cm)	200 (100)
	Core diameter (cm)	379.5
	Pins per assembly	91
	Fuel material	U-5Zr
	Cladding material	HT9
	Rod outer diameter (cm)	1.49
	Rod pitch (cm)	1.60175
Pin	Pitch per diameter (P/D)	1.075
	Cladding thickness (cm)	0.04
	Duct wall thickness (cm)	0.3
	Duct inside flat to flat distance (cm)	15.6
	Average heat flux (W/cm^2)	17.5

2.2 Subchannel analysis data of UCFR-100

Table 2 shows the results of coolant exit temperature from the core of UCFR-100. The average coolant exit temperature of BOC is 485℃ on average and 529℃ as considering peaking factor, while the coolant temperature at the MOC is 485℃ on average and 526℃ in the hot channel. And the coolant exit temperature at the EOC is 485℃ on average and 517℃ in the hot channel. The detailed information about a radial peaking factor is described in [6].

Table 2. Subchannel analysis results of UCFR-100 [6]

Subchannel parameters	
Coolant exit temperature from core at BOC (℃)	529
Coolant exit temperature from core at MOC (℃)	526
Coolant exit temperature from core at EOC (℃)	517
Coolant mass flow rate (kg/s)	10.08
Maximum pressure drop (kPa)	20

3. Design considerations for power cycle

For a thermodynamic study on power cycle of UCFR-100, closed Brayton cycle composed of single intercooling and recuperator process is considered. The schematic layout of Brayton cycle for UCFR-100 and the corresponding T-s diagram are shown in Fig. 1 and Fig. 2, respectively.

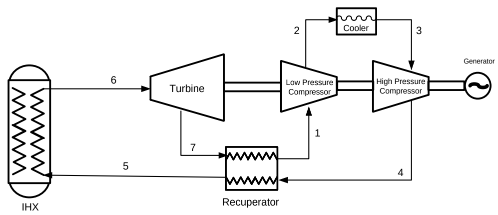

Fig. 1. Schematic layout of Brayton cycle for UCFR-100

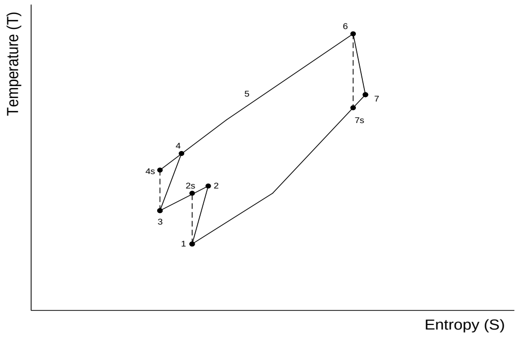

Fig. 2. T-s diagram of proposed Brayton cycle for UCFR-100

Based on the proposed Brayton cycle, the theoretical cycle efficiency is given by following expression [7].

$$\eta_{cycle} = \frac{w_{cycle}}{q_{cycle}} = \frac{w_t - w_{lpc} - w_{hpc}}{q_{cycle}} \quad (1)$$

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.

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

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

$$\eta_t = \frac{h_6 - h_7}{h_6 - h_{7s}} \quad (3)$$

$$\eta_{lpc} = \frac{h_{2s} - h_1}{h_2 - h_1} \quad (4)$$

$$\eta_{hpc} = \frac{h_{4s} - h_3}{h_4 - h_3} \quad (5)$$

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

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

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

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

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

4. Sensitivity study on power cycle

For a sensitivity study on power cycle of UCFR-100, several parameters were controlled. The major parameters included 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 at BOC, MOC, and EOC, with nitrogen as a working fluid (N_2). The sensitivity test range of each parameter is shown in table 2.

Table 3. Major controlled parameters

Parameters	*Range*
Maximum pressure (bar)	10 - 150
Turbine isentropic efficiency (%)	90 – 95
Low pressure compressor isentropic efficiency (%)	85 – 90
High pressure compressor isentropic efficiency (%)	85 – 90
Pinch point of heat exchanger (°C)	15 – 30
Core exit coolant temperature at BOC (°C)	529
Core exit coolant temperature at MOC (°C)	526
Core exit coolant temperature at EOC (°C)	517

The mass flow rate of Na coolant in intermediate loop was assumed to be same as that in primary loop. The effectiveness of heat exchangers and recuperator were 95%. The cold point of the cycle was set as 20°C. The low pressure compressor and high pressure compressor were optimized as 1.4 and 1.6, respectively [8]. Pressure drop was assumed to be 40 kPa for the heat exchanger and recuperator.

4.1 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°C. Corresponding maximum mass flow rates of coolant were 724 kg/s for intermediate sodium and 2139 kg/s for nitrogen. Then calculated minimum turbine inlet temperature was 487°C.

Among the design parameters, maximum pressure shows the most significant effect on the overall efficiency. Figure 3 shows the overall efficiency of the cycle with increasing maximum pressure at three different stages. In the range of 10 – 150 bar of the maximum pressure, overall efficiency was varied from about 27% to 41%. At the lower pressure, the overall efficiency increases drastically, while it becomes saturated after about 80 bar. Furthermore, the power cycle of UCFR-100 maintains its performance during the operation comparing overall efficiency of each stage. Thus, the system maximum pressure should be optimized at about 80 bar, since the pressure over 80 bar damages the components of the power cycle rather than increases the overall efficiency.

