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고출력 SOEC 시스템의 매개변수 연구

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Parametric Study on High Power SOEC System

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Abstract >> In the near future, with the urgent requirement of environmental protection, hydrogen based energy system is essential. However, at the present time, most of the hydrogen is produced by reforming, which still produces carbon dioxide. This study proposes a high-power electrolytic hydrogen production system based on solid oxide electrolysis cell with no harmful emissions to the environment. Besides that, the parametric study and optimization are also carried to examine the effect of individual parameter and their combination on system efficiency. The result shows that the increase in steam conversion rate and hydrogen molar fraction in incoming stream reduces system efficiency because of the fuel heater power increase. Besides, the higher Faraday efficiency does not always result a higher system efficiency.

Key words : Solid oxide electrolysis cell(고체 산화물 전해전지), Parametric study(매개변수 연구), Faraday efficiency(파라데이 효율), Steam conversion rate(스팀 전환율)

1. Introduction

Currently, the pressure on fossil fuel reduction is increasing year by year due to global warming and climate change. This scenario opens a very promising future for hydrogen production. Not only playing as a clean fuel, hydrogen is also an alternative energy storage chemical in which electricity can be converted into hydrogen to be stored. Most of the current hydrogen produced is by reforming technologies because these technologies are mature at the time and low production cost, between 1-2 dollars[1). However, producing hydrogen by reforming also generates carbon dioxide as by product while the future hydrogen society definitely requires a less polluted or even zero-carbon emitted technology. Electrolysis hydrogen production has recently been the center of focus because it can effectively utilize the excess electricity generated from renewable sources such as wind energy, solar energy, etc. The most challenging barrier of electrolysis hydrogen production is its high cost, normally from 3 to 6 \$/kg H_2 in case of polymer exchange membrane electrolysis cell[2], or 2.8 to 5.8 \$/kg H_2 in case of solid oxide electrolysis cell (SOEC)[3,4], a more efficient cell. In order to reduce production cost, there are several ways. Among them, increasing stack power to produce more hydrogen with the same capital cost attracting attention from researchers[1,5]. This study introduces a high power SOEC system, then parametric study will be used to find optimal point.

2. High power SOEC system and its modeling by simulation

2.1 Description of analyzed system

Fig. 1 shows a flow diagram of the analyzed high power SOEC system. Liquid water is fed to pre-vaporizer where it is heated up by the high temperature flow out from fuel heat exchanger (F-HEX). After pre-vaporizer, hot water comes to vaporizer, receiving heat from heat source such as nuclear reactor, concentrated solar panel, etc. vaporizes into steam. This steam recuperates the heat from extremely hot flue gas stream out from SOEC at the F-HEX, before going through an electrical heater (F-heater) which increases the steam temperature to SOEC operating temperature. In the remaining side of SOEC, air is blown to an air heat exchanger (A-HEX) where it receives heat from the outgoing air stream from SOEC, then once again the air stream is heated up by an electrical heater (A-heater) before being supplied to SOEC. Through the electrochemical reaction of SOEC, the supplied electricity and steam are converted into oxygen and hydrogen. Then, mixes with the unconverted steam to be H_2-rich hot stream, exiting SOEC to F-HEX. After transferring heat to cold steam at F-HEX and pre-vaporizer, H_2-rich stream is split into two streams; one stream is recirculated to vaporizer to recover steam and also keep H_2 molar fraction in inlet steam higher than certain value[6]. The remaining flows through condenser where steam condenses, and is removed from gaseous mixture which is finally

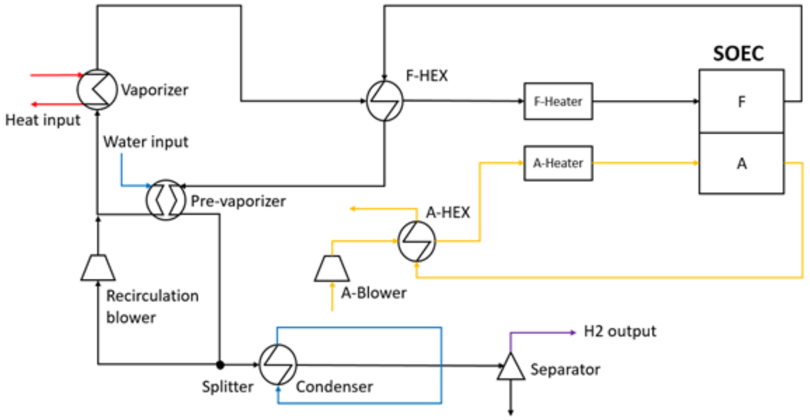

Fig. 1. Flow diagram of the high power SOEC system

separated to get pure hydrogen.

