Development of Computational Code for Heat Balance Analysis in N_2 Brayton Cycle Power Conversion System coupled with an SFR

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1. Introduction

A traditional Rankine cycle power conversion system (PCS) has been employed in most nuclear power plants using various well-proven technologies. In case of a sodium-cooled fast reactor (SFR), however, the use of a Rankine cycle PCS necessarily results in a potential chemical reaction between liquid sodium and water (hereafter called sodium-water reaction, SWR) when an anticipated pressure boundary failure takes place in a steam generator unit. To cope with this kind of an unexpected event, lots of countermeasures to protect or mitigate an SWR event have been employed in conventional SFR designs. However, most design features against SWRs would eventually result in deteriorations of plant economics.

In order to resolve the crucial safety and economic issues, a gas turbine Brayton cycle power generation using CO_2 [1], He [2], and N_2 [3] as its working fluid have been taken into account for the main power conversion option in SFRs. It has been recently reported that supercritical CO_2 Brayton cycle PCS can achieve higher thermo-dynamic efficiency than that of other gas turbine cycles using He, air, or N_2. This is mainly due to minimized compression works near the critical point of supercritical CO_2. Based on its basic nature, much smaller size of gas turbine can be accomplished and the construction cost would be reduced drastically.

For the case of SFRs coupled with supercritical CO_2 power cycle, however, there can be still higher possibility of potential pressure boundary failure and consequential chemical reaction between liquid sodium and CO_2 gas (hereafter called sodium-CO_2 interaction). According to previous researches on this issue [1], sodium-CO_2 interaction also shows critical design concerns during a pressure boundary rupture event, which are auto-combustion of sodium coolant, solid reaction product formation and its traveling inside the system. This feature actually makes the application of supercritical CO_2 Brayton cycle power conversion option to SFR designs very hesitating.

To this end, an N_2 or an air Brayton cycle PCS options have been recently considered for the design of SFR system. Since most design techniques of turbo-machineries for air have been already proven well, the use of N_2 can be very promising for near-term deployment for an advanced power conversion options for SFRs. Moreover, a chemically inert feature of N_2 gas is one of the most essential benefits free from a conventional SWR event.

In this paper, the computational code to set the heat balance and to obtain cycle efficiency of N_2 Brayton cycle power conversion system coupled with an SFR has been developed and its verification process has been introduced by using the reference design of N_2 PCS in ASTRID [4].

2. Methods and Results

2.1 Methodology

In order to obtain key design factors of N_2 Brayton cycle PCS, a new one-dimensional computational code of RECOBA-N has been developed. A typical Brayton cycle power cycle with intercooling and regeneration process using N_2 as the working fluid was configured as shown in Fig.1 [4]. Most of the equations have been derived to obtain heat balance and thermo-dynamic efficiencies comprising two compressors, single turbine, and recuperators were set up. The state quantities at each point of the cycle were determined. It is assumed that the efficiencies of the compressor, turbine, and recuperator are constant for varying flow rates of the working fluid. Also, it is assumed that the pressure drop in the piping and each cycle component is constant ideally regardless of the flow rate. The outlet conditions of the compressor and turbine were also set up based on the definition of isentropic efficiency.

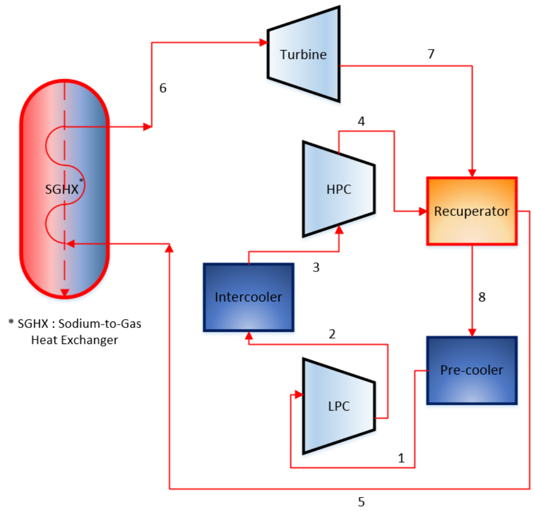

Fig. 1. Schematic of N_2 Intercooling and Regeneration Brayton Cycle

The heat balance equations for the Na-N_2 heat exchanger and the recuperator are as follows.

