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Preliminary analysis of hydrogen production of water electrolysis using NPP

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1. Introduction

The energy production from variable renewable energy (VRE) sources is increasing globally and domestically. Globally, according to the United Nations World Climate Convention, the ratio of renewable energy (RE) is expected to increase to reduce greenhouse gas (GHG) emission. In South Korea, the energy policy 3020 was announced, which aims to increase the ratio of RE (including VRE) to 20% by 2030 [1]. However, as the proportion of VRE increases, major technical challenges also arise.

Solving the intermittency issue of VRE is one of the major challenges. Power generation from VRE is mostly affected by weather and climate conditions and therefore it cannot always generate power when the demand is high. This issue can be alleviated by load-following operation of a nuclear power plant (NPP). However, it is not economical to control power output of the reactor in an NPP. Hydrogen (H_2) production from water electrolysis coupled with the NPP can solve this issue. Hydrogen has an important role in the future and is expected to be used instead of fossil fuels in numerous applications [2]. There are many ways that hydrogen can be produced. Currently, commercial hydrogen used in the industry is produced from hydrocarbons, which releases carbon dioxide. Thus, it is unsuitable for future green hydrogen. Nowadays, hydrogen production through steam electrolysis, one of the green hydrogen production methods, is being studied worldwide.

Therefore, in this paper, preliminary analysis of hydrogen production from water electrolysis using NPP is presented. The performance of hydrogen production in terms of the hydrogen production efficiency is presented in this paper.

2. Thermodynamic modeling

2.1 Concept of water electrolysis using NPP

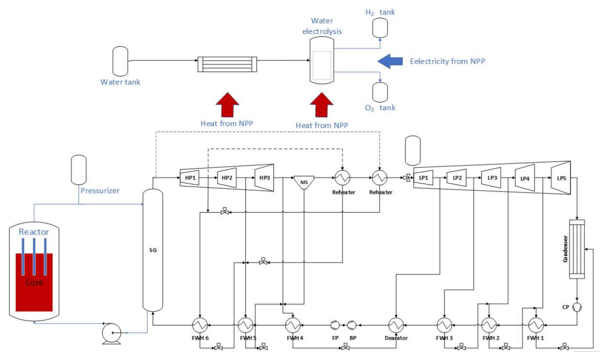


Figure 1. Concept of water electrolysis using NPP

This paper presents the preliminary study of the hydrogen production of water electrolysis using heat and electricity from NPP. Thus, the simple relationship between temperature and efficiency in hydrogen production using electricity and heat of NPP is studied thermodynamically first. As shown in Figure 1, it is how the hydrogen can be produced using NPP. There are three types of energy needed for hydrogen production: heat from heat exchanger (HX), electricity energy from electrolysis and heat from electrolysis. Firstly, heat from HX is the heat for high temperature of water-electrolysis. Then, both of electricity and heat should be needed during water-electrolysis. In other words, the water from water tank flows to heat exchanger and receives heat from NPP to increase its temperature. Then, it flows to water-electrolyzer and is electrolyzed into oxygen and hydrogen using electricity and heat from NPP.

2.2 Thermodynamic modeling

Assumptions used for the modeling are as follows:

(1) Water, hydrogen and oxygen tanks have the same temperature, pressure, and therefore, thermophysical properties at the inlet and outlet, respectively.
(2) There is no pressure drop in the pipelines.
(3) There are no changes in potential and kinetic energies

The reaction of water electrolysis is given below.

$$H_2O \rightarrow H_2 + (1/2)O_2$$

The enthalpy of reaction (ΔH(T)) consists two parts as seen in the below equations. ΔG(T) is the Gibbs free energy of reaction and has to be applied in the form of electricity. This is also called the change in Gibbs free energy. Then, Q(T) is the product of the thermodynamic temperature (T) and the entropy of reactions (ΔS(T)) and can be applied in the form of thermal energy.

$$\Delta H(T) = \Delta G(T) + Q(T)$$
$$Q(T) = T\Delta S(T)$$

The above thermodynamic parameters are functions of temperature. Thus, using Kirchhoff's equation, entropy equation and Table 1, they can be calculated as shown in below equations [3].