2.2 Assumption used in the system simulation

Table 1 summarizes the assumptions used in system modeling and simulation[7-11]. The current density is assumed to be 1 A/cm^2 higher than almost normal SOEC[5,12,13]. Beside, operating condition of cell is chosen at 715˚C and 1 atm. Furthermore, the 36 kW stack includes 380 cells. Other essential coefficients such as inverter efficiency, Faraday efficiency, heat loss are set at widely used values: 92%, 92%, and 5%, respectively[10]. Lastly, the heat supplied to SOEC system is assumed from a 300˚C waste steam stream with mass flow rate of 15 kg/h.

2.3 Genetic algorithm optimization

The analyzed cycle was modeled using the EBSILON® (Steag, Zwingenberg, Germany) Professional commercial software package[14]. Fig. 2 shows a screenshot of the EBSILON software used for the analyzed cycle. During optimization process genetic algorithm is employed to find optimal point. Though genetic algorithm does not guarantee the global optimal point, this result suggests a parameter set for further investigation or analysis.

Table 1. Assumptions and parameters used in system simulations

Parameter	Value	Unit
SOEC stack		
Operating pressure	1	atm
Temperature	715[7]	°C
Current density	1[8]	A/cm^2
Cell voltage	1.285[9]	V
Cell number	350	cells
Faraday efficiency	92	%
Heat loss	5[10]	%
Input heat (external steam)		
Temperature	300[11]	°C
Mass flow rate	15	kg/h

3. Performance analysis

To examine the performance of SOEC system, parametric analysis method is conducted with external steam temperature, heat exchanger effectiveness, steam conversion rate, hydrogen molar fraction, Faraday efficiency, and cell voltage. Table 2 shows the range of each variable in parametric study and optimization[6,9,11,15]. In each examination, only studied parameter varies, others are kept at design condition. On the other hand, in the final step all listed parameters with their ranges are brought into an optimization to find the optimal condition. In both

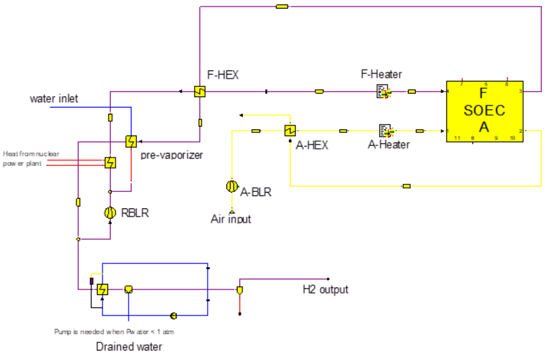

Fig. 2. Screenshot of the EBSILON software used for the simulation

Table 2. Variable range in parametric study and optimization

Variable name	Unit	Range
HEX eff	-	0.7-0.9
Steam temperature	˚C	200-700[11]
Steam conversion rate	-	0.5-0.8[15]
H_2 molar fraction (xH_2)	-	0.2-0.5[6]
Faraday efficiency	-	0.92-0.97
Cell voltage	V	1.285-1.305[9]

parametric studies and optimization, system efficiency is measured for comparison. Eq. (1) describes how system efficiency is calculated.

$$\eta_{sys} = \frac{\dot{m}_{H_2out} \times LHV_{H_2}}{E_{in}} \tag{1}$$

where:

η_{sys} : system efficiency

$\dot{m}_{H_2out}$: mass flow rate of produced hydrogen

LHV_{H_2} : low heating value of hydrogen at 25˚C

4. Result and discussion

4.1 Effect of external steam temperature and heat exchanger effectiveness

The figures show the system efficiency as function of each parameter in parametric study. In Fig. 3, external steam temperature is proportional to the amount of heat fed to the system, so the system efficiency increases when steam temperature increases, as expected. In the same way, the HEX effectiveness also affects positively to the system efficiency because it performs the heat recuperation of heat exchanger as shown in Fig. 4. Moreover, the dependence of system efficiency to HEX effectiveness is

