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Development of Prototype Transient Models for Delivering Multiple Sources as an Application of VHTR

Eojin Jeon[a], Gyunyoung Heo[a*], Sang-IL Lee[b], Deok Hoon Kye[b]
[a] *Department of Nuclear Engineering, Kyung Hee University, Gyeonggi-do, Korea*
[b] *Nuclear Team Engineering Center, Hyundai Engineering Company, Seoul, Korea*
[*] *Corresponding author: gheo@khu.ac.kr*

1. Introduction

Since 2017, Kyung Hee University has worked with Hyundai Engineering Company on heat balance studies for hydrogen, process heat, and electricity generation using high temperature helium from a VHTR, which was sponsored as a governmental project. Especially in the way of hydrogen production, SI (Sulfur Iodine thermo-chemical), HTSE (High Temperature Steam Electrolysis), and SMR (Steam Methane Reforming) methods have been investigated focusing primarily on the thermo-economical aspect in the steady-state state. [1~5]

In this paper, we will show how to distribute necessary helium considering load-following of varying hydrogen, process heat, and electricity consumption over time as the last part of the project. As a modeling tool, we use Flownex (Simulation Environment) in a transient mode by adopting the proper controllers and examine the results. The transient model to be discussed here is simply a model conjunction with the virtual PID (Proportional, Integral, Derivative) controller related to the flow distribution of the high temperature helium, which is a kind of prototype for the detailed design stage in the future.

We will discuss the controller design and the results by presenting the case calculation for the load-following operation within a day.

2. Methods and Results

2.1 Brief Summary of Steady-State Modeling

The flow sheet of the combined cycle with a VHTR is shown in Fig 1. [1] There were several assumptions on heat balance calculation such as:

1. The total thermal output of VHTR was fixed at 350 MWth, and hydrogen production rate was 4,200 mol/min (i.e. 504 kg/hour).
2. The temperature of the process heat was maintained at minimum 550℃.
3. The flowsheets through Path 1 that is associated with hydrogen production were provided by KAERI including helium flow rate, electricity consumption, amount of substance, and the throughput of hydrogen. [6]
4. The criteria used in economic evaluation was the customary price of purified hydrogen, heat (clean steam), and electricity for ease of calculation.
5. This study excluded the costs of construction, operating & maintenance of facilities and only the material cost that is put into operation was considered.

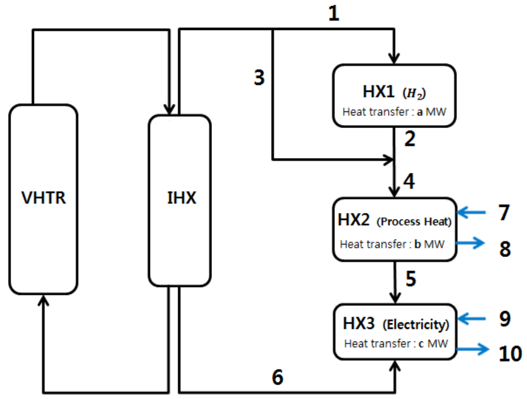

Fig.1. Flow sheets for combined cycle

Thermodynamic simulations were performed to analyze and compare the performances depending on the outlet temperature (950, 850, and 750℃) of a VHTR and hydrogen production method. In order to compare the economical aspect for each method, the cost of all materials at inputs and outputs are taken into account. For example, in the case of the SMR, the cost for methane extracted from LNG (Liquified Natural Gas), water, electricity, carbon-dioxide emission was deducted. Meanwhile, in the case of HTSE and SI methods, only the water and electricity were counted in the hydrogen production. [2] Sensitivity analysis was performed on variables that could be changed in economic analysis. Here, the sales were evaluated by adjusting prices for revenue such as hydrogen, process heat, and electricity as well as cost such as carbon dioxide emission and methane prices. A total of 243 combinational cases was investigated.

Generally, it was observed that SMR, HTSE, and SI rankings did not fluctuate within a certain range. That is, SMR is usually economical in terms of cost-benefit analysis. However, it is noted that for the cost of methane and carbon-dioxide emission, the SMR option can be affected a lot so that other methods can have superiority. [5]

Another topic in the heat balance calculation was the daily load-following operating in the energy independent island of Korea (Geomundo) which is shown in Fig. 2. [7] 4.5 MW power is produced, and it is used according to seasonal needs, and the remaining surplus electricity uses for other purposes. The base load and surplus electricity are shown in Fig. 3, where the maximum electric load of 3.5 MW was used by dividing electric power by load time interval, and the surplus electricity is then used for hydrogen production and electric charging.

