Heat Balance Study on Integrated Cycles for Hydrogen and Electricity Generation in VHTR - Part 2 -

Sang Il Lee[a*], Yeon Jae Yoo[a], Gyunyoung Heo[b], Soyoung Park[b], Yeon Kwan Kang[b]
[a] *Hyundai Engineering Company Ltd., Jongno-gu, Seoul 110-920, Korea*
[b] *Kyung Hee University, Yongin-si, Gyeonggi-do, 446-701, Korea*
[*]*Corresponding author: sang@hec.co.kr*

1. Introduction

The concept study of Hyundai Engineering Co., Ltd. on high temperature gas reactor was conducted from 2012 to 2014. A point design task related to preliminary feasibility study report is underway from 2015 to 2016 in order to demonstrate the research and apply for preliminary feasibility study of the government.

The support the research above, a previous paper [1] conducted concept design and analysis of thermal cycle. In the paper, reverse engineering was performed on SC-MHR proposed by NGNP to reconstruct it into PEPSE. This model was used to analyze sensitivity of key variables. The paper also presented a concept design of thermal cycle, where heat of nuclear reactor is partially used for hydrogen production and remaining heat is used to generate power through IHX.

This study introduces the results of concept designs on thermal cycle constructed using methods that are somewhat different from the previous results. As for the first method, efficiency under main steam condition proposed by NGNP was analyzed using ultra supercritical steam cycle, which exhibits highest efficiency among commercial technologies available. Another method was to prepare heat balance using supercritical CO2 cycle, which has recently been commercialized in small scale and is undergoing R&D efforts for scale-up.

2. Methods and Results

2.1 Reference Plant

In order to compare the benefits with the conventional ideas, we referred a steam / cogeneration process as a reference model, SC-MHR (Steam Cycle-Modular Helium-cooled Reactor) that proposed by the NGNP (Next Generation Nuclear Plant) as shown in Fig. 1 [1].

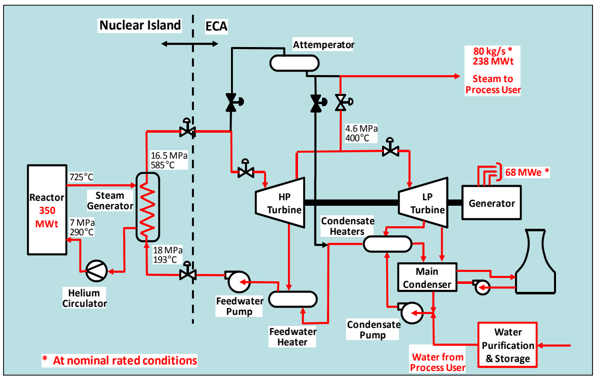

Fig. 1. SC-MHR configuration for conceptual design

SC-MHR can have several operating modes which are relevant for multiple demand-side purposes. All-Electrical Mode (AEM) operates only for the purpose of electricity generation. Rated Cogeneration Mode (RCM) uses approximately 60% of the total flow as process heat. The last, Turbine Bypass Mode (TBM) will be used to supply the process heat by blocking all flow to the turbines. If the nuclear side uses a part of heat for hydrogen production, the turbine side can use the only remaining heat source after subtracting it. As a reference case, the cycle performance indices are summarized in Table I. The inlet and outlet conditions in the steam generator are calculated in Table II.

Table I. Comparison of heat output per cycle performance indicators

	Without Hydrogen Production 350 MW		With Hydrogen Production 300 MW	
	Electrical output (MW)	Heat rate (kcal/kW-hr)	Electrical output (MW)	Heat rate (kcal/kW-hr)
AEM	148.831	2,035.7	129.204	2,034.4
RCM	67.884	4,467.2	62.177	4,230.3

Table II. Steam generator inlet and outlet conditions

	Inlet conditions				
	Temp (℃)	Pressure (kPa)	Enthalpy (kJ/kg)	Flow (kg/hr) *	Flow (kg/hr) **
AEM	193.3	20,684.3	831.3	469,785.7	402,673.5
RCM	193.3	20,684.3	831.5	469,785.7	402,673.5
TBM	193.3	18,762.7	830.6	345,505.9	-
	Outlet conditions				
	Temp (℃)	Pressure (kPa)	Enthalpy (kJ/kg)	Flow (kg/hr) *	Flow (kg/hr) **
AEM	585.0	16,499.2	3,530.2	469,785.7	402,673.5
RCM	585.0	16,499.2	3,530.2	469,785.7	402,673.5
TBM	585.0	16,499.2	3,530.2	345,505.9	-

