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

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1. Introduction

Korea has experience of only using water as a coolant such as pressurized water reactors and heavy water reactors, while foreign countries have a number of operational performances for gas cooled reactors. Power density of the gas cooled reactor is lower, so there is no possibility of core melt. Also when the loss of coolant accident occurs, it has no risk of explosion caused by hydrogen generation due to no use of water. A gas cooled reactor has the advantage of being able to create a higher temperature coolant than a water cooled reactor. We can take advantage of supplying electricity as well as process heat. Recently, taking the export opportunity of a commercial nuclear power plants in UAE, Middle East area where politically stable and resource-rich seems promising for further nuclear business. Even if construction cost is more expensive than water cooled reactors, a high-temperature gas cooled reactor is an attractive option from the viewpoint of safety. It can reduce the domestic use of fossil fuels and secure power and water, which is the most important part of people's daily life. For example, using a gas cooled reactor the steam of 80 ~ 200 ℃ required for power generation and desalination can be supplied with high efficiency.

In this paper, we conducted the performance analysis and sensitivity study for a conceptual gas cooled reactor, particularly focusing on secondary system that can supply electricity and process heat. First, on the basis of the concept presented in previous studies, reverse engineering was performed to ensure the design heat balance diagram and the sensitivity analysis based on key variables was carried out. Next we changed the design options and performed additionally heat balance analysis for integrated cycles of hydrogen and electricity production.

2. Methods and Results

2.1 Reference Models

In this study, we adopted 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 Figure 1. SSCs (Structures, Systems and Components) of SC-MHR are consists of two main areas of NI (Nuclear Island) and ECA (Energy Conversion Area). The NI generates hot gas by nuclear power and provides them to the ECA. Part of the high energy in ECA is converted into electric power or process heat.

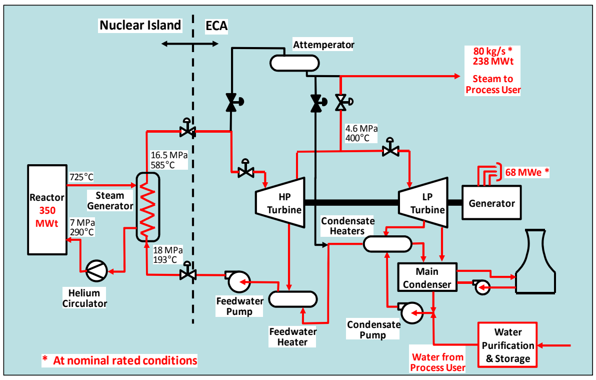

Figure 1. SC-MHR configuration for conceptual design

Thus the operational modes of ECA are divided in several ways depending on the operation purpose. 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. We use a part flow exiting the high pressure turbine of end portion to the process heat, and the flow channel to a heat exchanger and a deaerator is changed at this time. Turbine Bypass Mode (TBM) will be used to supply the process heat by blocking all flow to the turbines. On the other hand, if the NI side uses a part of heat for hydrogen production, the ECA side can use the remaining heat source after subtracting it. However, because the inlet and outlet conditions of the steam generator should be maintained, the flow rate needs to be adjusted. Inlet and outlet conditions in the steam generator of NI and ECA are shown in Table 1 and Table 2. For the TBM case, it can be flexible in case of hydrogen production according to conditions.

Table 1. Steam generator inlet and outlet conditions (Without hydrogen production)

	Inlet conditions			
	Temperature (°C)	Pressure (kPa)	Enthalpy (kJ/kg)	Flow (kg/hr)
AEM	193.3	20,684.3	831.3	469,785.7
RCM	193.3	20,684.3	831.5	469,785.7
TBM	193.3	18,762.7	830.6	345,505.9
	Outlet conditions			
	Temperature (°C)	Pressure (kPa)	Enthalpy (kJ/kg)	Flow (kg/hr)
AEM	585.0	16,499.2	3,530.2	469,785.7
RCM	585.0	16,499.2	3,530.2	469,785.7
TBM	585.0	16,499.2	3,530.2	345,505.9