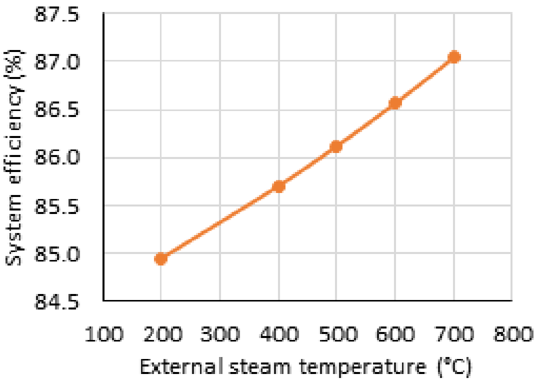

Fig. 3. System efficiency depends on the external steam temperature

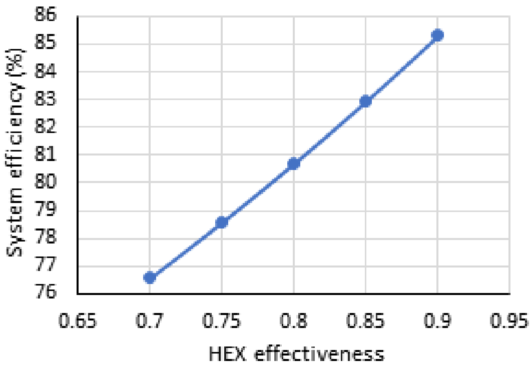

Fig. 4. System efficiency depends on the HEX effectiveness

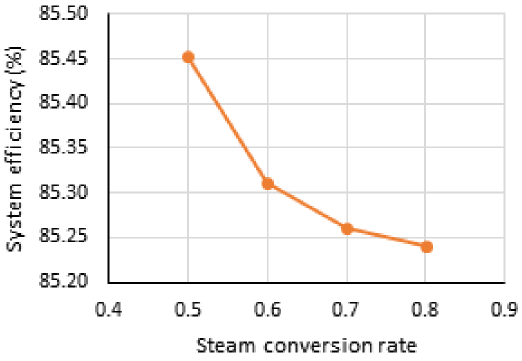

Fig. 5. System efficiency depends on the steam conversion

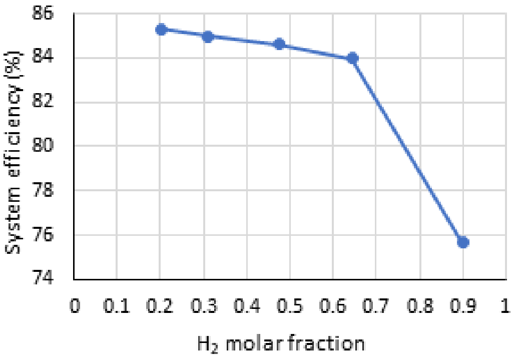

Fig. 6. System efficiency depends on the H_2 molar fraction

very high; about 10 percent points increases in system efficiency when HEX effectiveness changes from 0.7 to 0.9.

4.2 Effect of steam conversion rate and hydrogen molar fraction

Fig. 5 shows the system dependence on steam conversion. When steam conversion rate increases, the H_2 content in the output of SOEC stack is also higher, leading to the lower recirculation flow, and then less recovered heat from fuel off-gas. As a result, the fuel heater power increases, causing slightly decrease in system efficiency. In Fig. 6, the effect of hydrogen molar fraction is quite similar to that of steam conversion rate. A higher hydrogen molar fraction in stack inlet stream requires a smaller recirculation flow, leading to less recuperated heat amount. Consequently, the F-heater has to provide more heat to achieve deign temperature, reducing total system efficiency. However, the amplitude is bigger than that in Fig. 5 due to the higher recycle blower power consumption.

