Comparative study of Thermal Performance on Hydrogen Production Methods using VHTR

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1. Introduction

Hydrogen energy has received attention as an eco-friendly energy source without emission of environmental pollution such as carbon dioxide. However, since it is not extractive underground resource, it needs to be produced by supplying energy to other existing materials. To produce hydrogen efficiently, one of the options should be the VHTR (Very High Temperature Gas cooled Reactor) which is capable to supply high temperature heat source. VHTR contains a sturdy triple-coating fuel with low heat density. Therefore it does not cause a serious accident such as LWRs (Light Water Reactors), and generates less spent fuels due to lower excess reactivity than LWRs. There are a few methods to produce hydrogen using VHTR: SI (Sulfur Iodine), HTSE (High Temperature Steam Electrolysis) and SMR (Steam Methane Reforming) methods. [1, 2]

In this study, we proposed the thermal conversion system model which generates hydrogen, process heat, and electricity from a secondary system by receiving the heat source of a primary system. In addition, thermodynamic performance of the entire cycle was compared and analyzed using the results of KAERI (Korea Atomic Energy Research Institute) R&D for SMR and HTSE methods. The presentative operating scenarios for VHTR were considered as 3 temperature ranges which is 950 ℃-490 ℃, 850 ℃-390 ℃ and 750 ℃-290 ℃.

2. Methods and Results

2.1 VHTR Combined Cycle Modeling

The heat balance of the VHTR combined cycle for the hydrogen process is shown in Fig 1. The primary system is consisting of VHTR and supplies heat energy to the secondary system using IHX (Intermediate Heat Exchanger). Part of the high temperature helium of the secondary system flows through Path 1 to HX1 (heat exchanger 1) which supplies heat to produce hydrogen. The hydrogen generation process was designed by KAERI to supply 504 kg/h hydrogen.

After heat transfer, helium in Path 2 meets Path 3 which has the IHX exit conditions, then they flows into Path 4. Helium in Path 4 transfers heat through HX2 (heat exchanger 2) to produce the process heat of 550 ℃ steam used in the chemical process. Finally helium flows to Path 5 and passes through the HX3 (heat exchanger 3) which produces electricity, and then returns back through Path 6 to the IHX. When steam at Path 10 produces electricity, the part of it can be used in the hydrogen production or process heat delivery. The electricity production cycle was assumed to be Rankine cycle.

All thermodynamic conditions were calculated using the Engineering Equation Solver (EES).

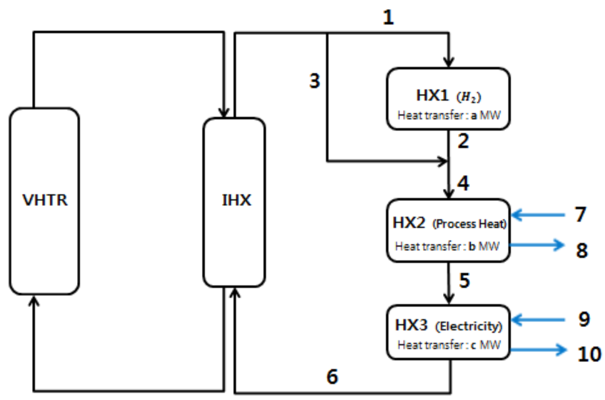

Fig.1. Heat balance of combined cycle

In this study, there were several assumptions on heat balance calculation.

1. The total thermal power of VHTR is 350 MWth.
2. The helium flow rate of the Path 1, heat load of the HX1, electricity consumption, and the throughput of hydrogen were all used in the data provided by KAERI.
3. In the HX2, the operating fluid of the Path 7(water) was heated up so that Path 8(steam) was fed to the 550 ℃ for specific chemical processes.
4. In HX3, the flow rate of Path 9(water) was adjusted to keep 350 MWth thermal power of VHTR.
5. The criteria used in economic evaluation are shown in Table I. This is the customary price of purified hydrogen, heat (Clean Steam), and electricity for ease of calculation, and price can be changed depending on market demand. [3]

Table I: Criteria used in economic evaluation

Purified H_2	5,000	won/kg
Heat (Clean Steam)	45,000	won/ton
Electricity	85	won/kW