* Without hydrogen production
** With hydrogen production

2.2 Reference Modelling

In the previous study, we performed the comparison of heat balances for the reference plant with AEM and RCM. Several assumptions were hypothesized. The entire cycle utilizes a loop using IHX (Intermediate Heat Exchanger) that has been proposed by KAERI (Korea Atomic Energy Research Institute) and NGNP. As shown in Fig. 2, the thermal output 350 MW is provided by the reactor, and 50 MW is assumed to move on the hydrogen production loop. The remaining 300 MW is used for generating electricity. The part enclosed by helium gas flows was analyzed by EES (Engineering Equation Solver), and the analysis of steam side was conducted by PEPSE. The basic assumptions are as follows.

- Supply heat to steam turbine cycle : 300 MWt
- First loop pressure drop : 10.13 kPa (0.1 atm)
- Second loop pressure drop : 10.13 kPa (0.1 atm)
- All rotating equipment's efficiency : 90 %
- Steam turbine cycle is a simple Rankine cycle.

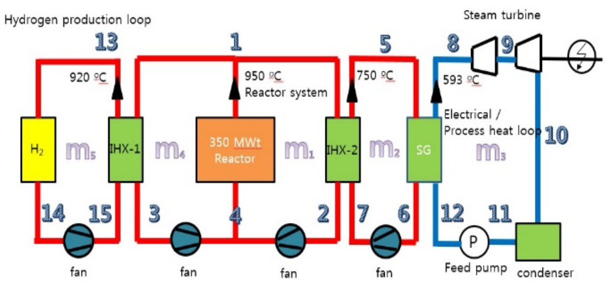

Fig. 2. IHX loop modeling

Table III. Main simulation results

No.	Temperature (℃)	Pressure (kPa)	Enthalpy (kJ/kg)	Flow (kg/kg)
1	950	7,000	4,822	416,217
2	445	6,900	2,203	469,959
4	450	7,000	2,227	328,124
5	750	7,000	3,784	
6	300	6,900	1,449	
7	303	7,000	1,465	
8	585	16,500	3,528	
9	384	4,600	3,166	
10	39	7	2,154	
11	39	7	163	
12	39	18,000	183	

Thermodynamic properties at each point that obtained by simulation is shown in Table III. The main results that can be obtained are summarized as follows.

- Gross efficiency (electrical output / reactor thermal output): 42 %
- Gross efficiency (electrical output / steam generator thermal output): 41 %
- Net efficiency ([electrical output – helium fan consumption in the first and second loop – pump consumption in the third loop] / reactor thermal output): 39%

Upon the additional calculation, we confirmed the results that approximately 5 % point net efficiency can be additionally achieved when regeneration and reheat cycle is attached. Therefore, if the additional optimization analysis is performed through the detailed design process, the net efficiency of the integrated cycle is expected to be at the level of 45 %.

2.3 Ultra-supercritical Steam Cycle

In Section 2.2, we conducted the simulation for an integrated cycle with nuclear and turbine side using IHX. In this case, the turbine side used the same operating conditions with those of NGNP. In this section, we assumed the nuclear side can provide better quality of heat such that higher pressure and temperature, for instance, ultra-supercritical condition steam can be supplied to turbine side.

Ultra supercritical cycle (USC) refers to a generation system operated at pressure higher than supercritical pressure based on critical point of water (pressure 225.54 kg/cm^2, temperature 374.15 ˚C). In other words, ultra-supercritical power plant is a power plant with steam pressure of 254 kg/cm^2 or above and main steam temperature of 593 ˚C or above. In general, efficiency is increased by 0.5 % when main steam temperature is increased by 10 ˚C and by 0.2 % when pressure is increased by 10 kg/cm^2. Studies are being actively conducted to increase temperature and pressure at power plants. Korea also experienced commercial construction for USCs in fossil-fueled plants. Starting with construction of Dangjin Thermal Power Plant Units 5 and 6 in 2006, a total of 10 power plant units are currently in operation [2].