$$\Delta H(T) = \Delta H^{\circ}{}_{298.15} + \int_{298.15}^{T} \Delta C_p \, dT$$

$$\Delta S(T) = \Delta S^{\circ}{}_{298.15} + \int_{298.15}^{T} \frac{\Delta C_p}{T} \, dT$$

Table1. Heat capacity of molecules

	Heat capacity (C_p, J/mol·K)
H_2(g)	$(29.07-0.836)*10^{-3}T + 20.1*10^{-7}T^2$
O_2(g)	$(25.72+12.98)*10^{-3}T - 38.6*10^{-7}T^2$
H_2O(l)	75.30
H_2O(g)	$(30.36+9.61)*10^{-3}T + 11.8*10^{-7}T^2$

The thermodynamic parameters at the range of 298.15–1273.15K were calculated according to the above equations and shown in Figure 2. The results show that the total energy demand increases slightly with the increase of temperature over 373.15K, while electrical energy demand decreases because of the increase of heat demand.

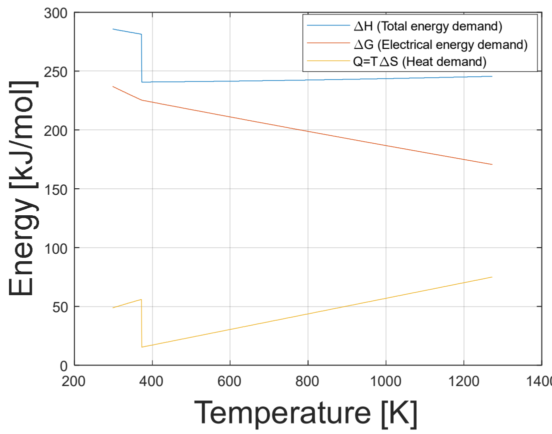


Figure 2. Energy demand for water and steam electrolysis

2.3 Modeling of parameters

Table2. Design parameters

Parameters	Value	Unit
Temperature of water tank	25	℃
Pressure of water tank	101.325	kPa
Total thermal energy from NPP	400	MW
Efficiency of NPP	35	%
Molar mass of water	18	g/mol
Molar mass of oxygen	16	g/mol
Molar mass of hydrogen	2	g/mol
Enthalpy of water vaporization	40.7	kJ/mol

Table3. Variables

Parameters	Range of Variation	Unit
Temperature of water electrolysis	25-1000	℃

The design parameters are shown in Table 2 and the variables and ranges of variation are shown in Table 3.

3. Thermodynamic evaluation and Results

An efficiency of hydrogen production (η_{H_2}) is the ratio of the energy carried by unit amount of produced hydrogen, in terms of a high-heat value of hydrogen (HHV=285.8kJ/mol), to the $Q_{overall}$ in the process of hydrogen production. This is the criteria for this system.

The efficiency of hydrogen production in this system can be calculated using the next equation [4],

$$\eta_{H_2} = \frac{HHV}{Q_{overall}} = \frac{HHV}{Q_{el} + Q_{th,Electrolysis} + Q_{th,HX}}$$

where Q_{el}, $Q_{th,Electrolysis}$ and $Q_{th,HX}$ represent the electricity energy from electrolysis, heat from electrolysis and heat from HX, respectively.