2.2 Case 1: Combined cycle with SMR (Steam Methane Reforming) method

In this part, it is assumed that hydrogen is produced using SMR method. The SMR method is a commercially available technology and the most commonly used technology of hydrogen production today: i.e. technology used for producing about 95 % of the world's hydrogen. This method produces hydrogen by reacting methane with water using a very-high temperature helium heat source. Steam reforming[1] and Shift reaction[2] of chemical formula for SMR method are as follows [4]:

[1] Steam reforming

$CH_4+H_20=CO+3H_2$ (Endothermic reaction)

[2] Shift reaction

$CO+H_20=CO_2+H_2$ (Exothermic reaction)

KAERI considered the VHTR using SMR method with outlet and inlet temperature as three temperature ranges of 950 ℃-490 ℃, 850 ℃-390 ℃, 750 ℃-290 ℃, and calculated flow sheets for each temperature range to produce 504 kg/h of hydrogen. Table Ⅱ is the results of that data.

TableⅡ: SMR method data by KAERI

$T_{VHTR\ outlet}$	T_1	T_2	Thermal Energy (kWth)	Electrical Energy (kWe)	He flowrate (kg/h)	H_2 (kg/h)
950	900	820	25137	311.3	34384.8	504
850	800	670	29602	373.2	22768.56	504
750	700	540	49955	562.9	20549.04	504

Based on the assumptions in Section 2.1 and using Table Ⅱ, heat balance of the VHTR combined cycle using the SMR method was calculated. Based on these results, economical evaluation of VHTR combined cycle was conducted for each temperature range. The results of the economic evaluation are shown in Table Ⅲ.

Table Ⅲ: SMR economic evaluation result by $T_{VHTR\ outlet}$.

950℃	H_2	504	kg/h	₩2,520,000
	Process Heat	252.071	ton/h	₩11,343,195
	Electricity	23949.7	kW	₩2,035,725
	Total amount(₩/h)			**₩15,898,920**
850℃	H_2	504	kg/h	₩2,520,000
	Process Heat	186.000	ton/h	₩8,370,000
	Electricity	40528.8	kW	₩3,444,948
	Total amount(₩/h)			**₩14,334,948**
750℃	H_2	504	kg/h	₩2,520,000
	Process Heat	106.200	ton/h	₩4,779,000
	Electricity	55681.1	kW	₩4,732,894
	Total amount(₩/h)			**₩12,031,894**

In the combined cycle using the SMR method, it can be seen that the lower outlet temperature of the VHTR is less profitable. Since hydrogen production is fixed at 504 kg/h in all temperature ranges, therefore the monetary outcome from hydrogen production is the same in all three temperature ranges. However, the outlet temperature of the VHTR is lowered, the temperature of the helium (T_4) flowing into the HX2 is lowered. Furthermore assuming that the HX2 performances are the same in the three temperature ranges, when temperature of the helium (T_4) is lowered, the heat load for making 550 ℃ steam is also reduced. As the VHTR outlet temperature decreases, the heat load decreases and the flow rate in Path 7 is reduced because for fit T_8 to 550 ℃. Accordingly production the amount of process heat is reduced.

In order to keep total thermal output of VHTR, 350 MWth, the lower outlet temperature of the VHTR, the higher heat load that required for power production. On the same principle as above, assuming that the HX3 performances are same in all three temperature ranges, when heat load is increased, the flow rate of Path 9 is increased. Therefore, as the outlet temperature of the VHTR decreases, the flow rate at Path 9 increases and the electricity obtained from the Rankine cycle increases. However, the electricity is cheaper than the process heat so the total amount is decreased as the outlet temperature decreases.

