Comparative study of Thermal Performance on Hydrogen Production Methods using VHTR – Part 2

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1. Introduction

To produce hydrogen in cost effective and environmental friendly manner, one of the options should be the VHTR (Very High Temperature Gas cooled Reactor) which is capable to supply high temperature heat source without carbon dioxide release. The potential methods to practically generate hydrogen are under investigation such as SI (Sulfur Iodine thermo-chemical), HTSE (High Temperature Steam Electrolysis) and SMR (Steam Methane Reforming) methods. [1, 3, 4]

This paper continues the research results in 2017 [1] and described the addition of the hydrogen production option, and appended the sensitivity analysis of the throughput fraction and the price change, respectively. Particularly in this study, we conducted thermodynamic performance of the energy conversion upon the options, and compared them each other. The process diagrams for hydrogen generation was provided from the national project by KAERI (Korea Atomic Energy Research Institute).

2. Methods and Results

2.1 Combined Cycle Modeling

The flow sheet model of the VHTR combined cycle for the hydrogen process is shown in Fig 1. [1] The high temperature helium flows through Path 1 to HX1 (heat exchanger 1) which supplies heat to produce hydrogen. The helium into 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. The electricity production cycle was assumed to be Rankine cycle.

In this study, there are several assumptions on heat balance calculation, which was revised and improved from the model developed in the previous reference. [2]

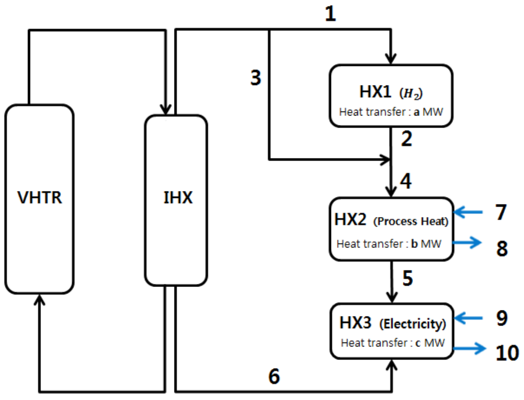

Fig.1. Flow sheets for combined cycle

1. The total thermal output of VHTR is applied to fixed values of 350 MWth, and hydrogen production rate is 4200 mol/min (504 kg/hour).
2. The helium flow rate of the Path 1, heat load of the HX1, electricity consumption, amount of substance to be continuously injected, and the throughput of hydrogen were all used in the data Table 1 provided by KAERI. [5]
3. The criteria used in economic evaluation are shown in Table 2. 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. [6]
4. This study excludes the costs of construction, operating & maintenance of facilities and only the material cost that is put into operation was considered.

Table.1 Material balance for SMR, HTSE, SI methods

Method	T_{VHTR}	T_1	T_2	Thermal Energy (kWth)	Electrical Energy (kWe)	He flowrate (kg/hr)	H_2 (kg/hr)
SMR	950	900	753	7,295	311	34,384	504
	850	800	650	8,216	373	22,768	504
	750	700	340	10,695	562	20,549	504
HTSE	950	900	395	4,460	17,924	6,112	504
	850	800	395	7,710	17,296	13,185	504
	750	700	395	17,347	17,306	39,388	504
SI	950	900	396	50,873	16,690	69,940	504
	850	800	397	62,355	16,690	107,908	504
	750	700	395	84,917	16,690	193,392	504

Table.2. References used in cost evaluation

H_2	5,000	KRW/kg
Heat(Clean Steam)	45,000	KRW/ton
Electricity	85	KRW/kW
H_2O	500	KRW/ton
CH_4	690	KRW/kg
Emission cost of CO_2	25,000	KRW/ton

2.2 Heat Balance Calculation

Based on the assumption in Section 2.1, thermodynamic simulations were performed to compare and analyze the thermodynamic performance of VHTR outlet temperature and hydrogen production method. Fig. 2 shows the results of heat balance calculation at 950℃ of VHTR outlet for each method. Similarly, we have completed to calculate and develop the material sheets for other temperature cases. In this case, we assumed the amount of hydrogen production would be fixed as 504 kg/hour.