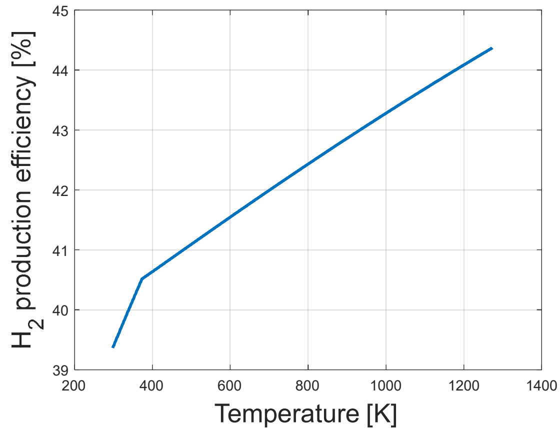


Figure 3. Temperature of water electrolysis vs Efficiency of H_2 production

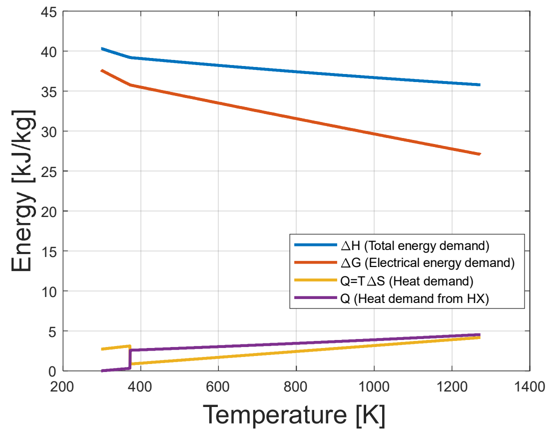
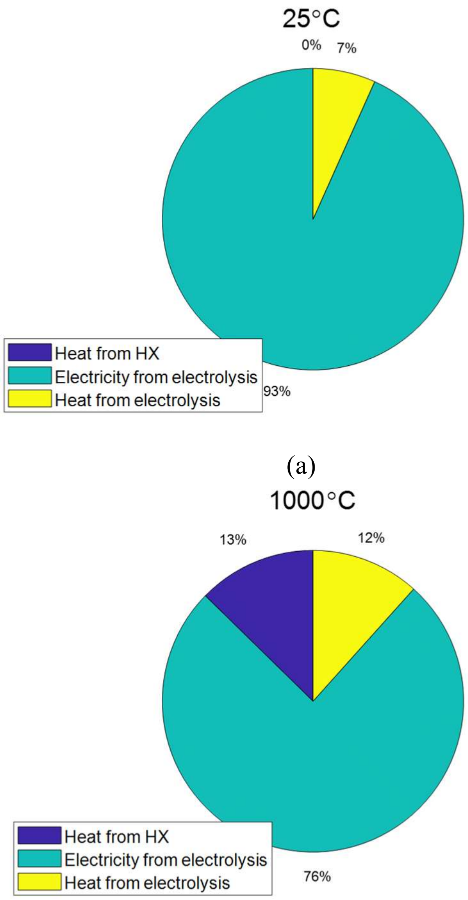


Figure 4. Temperature of water electrolysis vs Energy

As shown in Figure 3, it has the efficiency of H_2 production of 39.5-44.5%. As the temperature of water electrolysis increases, the efficiency increases. As seen in Figure 4, as the temperature increases, both of total energy demand and electrical energy demand decrease and heat demands from HX and water electrolysis increase. As explained in Figure 2, according to the increase of temperature, the heat demand and the total energy demands increase, but the electrical energy demand decreases. However, the total energy demand in Figure 4 decreases since the efficiency of electrical energy made from heat is quite low. Thus, as seen in Figure 5, when the ratio of electrical energy demand decreases, the total energy demand decreases. In other words, efficiency of H_2 production increases. Then, using 400MW of NPP total thermal energy, 11.17kg/s of H_2 can be produced.



(b)

Figure 5. The ratio of energies needed at 25°C (a) and 1000°C (b) as water electrolysis temperature

4. Summary and Future works

From the result of hydrogen production using water electrolysis coupled to NPP, it is shown that as the temperature increases, the efficiency of H_2 production increases. The maximum efficiency is about 44.4%. Moreover, the total energy demand decreases with respect to the decrease of ratio of electrical energy demand due to the low efficiency of electrical energy. Thus, the relation between the efficiency and hydrogen production is needed to be studied. In addition, how water electrolysis is integrated to NPP and this feasibility compared to other power plants will be investigated in the future.

Further investigation will commence soon regarding the feasibility of water electrolysis integrated to NPP by suggesting the process for NPP integration to water electrolysis. Comparison to other power sources will be also conducted as well.

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