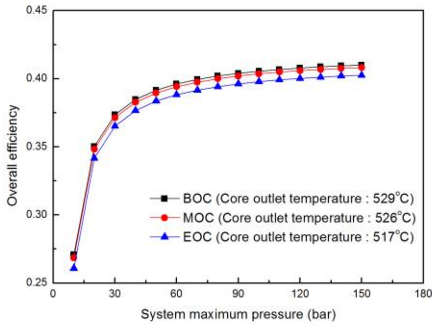

Fig. 3. The overall efficiency as a function of maximum system pressure (nitrogen, pinch point : 15 ℃, ε_T, ε_{lpc}, ε_{hpc} : 90%, 85%, 85%, with intermediate loop)

4.2 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℃. Corresponding maximum mass flow rates of coolant were 724 kg/s for intermediate sodium and 1719 kg/s for nitrogen. Then the calculated minimum turbine inlet temperature was 487℃.

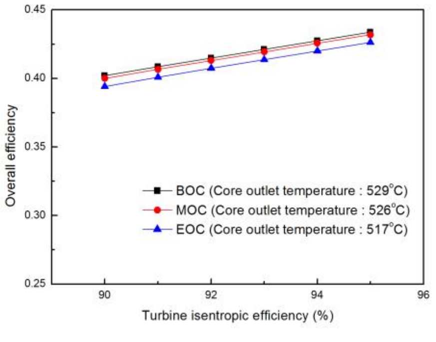

Fig. 4. The overall efficiency as a function of turbine isentropic efficiency (nitrogen, maximum pressure : 80bar, pinch point : 15 ℃, ε_{lpc} , ε_{hpc} : 85%, 85%, with intermediate loop)

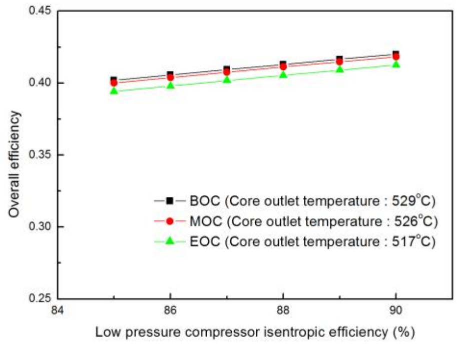

Fig. 5. The overall efficiency as a function of low pressure compressor isentropic efficiency (nitrogen, maximum pressure : 80bar, pinch point : 15 ℃, ε_T , ε_{hpc} : 90%, 85%, with intermediate loop)

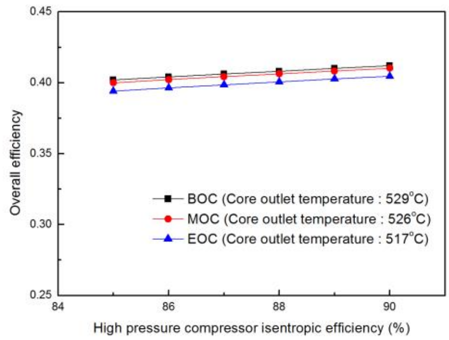

Fig. 6. The overall efficiency as a function of high pressure compressor isentropic efficiency (nitrogen, maximum pressure : 80bar, pinch point : 15 ℃, ε_T , ε_{lpc} : 90%, 85%, with intermediate loop)

Figs. 4, 5, and 6 show the overall efficiencies of the cycle as a function of component efficiency at three different stages. For the all cases, it is obvious that increasing efficiency of each component enhances the overall efficiency, while their sensitivities are very small. Thus, the efficiency of component should be optimized in the aspect of material constraint or manufacturing process.

4.3 Pinch point

In the case that the coolant outlet temperature from the core is restricted, the pinch point significantly affects to the design of heat exchanger. For the optimization of pinch point of the heat exchanger, sensitivity study in the range of 15 – 30℃ was performed. 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 724 kg/s for intermediate sodium and 1806 kg/s for nitrogen. Then the calculated minimum turbine inlet temperature was 457°C.

Figure 7 shows the overall efficiency of the cycle with increasing pinch point of heat exchanger at three different stages. As the pinch point increases, the temperature difference between sodium inlet and gas outlet from the IHX increases reducing the overall efficiency of the cycle. Thus, heat exchanger should keep minimal value of pinch point based on its own product characteristic to optimize the overall power cycle.

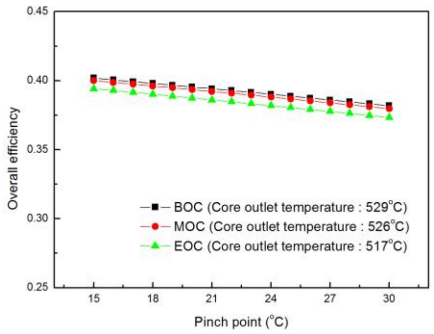

Fig. 7. The overall efficiency as a function of pinch point (nitrogen, maximum pressure : 80 bar, ε_T, ε_{lpc} , ε_{hpc} : 90%, 85%, 85%, with intermediate loop)

5. Conclusions

Nitrogen Brayton cycle coupled with UCFR-100 was optimized from the sensitivity studies including system maximum pressure, efficiency of each component and the pinch point of the heat exchanger. The system maximum pressure significantly affects to the overall efficiency of cycle, while other parameters show little effects. Little differences of the overall efficiencies for all cases between three stages (BOC, MOC, EOC) indicate that the power cycle of UCFR-100 maintains its performance during the operation. The comparison with other gases will be the next work to optimize the power cycle for UCFR-100.

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