Table 2. Steam generator inlet and outlet conditions (With hydrogen production)

	Inlet conditions			
	Temperature (°C)	Pressure (kPa)	Enthalpy (kJ/kg)	Flow (kg/hr)
AEM	193.3	20684.3	357.4	402,673.5
RCM	193.3	20684.3	357.5	402,673.5
	Outlet conditions			
	Temperature (°C)	Pressure (kPa)	Enthalpy (kJ/kg)	Flow (kg/hr)
AEM	585.0	16,499.2	3,530.2	402,673.5
RCM	585.0	16,499.2	3,530.2	402,673.5

2.2 Development of Heat Balance Models

In this study, we used PEPSE version 77 to simulate heat balance models. PEPSE is widely used in laboratories and engineering companies, which is developed by Scientech, USA. This code has the function of calculating and analyzing the thermal performance, efficiency when the boiler and turbine cycle of the plant are steady state. We can use in optimization study, sensitivity study, heat balance design, and performance prediction etc.

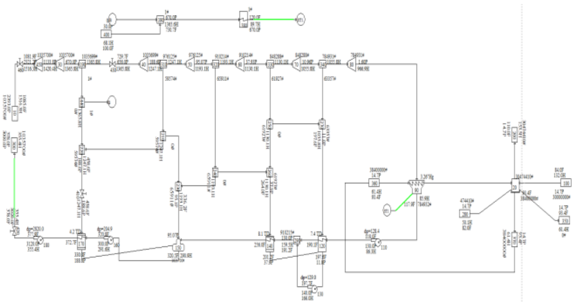

Figure 2. Modeling turbine cycle of the reference model with PEPSE

Figure 2 shows the model of the ECA using PEPSE, and it was compared with the reference heat balance provided by NGNP to ensure accuracy of the model. We adjusted the thermodynamic properties at each point, electrical output, heat rate, and Mollier Diagram within 0.5%

2.3 Sensitivity Studies

We performed a sensitivity analysis for the following variables:

○ Process heat flow vs. Electrical output (and heat rate)
A sensitivity analysis was performed by RCM because it treats the process heat. Increasing the flow that goes to process heat, the electrical output and heat rate are decreasing. This is the result that can be easily estimated because the flow going to the turbine decreases.

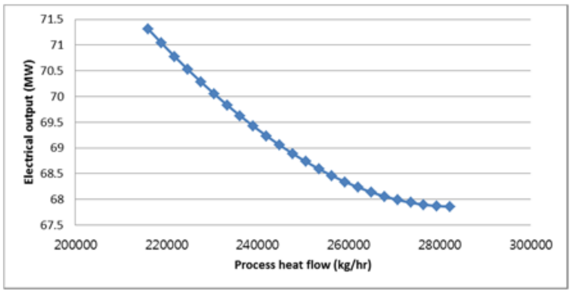

Figure 3. Changes in electrical output according to process heat flow

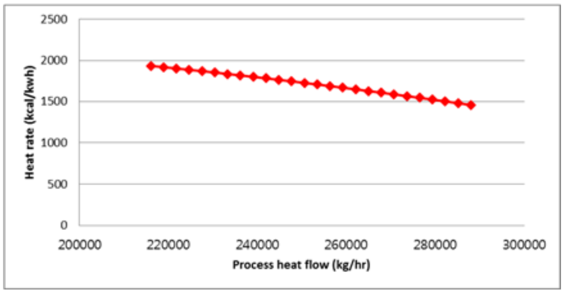

Figure 4. Changes in heat rate according to process heat flow

○ Seawater temperature (without cooling tower) vs. Electrical output (and heat rate)
This analysis was performed for AEM. In Figure 5 and 6, if sea temperature is going lower, electrical output is increasing, and heat rate is decreasing. Since the condenser vacuum is improved, we can understand efficiency will be higher.