This section summarizes the result of sensitivity analysis on key variables, which was performed by entering main steam conditions of NGNP into a simulation model developed to fit the ultra-supercritical power plant introduced earlier. The model was constructed using PEPSE

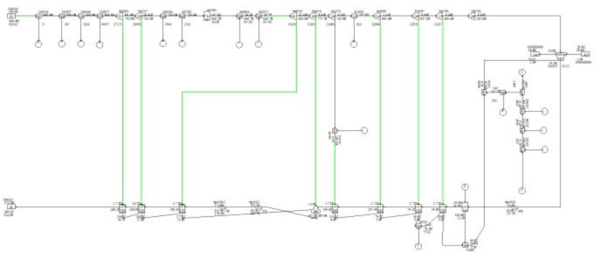

Fig. 3. Heat balance of ultra supercritical plant using NGNP steam conditions

A large-scale USC was modeled as a reference power plant for the USC cycle for comparing the performance of USC with that of the NGNP cycle. Since the model for USC was chosen in a typical design conditions, a more optimized design can probably be achieved in the engineering step. Table IV shows the thermodynamic properties at representative points in a heat balance.

Table IV. Results of reference USC model

No.	Descriptions
1	Steam Generator Outlet
2	High Pressure Turbine Outlet
3	Intermediate Pressure Turbine Outlet
4	Low Pressure Turbine Outlet
5	LP Feed Water Heater Outlet
6	HP Feed Water Heater Outlet

No.	Temperature (℃)	Pressure (kg/cm^2)	Enthalpy (kJ/kg)	Flow (kg/hr)
1	585.0	168.0	842.4	444118
2	342.6	28.8	741.4	367375
3	425.4	8.1	793.3	353723
4	32.6	0.1	595.0	299143
5	144.6	20.0	145.7	360166
6	260.2	212.2	271.0	444105

◯ Thermal load vs. Electrical output (Heat rate)

Assuming the case in which heat needed for hydrogen production is used on the nuclear side, electrical output and efficiency according to heat load supplied to the turbine side were calculated. Accordingly, heat load delivered to the turbine side with no hydrogen supply was assumed to be 100%.

Decreasing heat load yields decreasing electrical output and heat consumption rate. This result can be predicted easily because flow going into turbine is reduced.

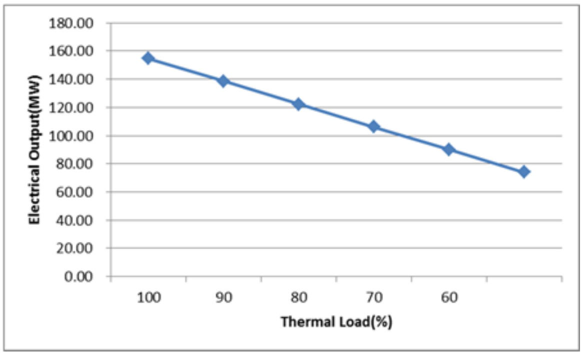

Fig. 4. Changes of electrical output (MW) according to thermal load (%)

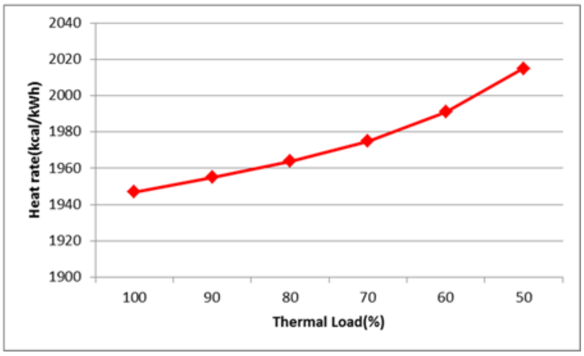

Fig. 5. Changes of heat rate (kcal/kWh) according to thermal load (%)

Table V below compares operating conditions of NGNP, supercritical (SC) cycle, and ultra-supercritical (USC) cycle. These are approximate values, and detailed operating conditions may somewhat differ for each power plant.