2.3 Case 2: Combined cycle with HTSE (High Temperature Steam Electrolysis) method

In this part, it is assumed that hydrogen is produced using HTSE method. The HTSE method is also a commercially available technology and since 2008, KAERI has developed a laboratory-scale plant with a capacity of 47.33 NL/h which operates at 750 ℃. This method produces hydrogen by steam electrolysis reaction[3] with water using a very-high temperature helium heat source and electricity. The steam electrolysis reaction of chemical formula for HTSE method is as follows [5]:

[3] Steam Electrolysis reactions
(Overall reaction) $H_20=H_2+1/20_2$
(Cathodic reaction) $H_20+2e=H_2+O^{-2}$
(Anodic reaction) $O^{-2}=1/2O_2+2e$

Similar to the SMR method, KAERI considered the VHTR using HTSE method with outlet and inlet temperature as three temperature ranges of 950 ℃-490 ℃, 850 ℃-390 ℃, 750 ℃-290 ℃, and calculated flow sheets for each temperature range to produce 504 kg/h of hydrogen. Table Ⅳ is the results of that data.

Table Ⅳ: HTSE method data by KAERI

T_{VHTR} outlet	T_1	T_2	Thermal Energy (kWth)	Electrical Energy (kWe)	He flowrate (kg/h)	H_2 (kg/h)
950	900	395	4460	**17924.0**	**6112.80**	504
850	800	395	7710	**17296.8**	**13185.60**	504
750	700	395	17347	**17306.3**	**39388.80**	504

Based on the assumptions in Section 2.1 and using Table Ⅳ, the heat balance of the VHTR combined cycle using the HTSE method was calculated. Based on these results, economical evaluation of VHTR combined cycle was conducted for each temperature range. The results of the economic evaluation are shown in Table Ⅴ.

Table Ⅴ: HTSE economic evaluation result by $T_{VHTR\ outlet}$.

950℃	**H_2**	**504**	**kg/h**	**₩2,520,000**
	Process Heat	**253.800**	**ton/h**	**₩11,421,000**
	Electricity	**11766.0**	**kW**	**₩1,000,110**
	Total			**₩14,941,110**
850℃	**H_2**	**504**	**kg/h**	**₩2,520,000**
	Process Heat	**174.960**	**ton/h**	**₩7,873,200**
	Electricity	**32696.2**	**kW**	**₩2,779,177**
	Total			**₩13,172,377**
750℃	**H_2**	**504**	**kg/h**	**₩2,520,000**
	Process Heat	**88.560**	**ton/h**	**₩3,985,200**
	Electricity	**52317.7**	**kW**	**₩4,447,005**
	Total			**₩10,952,205**

Similar to the SMR method, in the combined cycle using the HTSE method, it can be seen that the lower outlet temperature of the VHTR is less profitable. Hydrogen production, process heat, and power outlet temperature change in HTSE method has same trend of SMR method, therefore no further explanation is given in this part.

Since the HTSE method using steam electrolysis reaction, thermal energy is less but the electric energy is more needed than the SMR method. The remaining heat energy can be used to produce electricity in HX3, so more electricity is produced than SMR. However, when VHTR outlet temperature is the same, the HTSE method used considerable amount of electricity for the steam electrolysis reaction. Therefore, the HTSE total amount per hour is less than SMR. It means SMR is more economical. Table Ⅵ summarizes the total amount of SMR and HTSE for each temperature range.

Table Ⅵ: Comparative total amount of two methods.

$T_{VHTR\ outlet}$	SMR(₩/h)	HTSE(₩/h)	ΔTotal amount (SMR-HTSE)
950	15,898,920	14,941,110	957,810
850	14,334,948	13,172,377	1,162,571
750	12,031,894	10,952,205	1,079,689

3. Conclusions

In this study, the VHTR combined cycle model using the SMR method that produced hydrogen through steam reforming and shift reaction and the HTSE method that producing hydrogen using steam electrolysis reaction are proposed, respectively. The VHTR combined cycle generates hydrogen, process heat, and electricity sequentially from the secondary system by receiving the high temperature helium heat source of primary system. Depending on the temperature specification of VHTR, the economics of hydrogen, process heat and electricity were evaluated.

While HTSE uses less thermal energy than SMR, hydrogen production process of HTSE used considerable amount of electricity in the steam electrolysis reaction. As a result, it was evaluated that SMR is more economical than HTSE in all three temperature ranges.

The information in Table Ⅱ, the price of hydrogen, process heat, and electricity at the same thermal power was assumed in the order of hydrogen > process heat > electricity. However, if market demand and flow distribution within the combined cycle changes, the result might be affected, which will be presented in the next conferences.

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