4.3 Effect of Faraday efficiency and cell voltage

Fig. 7 shows the dependency of system efficiency on Faraday efficiency. The SOEC efficiency increases with Faraday efficiency. However, it affects the heat release from or absorption into SOEC stack, consequently the whole system efficiency does not

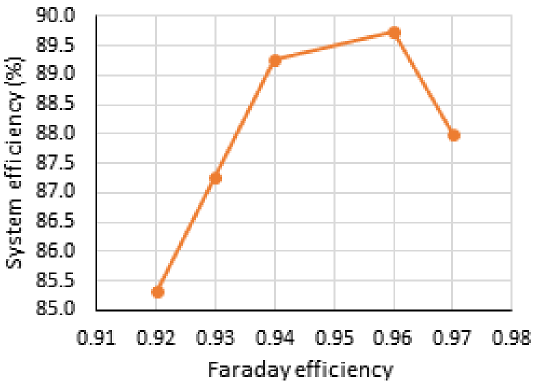

Fig. 7. System efficiency depends on faraday efficiency

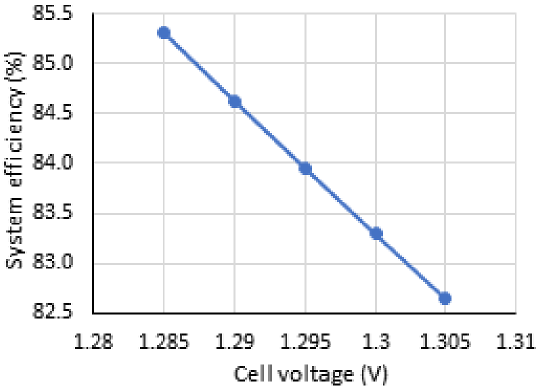

Fig. 8. System efficiency depends on the cell voltage

Table 3. Optimization result

Faraday efficiency	Cell voltage	HEX effectiveness	External steam temperature	Steam conversion rate	H_2 molar fraction inlet	System efficiency
0.92	1.285	0.9	700	0.58	0.280	87.167
0.93		0.9	700	0.68	0.251	88.833
0.94		0.9	700	0.58	0.207	91.382
0.95		0.9	700	0.75	0.285	91.437
0.96		0.9	700	0.58	0.201	92.133
0.97		0.787	700	0.57	0.200	92.434

always increase with Faraday efficiency's increase. The maximum system efficiency is 89.7% when Faraday efficiency is 0.96. In Fig. 8, system efficiency decreases when cell voltage increases because SOEC works at low faraday efficiency (0.92) that is in exothermic condition. Therefore, the higher voltage makes the higher loss.

4.4 Optimization

Because Faraday efficiency effect is not monotonous, it is set at discrete values from 0.92 to 0.97 in optimization. Besides, the cell voltage also chosen at 1.285 V where the stack is almost at thermal balance point, neither absorb nor release heat[9]. In addition, the parametric study in the previous section also pointed out the system efficiency is maximum with cell voltage value of 1.285 V.

Table 3 shows the optimization results with Faraday efficiency from 0.92 to 0.97. In all the cases, the optimal results are found at the boundary value of the external steam temperature, 700°C. However, the result also shows that, though the effect of all parameters are monotonous, the optimal point is not always achieved when the examined variables at the boundary. For example, when Faraday efficiency is 0.97, optimal point is achieved at HEX effectiveness of 0.787, steam conversion rate of 0.57 and hydrogen molar fraction of 0.200. This reveals the combination and correlation effect between the parameters.

Though genetic algorithm does not guarantee the global optimal point, this result suggests a parameter set for further investigation or analysis.

5. Conclusions

This study proposes a high power SOEC system and then, examined the effect each parameter including external steam temperature, heat exchanger effectiveness, steam conversion rate, hydrogen molar fraction, Faraday efficiency, and cell voltage to the system efficiency. Finally, the optimization based on genetic algorithm was conducted to see the combining effect of all listed parameters on system performance. In conclusion, there are several points can be summarized as following:

Higher steam conversion rate leads to high concentration of H_2 in the recirculation flow, hence the fuel heater power increases. As a result, the system efficiency drops as fuel utilization increases.

Faraday efficiency increase can make SOEC changes from exothermic to endothermic condition, thus the system efficiency trend and the optimal points of the operation changed too.

The genetic optimization method showed the optimal point in which endothermic operation is better option.

The concentration of H_2 in the feed fuel, steam conversion rate, and Faraday efficiency should be simultaneously considered in optimizing system operation.

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