Table V. Comparison of performance (NGNP, SC, USC)

Cycle Condition	Temperature (℃)	Pressure (kg/cm^2)	Heat Rate (kcal/kWh)
NGNP	585	168.3	2035
SC	538	203.9	1928
USC	600	245.8	1840

In the previous study, we performed a sensitivity analysis for a few variables such as process heat flow, seawater temperature, and so on. As the same manner, various sensitivity study is easily possible in this case, which will be scheduled in the further study.

2.4 Supercritical CO2 Cycle

As another option for comparison, the modeling of a cycle that uses supercritical CO2 (S-CO2) as a coolant was done in this study. Since S-CO2 has only been embodied on a small scale for research purpose, it is uncertain whether S-CO2 can be used in large nuclear plants. Active R&D efforts are underway because of various advantages. A simulation model was developed to evaluate its value as a possible future option.

Supercritical CO2 generation system is a technology for efficient power generation based on Brayton cycle that uses CO2 as the working fluid. This technology can be applied to most of heat sources including nuclear power, thermal power and solar power. This general-purpose cycle can overcome geographical limits of nuclear power plants through application of air-cooled cooler, increasing efficiency of existing system by 3% or more using waste heat recovery. It can also reduce generation cost of solar power or embody coal-fired thermal power plant which does not emit CO2.

High temperature part of S-CO2 cycle was configured within the range that can be provided by nuclear side condition of NGNP. Cooling part was configured at the level achievable under standard atmospheric condition. The concept map of the cycle was based on data proposed by Sandia Lab. This is referred to as S-CO2 reference model in this paper [3].

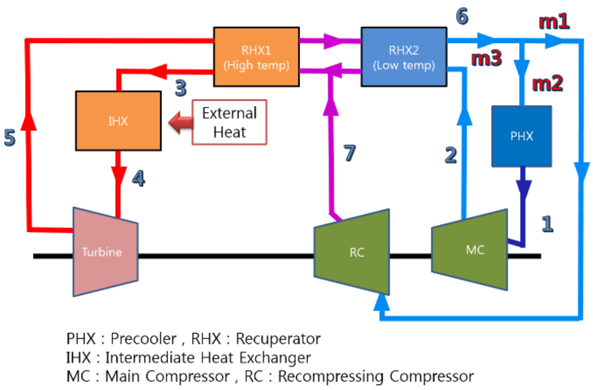

Fig. 6. Schematic diagram of S-CO2 cycle

Assuming that,

Turbine efficiency = $(h_{in}-h_{out})/(h_{in}-h_{out.isen})=0.9$
Compressor efficiency = $(h_{out.isen}-h_{in})/(h_{out}-h_{in})=0.9$
Compression ratio=$P_7/P_1=2.64$

Table VI shows the operating parameters of the main points when the external heat is assumed to be supplied to 350 MW.

Table VI. Main simulation results

No.	Temperature (℃)	Pressure (MPa)	Enthalpy (kJ/kg)	Flow (kg/s)
1	35.0	7.55	-111.7	1403
2	102.0	20.00	-75.9	1403
3	390.9	19.52	333.2	2338
4	512.8	19.29	482.9	2338
5	402.9	7.68	364.4	2338
6	105.8	7.50	24.29	2338
7	203.5	19.76	96.58	935

Cycle performance evaluation was replaced by sensitivity analysis of several design parameters because there is no existing reference cycle.

Assuming the case in which heat needed for hydrogen production is used on the nuclear side, electrical output and efficiency according to heat load supplied to the turbine side were calculated. Accordingly, heat load delivered to the turbine side with no hydrogen supply was assumed to be 100%.