2.3 Revenue Comparison

In order to calculate and compare the revenue for each method, we have to consider the cost and benefit together. In the case of the SMR, the net revenue that can be gained by hydrogen needs to be calculated by excluding the sum of the cost of CH4 input, water, and electricity. Additionally the CO2 emission cost should be deducted. Meanwhile, in the case of HTSE and SI thermochemistry methodology, only the water and electricity are used in the hydrogen production, so the net revenue can be expressed as the benefit of throughputs minus the cost of water and electricity.

Assuming a value of 1 for the revenue for hydrogen production per unit time in SMR, the other throughputs are shown in Fig. 3.

All nine cases produce the same amount of hydrogen at 504 kg/hr, but SMR has relatively fewer heat and electrical energy to be put into hydrogen production than the other two methods. Therefore, it seems an economical hydrogen production method. However, it should be noted that environmental pollution such as carbon dioxide generation is problematic. In the HTSE method, the method of electrolyzing water vapor at high temperature is advantageous in that no air pollutant such as carbon dioxide is generated. The power consumption in hydrogen production is relatively higher than the other two methods, and the net revenue that can be made with hydrogen is less than SMR. The SI thermos-chemical process has shown to be the least economical because it requires more heat and electrical energy than hydrogen or hydrogen.

From the viewpoint of the operating temperature, when the VHTR outlet temperature is as low as 750 ° C, it can be seen that the economical efficiency is remarkably reduced. The lower the outlet temperature, the greater the amount of heat and electrical energy needed to produce hydrogen within the same hydrogen production process. As a result, the flow rate of helium in path 1, which is used to make hydrogen only, increases. This means that there is less heat source used for subsequent process heat and electricity production.

2.4 Sensitivity Study for Cost

Sensitivity analysis was performed on variables that could be changed in revenue analysis. Here, the revenue was evaluated by adjusting prices for products such as hydrogen, process heat and electricity, carbon dioxide emission and methane prices. We tried to give the above calculation results a plausibility by making the variation width conservative. The (standard) below was referred from Table 2.

