Thermodynamic Analysis of Hydrogen Production Integrated Pressurized Water Reactor

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1. Introduction

Interest in low-carbon power generation technology is increasing due to concerns of climate crisis due to greenhouse gas emissions. By announcing ‘3020 implementation plan,’ S. Korea also intends to increase the share of renewable energy power generation. From the grid stability point of view, the problem with renewable energy is its intermittency. In the case of solar and wind power generation, these power sources are vulnerable to weather change, and power demand and supply do not match depending on environmental conditions. Since solar power generation rapidly increases during the day and decreases sharply thereafter, it places a burden on other power sources, and in particular, the economic feasibility of power sources operated with a base load decrease. In order to solve the intermittency problem caused by the increase in proportion of renewable energy, flexible operation technology of existing power sources is required.

The increase in the proportion of renewable energy will inevitably cause an increase in demand for energy storage system (ESS). ESS can be an effective answer for stabilizing the power grid and solving the economic difficulties faced when renewable energy penetration is increased [1, 2]. Nuclear power plants with flexible operation can play an important role in decarbonization [3]. Among several ESSs, interest in hydrogen energy storage is increasing. Since only water remains as a byproduct after being used as energy, it is recognized as the most suitable next-generation energy source for the new climate system. The Korea Energy Economics Institute (KEEI) and Idaho National Laboratory (INL) presented the potential for hydrogen production in pressurized water reactors (PWR) [4, 5]. Therefore, in this study, the layout of hydrogen production integrated PWR is suggested and the off-design operation of the PWR secondary side due to hydrogen production are analyzed thermodynamically.

2. Hydrogen production using secondary side steam

As shown in Fig. 1, the basic principle of high-temperature steam electrolysis (HTSE) using PWR is to reduce the amount of electrical energy required to decompose water molecules by supplying thermal energy. Since the PWR can produce steam, it has the advantage of supplying both steam and electricity required for HTSE.

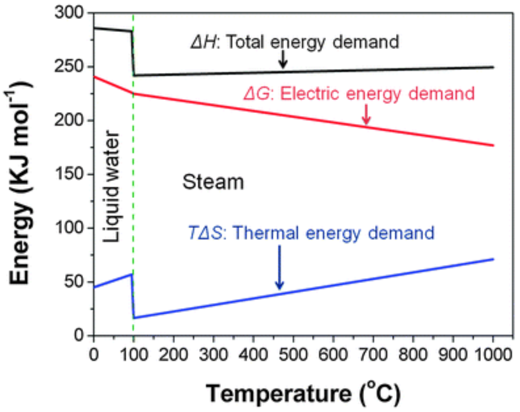

Fig. 1. Electric, thermal and total energy demand for H_2O electrolysis as a function of temperature [4]