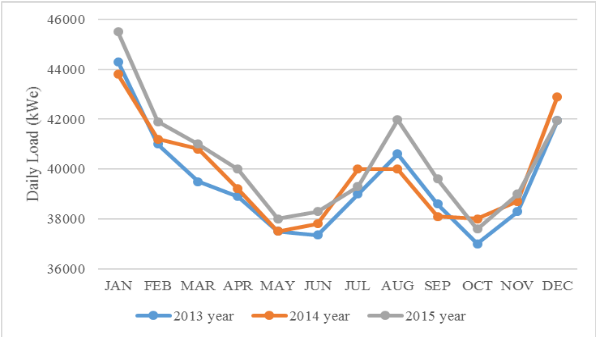

Fig. 2. Seasonal Pattern of Daily Load in Geomundo

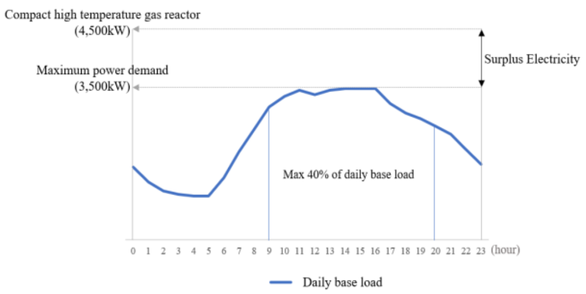

Fig. 3. Daily Base Load and Surplus Electricity

Based on this information, the simulation scenarios were slightly modified and decomposed into summer, winter, and others as shown in Fig. 4, such that the pattern of daily energy use per season can be composed of hydrogen, process heat, and electricity in terms of percentage. We allocated total thermal energy of 350 MWth according to the percentage of each product in Fig. 4. Next, the amount of hydrogen, process heat, and electricity produced within the allocated energy range is calculated, and the cost balance analysis is performed considering, which is the same as previous heat balance calculation.

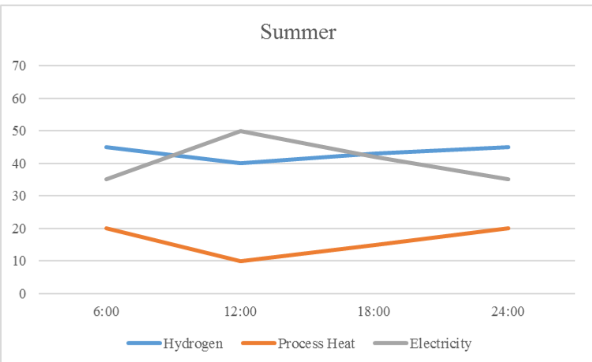

Fig. 4. Seasonal Daily Load Following Patterns in Summer

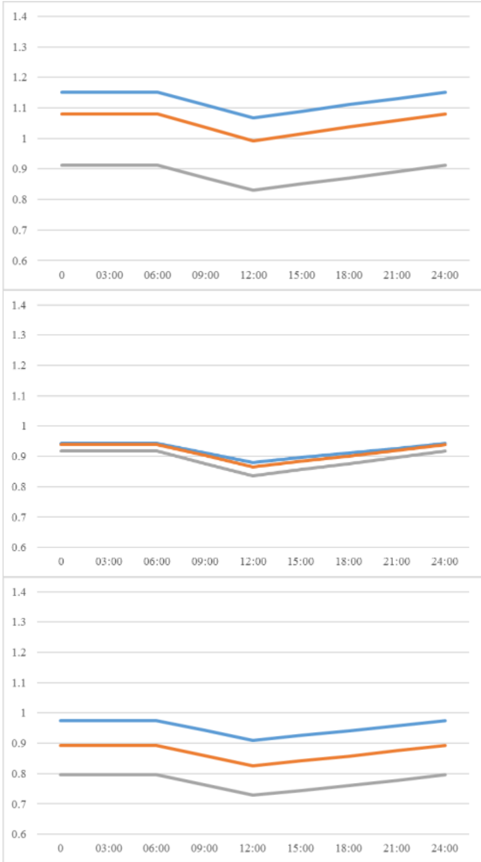

Fig. 5. Revenue Analysis for Daily Load Patterns in Summer
(Upper: SMR, Mid: HTSE, Lower: SI,
In the graphs, Top: 950 °C, Middle: 850 °C, Bottom: 750 °C)

The results are shown in Fig. 5, and the vertical axis represents the revenue sum of all products. In order to increase the readability for comparison, all values were divided by a certain constant so that the graph can be normalized at 1.0.