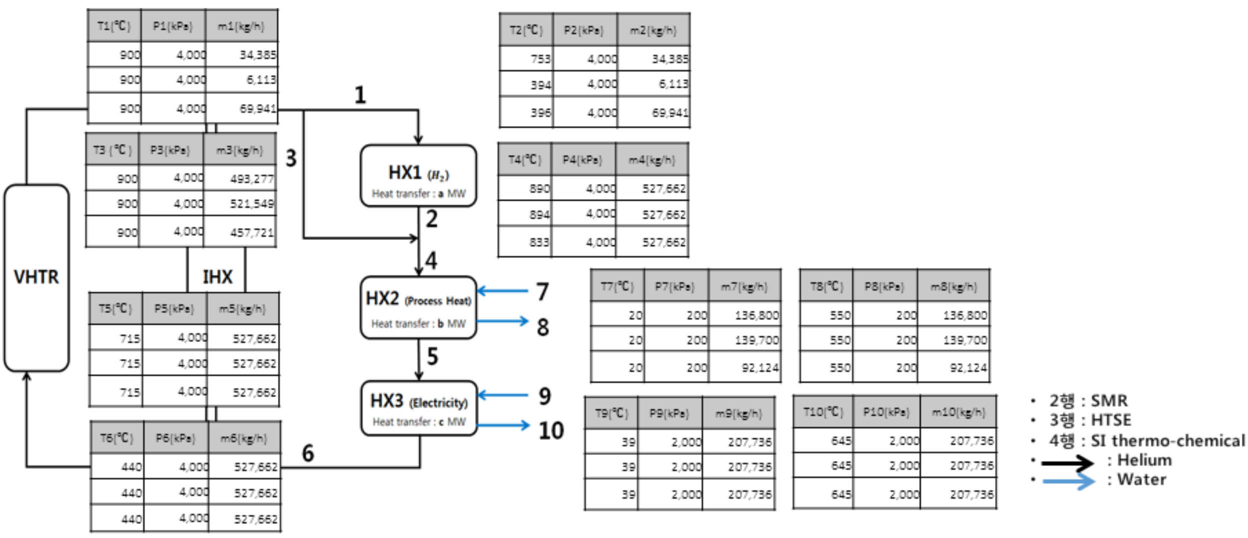

Fig.2. Heat balance calculation for each method

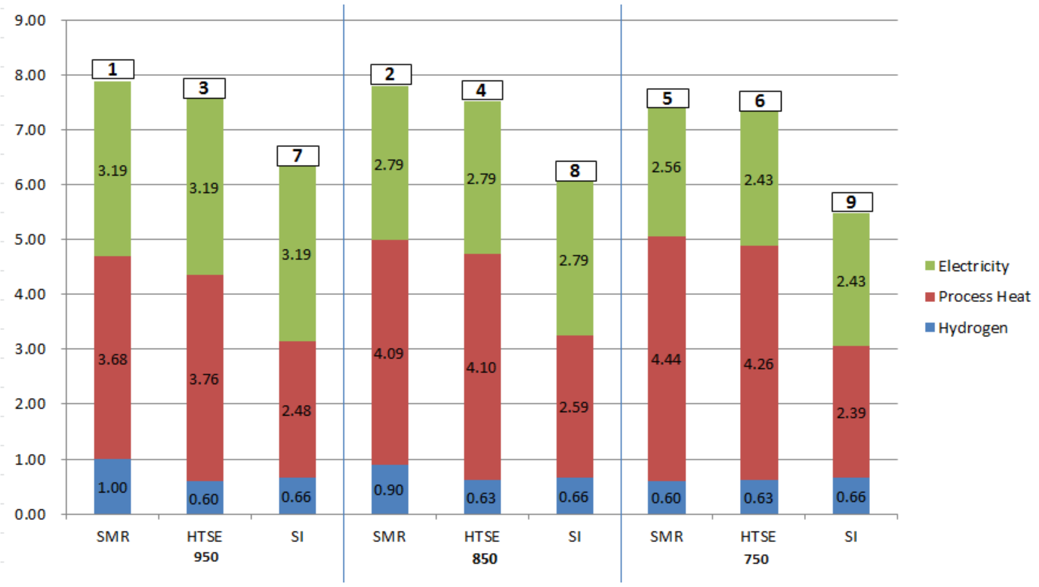

Fig.3. Comparison between hydrogen production options normalized by the revenue for hydrogen of SMR

- Hydrogen: 2,500, 5,000 won (standard), 10,000 KRW
- Process heat: 45,000 (standard), 67,500, 90,000 KRW
- Electricity: 85 (standard), 127.5, 170 KRW
- CO_2: 25,000 (standard), 37,500, 50,000 KRW
- CH_4: 690 (standard), 1,380, 2,170 KRW

If the number of cases is combined, a total of 243 cases will occur. For the sake of convenience, the representative results such as Fig.4 and Fig.5 are shown. They are assumed to be all the standard values except for the cost of the title. Generally it can be seen that SMR, HTSE, and SI rankings do not fluctuate within a certain range. However, for the cost of CH_4, the SMR option was affected a lot so that other methods can have superiority.

2.5 Sensitivity Study for Throughput Fraction

We can control the hydrogen production by controlling the flow rate of helium in path 1. Using this manner, the revenue analysis for throughput fraction on hydrogen, process heat, and electricity can be compared. Depending on the method, the magnitude of hydrogen production can be limited due to its process characteristics. Fig. 6, Fig. 7, and Fig 8. Shows the results of evaluation for the increasing hydrogen production from 1 time (standard) to the allowable maximum.

In all the figures, generally the higher temperature provides the better revenue, but it was observed that their superiority is turned over depending on the type of throughputs and their fractions. If three throughputs should be produced simultaneously, this kind of simulation models is required to give the insights which is not usually expected.