2.1 Branch point for hydrogen production

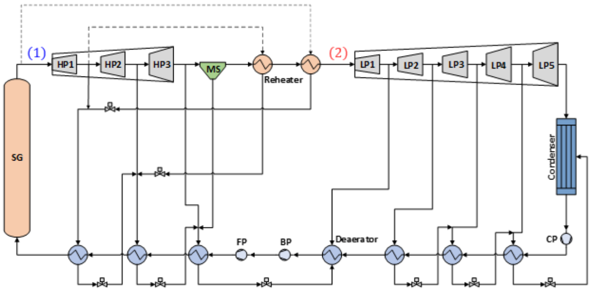

Fig. 2. Typical PWR secondary side

Table I: HPT and LPT inlet conditions of typical PWR

	Temperature [°C]	Pressure [MPa]
HPT	282.21	6.63
LPT	263.36	1.44

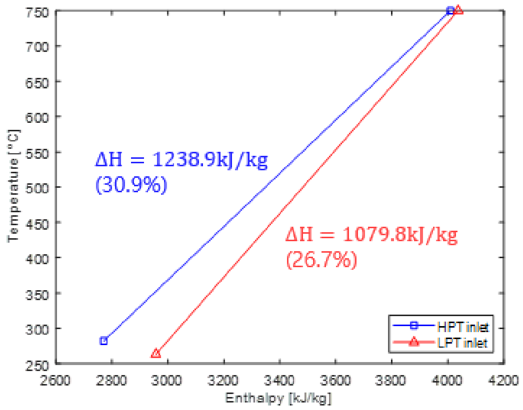

Fig. 3. Additional heat source energy

In Fig. 2, high-pressure turbine (HPT, (1)) and low-pressure turbine (LPT, (2)) can be candidates for branch point for hydrogen production. Assuming that it is 750°C HTSE, the additional heat required at each branch point is calculated. As shown in Fig. 3, about 30% of the additional heat is required, that is, about 70% of the total heating energy is contained in the steam produced in the PWR. This means that the steam in the PWR secondary side already has a large amount of heating energy for HTSE.

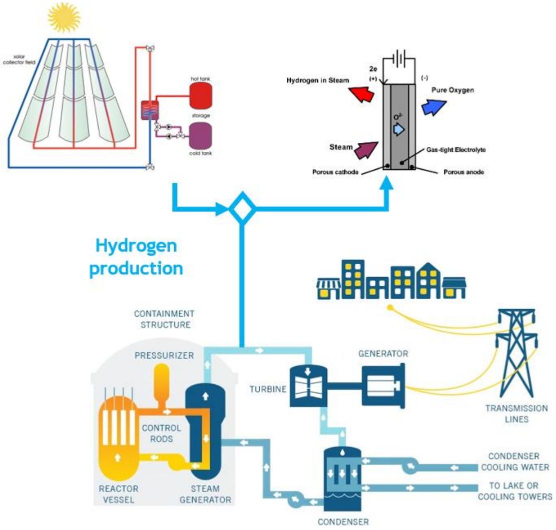

Fig. 4. Solar thermal energy as additional heat source

In this study, solar thermal energy is recommended as an additional heat source for HTSE. Solar thermal energy stores energy in the form of thermal energy, so it is easy to supply heat for hydrogen production. In the case of concentrated solar plant (CSP) and Thermal Energy Storage (TES), technology readiness level (TRL) is high because these systems are built and being operated worldwide [6].

2.2 Hydrogen production integrated PWR (HP-PWR)

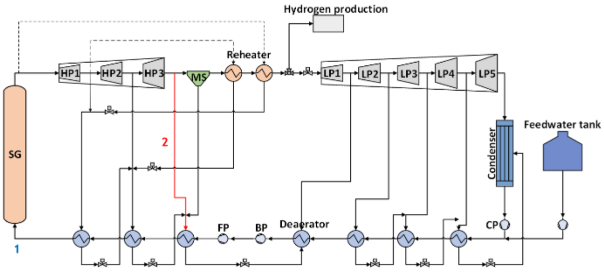

Fig. 5. Hydrogen production integrated PWR layout

It is recommended to produce hydrogen by branching the steam at the LPT inlet according to the results in Fig. 3. After the steam for hydrogen production is branched, it does not return to the secondary side, so additional mass flow rate must be injected near the condenser. In addition, after part of the LPT steam is branched, the LPT perform an off-design operation. This can affect the entire PWR. To minimize the impact of the primary side, the steam generator (SG) inlet (1) temperature should be maintained at the nominal temperature (232°C). The temperature of point 1 can be controlled by HPT outlet (2) branch flow [6].

3. Off-design operation of HP-PWR

To analyze off-design operation of HP-PWR, constant volumetric flow rate model and Ray`s semi-empirical equation are used for turbine and ε-NTU methods is used for feedwater heater [7, 8, 9].