$$Q_h = m_t(h_6 - h_5)$$

$$h_5 - h_4 = h_7 - h_8$$

Where Q_h is the heat source input from the IHTS loop sodium to the N_2 gas in PCS, h is the enthalpy, and m_t is the mass flow rate. Moreover, the formula of the isentropic efficiency of the two compressors and turbine, and the formula of the effectiveness of the recuperator are also obtained as follows;

$$\varepsilon_r = \frac{C_{p78}(T_7 - T_8)}{C_{pmin}(T_7 - T_4)}$$

$$\eta_t = \frac{h_6 - h_7}{h_6 - h_{7'}}$$

$$\eta_{c1} = \frac{h_{2'} - h_1}{h_2 - h_1}$$

$$\eta_{c2} = \frac{h_{4'} - h_3}{h_4 - h_3}$$

where η_t is the isentropic efficiency of the turbine, and η_{c1} and η_{c2} are the isentropic efficiencies of the two compressors. ε_r represents the effectiveness of the regenerative heat exchanger, and C_p represents the specific heat at constant pressure. Also, C_{pmin} represents the smaller one of the average specific heat at constant pressure in the high and low temperature of the recuperator represented by C_{p78} and C_{p54}.

Although the cycle processes 4-5, 5-6, 7-8, and 8-1 are theoretically dealt with isobaric conditions, there are practical pressure drops in those processes. Therefore, the cycle analysis has been made by considering this practical situation.

In the above equations, there are six unknowns, such as h_2, h_3, h_4, h_7, T_8, and m_t. Physical properties and the state quantities at each point were obtained by using the subroutines to provide adequate properties of N_2 using the calculated pressure and temperature, or pressure and enthalpy. Thus, each unknown was obtained with the solutions of six equations simultaneously using the Gauss-Seidel method. The cycle efficiency η_{th} was calculated using the following equation as well;

$$\eta_{th} = \frac{Work_{in} - Work_{out}}{Heat_{in}} = \frac{W_t - W_{c1} - W_{c2}}{Q_h}$$

where, W_t, W_{c1}, and W_{c2} represent the turbine work and those of two independent compressors used in the cycle, respectively.

2.2 Results

In order to make the computational code verification developed by using the methods described in section 2.1, the calculation results using RECOBA-N were compared to the results of thermo-dynamic performance analyses of the N_2 Brayton cycle PCS in ASTRID. Table 1 and 2 show the results of cycle configuration by using state quantities, turbine, compressor efficiencies, and recuperator effectiveness at each point set by Alpy et al. [4]. The temperature and entropy at each point in the cycle configuration are also shown in Fig. 2.

Iteration process in code calculation was performed six times at least and the convergence criteria were determined to have a maximum temperature residual of $1\text{x}10^{-4}$. The obtained net plant efficiency was estimated to be 37.94%, which is very similar to that of 37.8% [4]. The discrepancies coming from input and output heat in whole cycle was evaluated to be approximately $4.44\text{x}10^{-2}$ MW, which accounts for about 0.006% of the heat input through the sodium-to-gas (N_2) heat exchanger.

Table 1. Efficiencies of Compressors and Turbine

Efficiency		Value
Polytropic Efficiency	LPC	88 %
	HPC	89 %
	Turbine	93 %
Recuperator Effectiveness		98 %

Table 2. State Quantities in Each Point for RECOBA-N Code Verification

Case	Alpy et al.[4]		RECOBA-N	
	T(ºC)	P(MPa)	T(ºC)	P(MPa)
1	27.00	-	27.00	8.13
2	60.00	-	62.00	11.38
3	27.00	-	27.00	11.38
4	74.00	-	76.18	18.20
5	355.00	-	365.09	18.10
6	515.00	18.00	515.00	18.00
7	381.00	-	381.71	8.57
8	89.00	-	82.29	8.57

* The pressure at each point in Alpy et al. is not shown except point 6

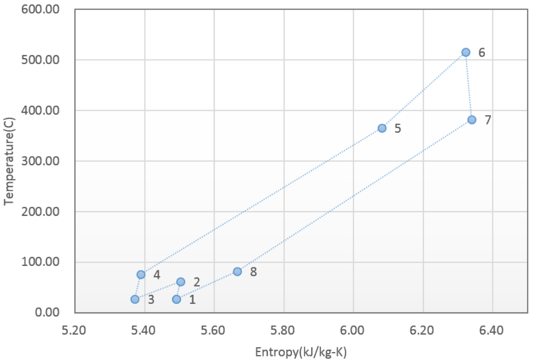

Fig. 2. T-s Diagram for ASTRID N_2 Brayton Cycle

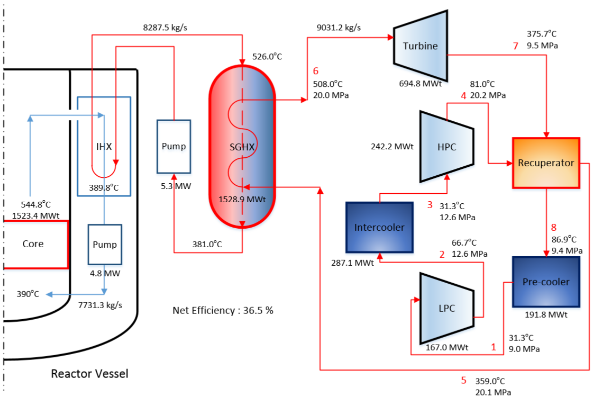

Fig. 3. Schematic of N_2 Brayton cycle for KALIMER-600

Table 3. State quantities comparison in each point between ASTRID and KALIMER-600