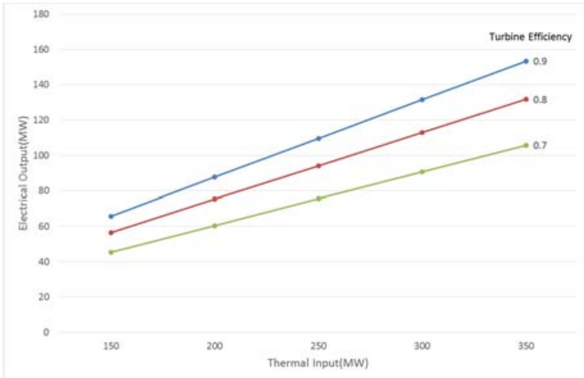

Fig. 7. Electrical output vs. Turbine efficiency and Thermal load

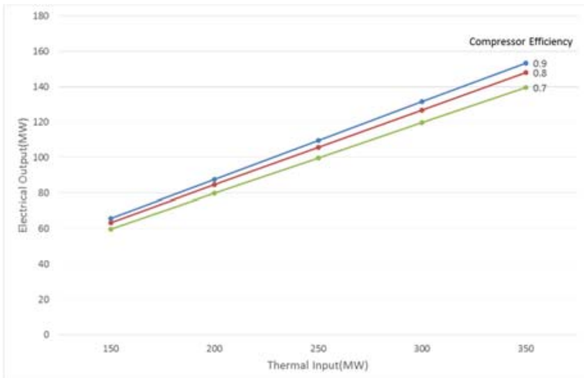

Fig. 8. Electrical output vs. Compressor efficiency and Thermal load

Since S-CO2 cycle has a simple structure with no surrounding facility, key performance indicators were calculated in this study while only changing efficiencies of turbine and compressor. Fig. 7 and Fig. 8 present data that analyzed heat load and electrical output according to efficiencies of turbine and compressor.

Table VII is the result for hypothesized conditions. The conditions at point 4 in Fig. 4 were referred from the original material. We assumed the conditions at point 4 as those of NGNP, those of supercritical rankine cycle, and those of ultra supercritical rankine cycle such that we can compare the benefit of S-CO2 with rankine cycles including SC or USC in Table 5. , the Another main steam condition was entered into the S-CO2 cycle reference model to observe changes. In order to compare changes with the result calculated in Section 2.3, the main steam condition adopted by SC and USC power plants in Section 2.3 was used as the main steam condition of S-CO2 for comparison. The results are as shown in Table 7.

Table VII. Comparison of S-CO2 performance on various inlet conditions

Cycle Conditions	Temperature (℃)	Pressure (kg/cm^2)	Heat Rate (kcal/kWh)
Reference	513	196.7	1880
Corresponds to NGNP	585	168.3	2094
Corresponds to SC	538	203.9	1774
Corresponds to USC	600	245.8	1519

Efficiency of S-CO2 increases when the main steam condition is improved, and it showed higher efficiency under same main steam condition compared to Rankine cycle.

3. Conclusions

As a part of concept design for high temperature gas reactor, this paper attempts different types of electricity generation cycle design and compares their advantages and disadvantages. A reference model was developed to change original design of NGNP. Sensitivity analysis can be performed according to changing performance of facility and external conditions. A Rankine cycle model operated under SC or USC condition was created by adding to a previous study to carry out key sensitivity analysis. In addition, a concept design model was also secured for S-CO2 cycle, which is receiving the spotlight as a future balance of plant. Data for future design will be prepared through supplementary study, and the ultimate objective is to make contribution to optimal design of high temperature gas reactor.

ACKNOWLEDGEMENT

This research was financially supported by Next Generation Nuclear System of Research Program for Nuclear Technology of Korea Ministry of Science, ICT & Future Planning (MSIP)

REFERENCES

[1] S. I. Lee, Y. J. Yoo, G. Y. Heo, S. Park, and Y. K. Kang, Heat Balance Study on Integrated Cycles for Hydrogen and Electricity Generation in VHTR, Transactions of Korea Nuclear Society Spring Meeting, Jeju, May 6-8, 2015.

[2] K. H. Ha, Technology trends of Ultra-Super critical (USC) power plants on domestic and foreign, Journal of the Electrical World / Monthly Magazine, p. 44-49, 2012.

[3] E. J. Parma, S. A. Wright, M. E. Vernon, D. D. Fleming, G. E. Rochau, A. J. Suo-Anttila, A. A. Rashdan, and P. V. Tsvetkov, Supercritical CO2 Direct Cycle Gas Fast Reactor (SC-GFR) Concept, Sandia National Laboratories, 2011.