3.1 Constant SG inlet temperature

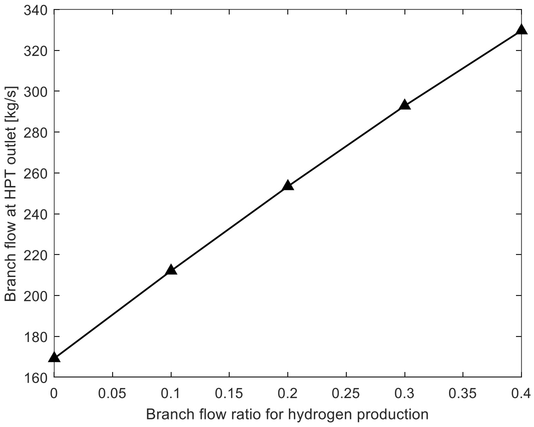

Fig. 6. Branch flow at HPT outlet change

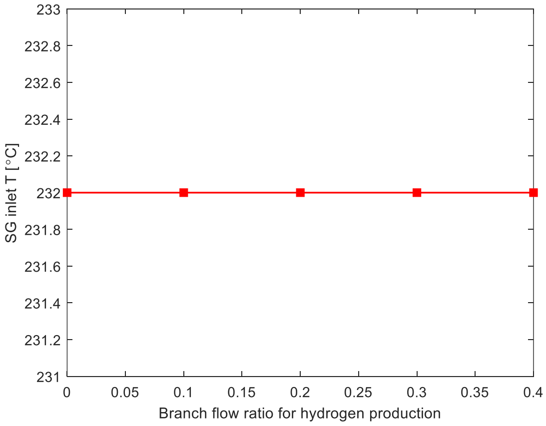

Fig. 7. SG inlet temperature change

$$Branch\ flow\ ratio = \frac{Branch\ flow\ for\ hydrogen\ production}{LPT\ inlet\ flow\ rate\ (On\text{-}design)} \quad (1)$$

Fig. 6 and Fig. 7 show that the temperature of point 1 is maintained at 232°C by controlling the branch flow at point 2. Branch flow of x-axis in graphs is defined as equation 1. As the flow rate flowing to the LPT decreases, the flow rate branched to the feedwater heater decreases, so the flow rate of point 2 must be increased to maintain the temperature of point 1.

3.2 Secondary side work change

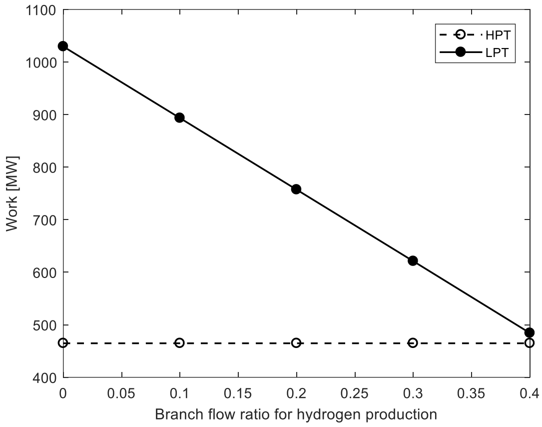

Fig. 8. HPT and LPT works change

Fig. 8 shows that the HPT work is maintained and the LPT work decreases according to the branch flow ratio at the LPT inlet. This is the PWR work loss for hydrogen production. The actual work loss is greater than this result because electricity is used for HTSE.

4. Conclusions and Further Works

In this study, as a solution to solve the difficulties of PWR caused by the increase in renewable energy, a layout of HP-PWR is proposed. The secondary side steam has enough energy for HTSE and the additional heat is received from solar thermal energy. It is recommended to branch the steam at LPT inlet to produce hydrogen.

When steam is branched at the LPT inlet for hydrogen production, the secondary side operates in off-design conditions. The SG inlet temperature can be maintained by controlling branch flow rate at the HPT outlet. However, hydrogen production will result in PWR work loss. Therefore, there must be a power generation technology by utilizing the produced hydrogen that can compensate for PWR work loss. This will be investigated next.

Acknowledgement

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