From the results, the seasonal revenue produced by the SMR method varied greatly, and the HTSE method was not significantly different. Generally, a higher revenue was found in the winter than summer, as process heat is sold at higher quantities and at a higher price in the winter. When the three products were to be provided as a mix, the revenue between hydrogen production methods was observed to be small or reversed, which was quite different from the previous observations.

2.2 Development of Transient Modeling

Transient modeling is dependent on purposes, but using a simple PID controller method to match the current research stage and the purpose of conducting thermal equilibrium studies, the helium flow distribution of the VHTR with increasing or decreasing demand for hydrogen, process heat, and electricity was calculated.

In order to verify the method for implementing PID controller in Flownex used in this study, the following simple and preliminary model was tried first. In a simple Rankine cycle model, the model is constructed to control the opening of the valve to feed the target turbine output to the PID controller and to form the flowrate to meet the target turbine output. In Fig. 6, the turbine output is set to 200 MW as the minimum value, 240 MW as the maximum value, and the valve opening is set to the minimum value of 0.3 and the maximum value of 0.7. Since there is no default setting in PID controller, the value must be found through PID tuning for proportional term Kp, integral term Ti, and differential term Td. For the tuning, the step-test was performed by Cohen-Coon Tuning Rule. [8]

At time 0 seconds, the target output of the turbine was set from 200 MW to 240 MW, which resulted in a larger valve opening, thereby increasing the flow to the turbine and ultimately the turbine output becoming closer to the target.

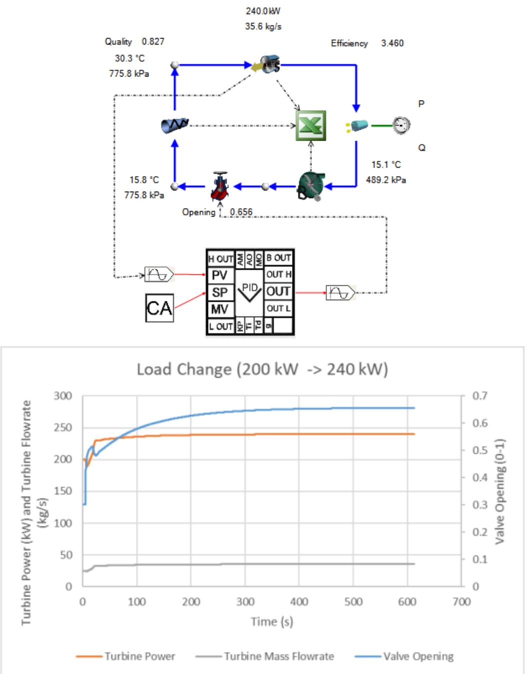

Fig. 6. Flow control example using PID controller

2.3 Transient Modeling for Daily Load-Following

The PID controller model of Flownex described in Section 2.2 was applied to the steady-state model of the VHTR described in Section 2.1 to calculate the transient conditions for the load demand fluctuation pattern. Since the detailed design and control algorithms for each process are not presented, the actual production of hydrogen, process heat, and electricity cannot be said to be equivalent with the result of the simulation. However, it should be noted that the purpose of the simulation model is to create a foundation that can accurately reflect the control algorithm as a result of detailed design.

The modeling assumptions for transient states are slightly different from those of steady-state's:

1. Electricity consumption and process heat are set as constraints and hydrogen is produced and stored as the product of remaining energy.
2. The temperature of Path 10 is fixed to 645 ° C, which is to set the target electric power so that electricity is generated according to the increase or decrease of the flowrate rather according to the temperature change of the turbine inlet.

The transient model is constructed as shown in Fig. 7. Fig. 7 shows that two PID controllers are used because the electricity and process heat must be controlled in sequence.