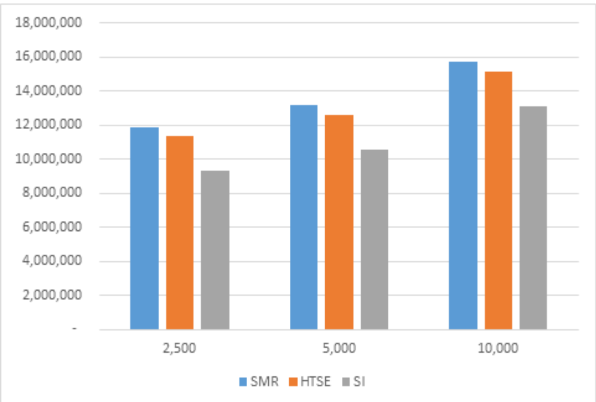

Fig.4. Revenue sensitivity for hydrogen cost variation

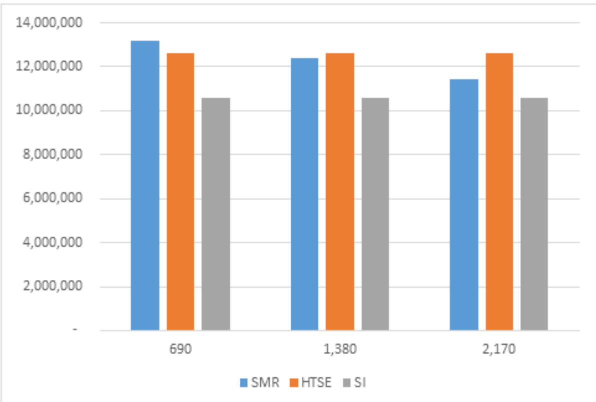

Fig.5. Revenue sensitivity for CH_4 cost variation

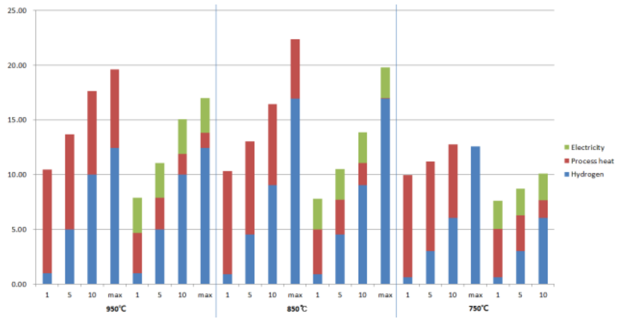

Fig. 6. Revenue sensitivity for hydrogen production (SMR)

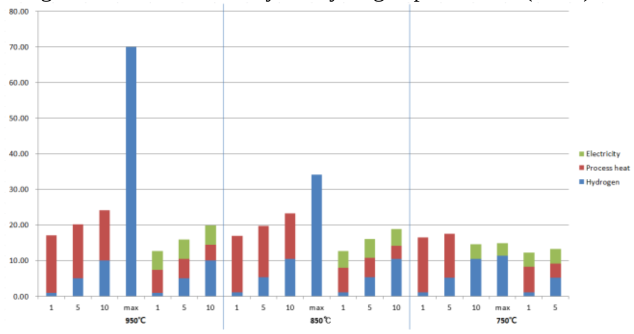

Fig. 7. Revenue sensitivity for hydrogen production (HTSE)

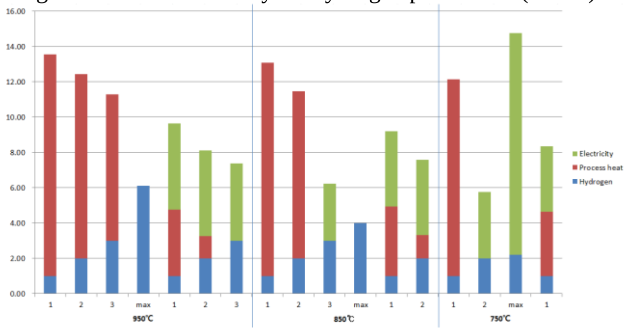

Fig. 8. Revenue sensitivity for hydrogen production (SI)

3. Conclusions

In this study, the VHTR combined cycle model using the SMR, HTSE, and SI thermo-chemical method were developed and compared in terms of their variation for individual factors. The combined cycle produces 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.

Generally speaking, the revenue of SMR and HTSE is better, but there must be something to be careful from the viewpoint of environmental aspect. Meanwhile, if a kind of constraints for example, the range of throughput fraction or the market cost for throughputs are given differently, then the revenue results can be different.

ACKNOWLEDGEMENT

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