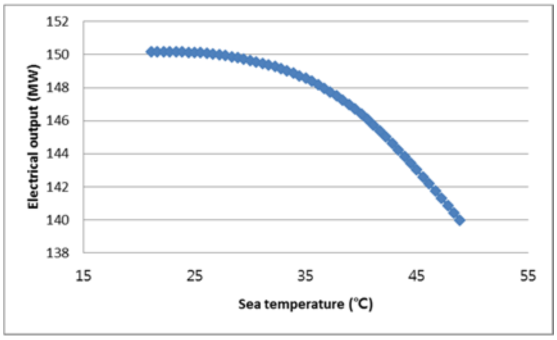

Figure 5. Changes of electrical output according to seawater temperature

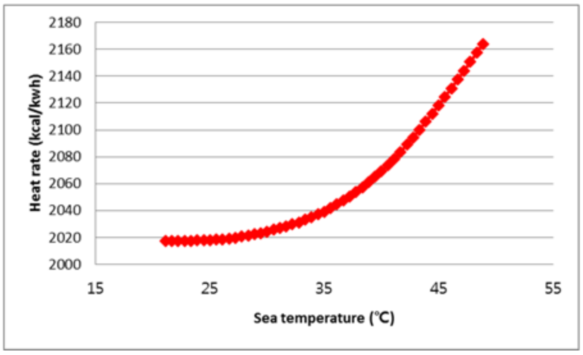

Figure 6. Changes of heat rate according to seawater temperature

○ Process heat and coolant temperature vs Electrical output

Tables 3 and 4 shows the output and heat rate according to the change of seawater temperature and the flow going to process heat on RCM.

Table 3. Changes of electrical output (MW) according to process heat and seawater temperature

Process heat / Sea temperature	50%	75%	100%
21.1 °C (70 °F)	90.9	76.5	68.5
26.7 °C (80 °F)	89.4	75.6	68.1
37.8 °C (100 °F)	86.1	73.5	67.2
48.9 °C (120 °F)	82.7	71.3	66.1

Table 4. Changes of heat rate (kcal/kWh) according to process heat and seawater temperature

Process heat / Sea temperature	50%	75%	100%
21.1 °C (70 °F)	8,918.9	7,869.6	5,711.5
26.7 °C (80 °F)	9,073.5	7,968.9	5,744.3
37.8 °C (100 °F)	9,415.6	8,191.1	5,822.9
48.9 °C (120 °F)	9,800.5	8,444.7	5,918.4

2.4 Integrated Cycle Analysis

We performed the comparison of heat balances between the reference case developed in Section 2.3 and another case using 300 MWt due to the distribution of nuclear energy to hydrogen generation process. We performed on AEM and RCM, and compared the electrical output and heat rate for each case. We assumed that performance of feedwater heater and condenser is kept constant. In addition, heat output is reduced to 86% on RCM so the flow rate supplied to the process heat is adjusted to 86% as well and performed the simulation. Summaries of performance for each case are shown in Table 5.

Table 5. Comparison of heat output per cycle performance indicators

	350 MW		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

Integrated 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 Figure 7, 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. Since PEPSE cannot deal with helium as a coolant, the portion in the 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.

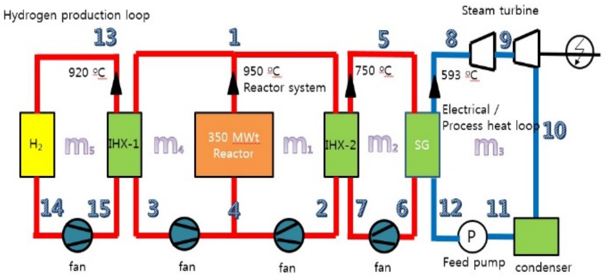

Figure 7. IHX loop modeling

Table 6. 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 6. 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%

In Figure 6, the simple Rankine cycle was simulated, but 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 %.

3. Conclusions

In this study, we evaluated a preliminary schematic diagram of the ECA part on high temperature gas cooled reactor, also performed thermodynamic evaluation of process heat and hydrogen production integrated system.

This study will go on with the development of the NI side such that the detailed design can be achieved in more optimized manner.

ACKNOWLEDGEMENT

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