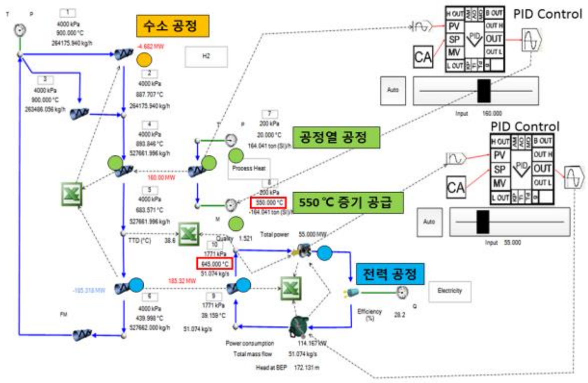

Fig. 7. Flowsheet configuration for transient state Flownex simulation model

Figure 8 shows the result of the calculation of the transient conditions in the same way as the daily load-following calculation using the steady-state model described above.

This result does not take into account the specific hydrogen production options and should be interpreted as the result of the helium distribution or the heat energy allocation presented in Fig. 4. Therefore, we need to further processes about Fig. 8 to calculate sales by hydrogen production option. However, this is not related to the development of the transient model, so the results are omitted.

When we look at only the characteristics of the transient states, we can observe that the peak appears temporarily at the beginning of the fluctuation due to the characteristics of the PID controller. We can also confirm a certain delayed pattern shown in Fig. 4 with some time, which is obvious due to the nature of PID controllers. The transient model is expected to bring more realistic results than the steady-state calculation because it confirms the fluctuating state of the actual process with time.

It is true that at this stage it is difficult to verify or validate the transient model. It is expected that hydrogen, process heat, and electricity production model should be composed of the transient model together with entering detailed design stage.

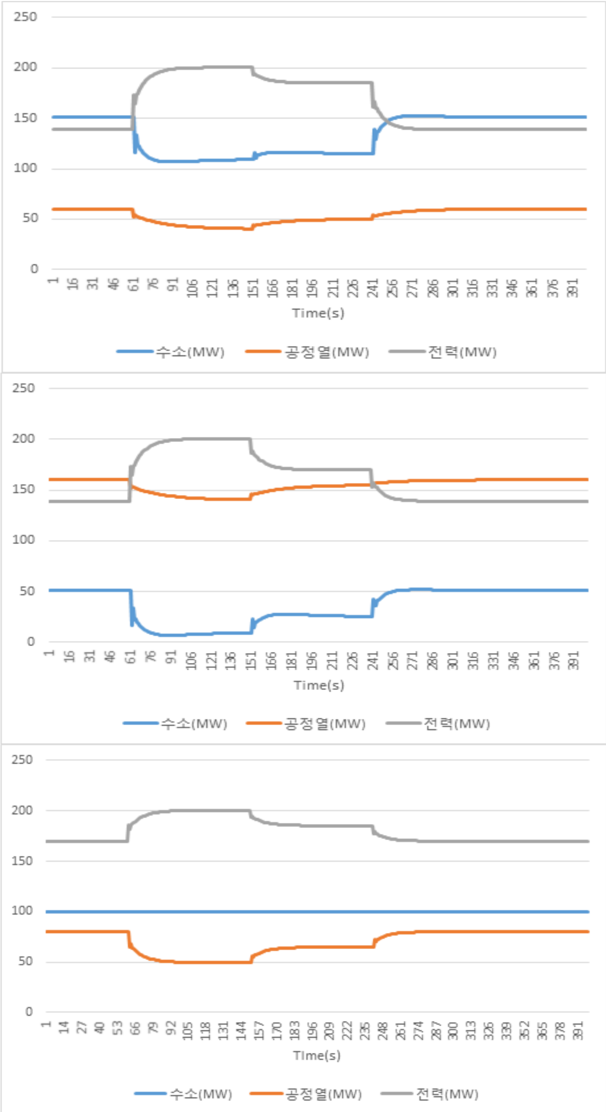

Fig. 8. Simulation of Transient states for daily energy use pattern by season (Upper: Summer, Mid: Winter, Lower: Spring / Autumn)

3. Conclusions

In this study, the combined cycle model supposed by the VHTR 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.

In general, 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.

In order to justify the applicability of the VHTR, it is recommended to conduct a series of consecutive analyses: heat balance and sensitivity studies assuming steady-state as well as transients conditions. Seasonal and daily operation can affect the thermo-economical results a lot. Over the past three years, the researches on the energy conversion of VHTRs have been carried out across combined options. We anticipate the possibility of the VHTR-based hydrogen production option being noticed ahead of the hydrogen economy era.

ACKNOWLEDGEMENT

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