Case	ASTRID		KALIMER-600	
	T(°C)	P(MPa)	T(°C)	P(MPa)
1	27.00	8.13	31.25	9.02
2	62.00	11.38	66.71	12.63
3	27.00	11.38	31.25	12.63
4	76.18	18.20	81.01	20.21
5	365.09	18.10	359.04	20.11
6	515.00	18.00	508.00	20.01
7	381.71	8.57	375.68	9.53
8	82.29	8.57	86.91	9.43

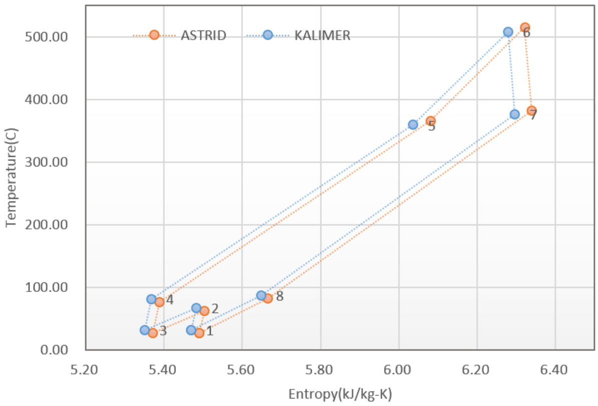

Fig. 4. T-s Diagram Comparison between ASTRID and KALIMER-600 N_2 Brayton Cycle

Based on the above backgrounds, the thermo-dynamic performance analysis of KALIMER-600 power conversion system coupled with N_2 Brayton cycle has been carried out with the similar cycle configuration as that of ASTRID [3]. As a result, the obtained net efficiency for N_2 Brayton cycle PCS for KALIMER-600 is approximately 36.5% as shown in Fig. 3. The comparison results in terms of state quantities between ASTRID and KALIMER-600 are also listed in Table 3 and depicted in Fig.4. It was found that the state of each point was somewhat different in both cases. This might be due to the differences from the outlet conditions (temperature and pressure) of the sodium-to-gas (N_2) heat exchanger. However, the T-s diagram that is depicted in Fig. 4 shows an almost similar pattern, which means that the computational code of RECOBA-N has been reasonably developed.

3. Conclusions

One-dimensional computer code of RECOBA-N was developed to obtain the heat balance data and cycle efficiency of N_2 gas Brayton cycle power conversion system coupled with an SFR.

In order to check the viability of the developed code, the key design variables configuring N_2 Brayton cycle system were compared with those of ASTRID employing N_2 Brayton cycle PCS. As a result, the state quantities at each point and cycle efficiency showed good agreement between both cases. As a future work, the optimized cycle configuration will be obtained by investigating cycle efficiencies in terms of cycle configuration changes. The design of each component constituting the thermo-dynamic cycle such as a turbine, compressor, recuperator, cooler, and so on will be carried out as well.

ACKNOWLEGEMENT

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REFERENCES

[1] J.H. Eoh, H.C. No, Y.H. Yoo, S.O. Kim, “Sodium-CO2 Interaction in a Supercritical CO_2 Power Conversion System Coupled with a Sodium Fast Reactor”, Nuclear Technology, Vol.173, No.2, pp.99-114, 2011

[2] Steven A. Wright, Milton E. Vernon, Paul S. Pickard, “Concept Design for a High Temperature Helium Brayton Cycle with Interstage Heating and Cooling”, Sandia Report, SAND2006-4147, Sandia National Laboratories, 2006.

[3] G. Laffont, L. Cachon, V. Jourdain, J.M. Fauque, “ASTRID Power Conversion System: Assessment on Steam and Gas Options”, International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13), 2013.

[4] N. Alpy, L. Cachon, D. Haubensack, J. Floyd, N. Simon, L. Gicquel, G. Rodriguez, M. Saez, G. Laffont, “Gas Cycle Testing Opportunity with ASTRID, the French SFR Prototype”, Supercritical CO_2 Power Cycle Symposium, 2011.