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Performance Analysis of a Combined Solar Thermochemical High-temperature Electrolysis System

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ABSTRACT

Solid oxide electrolysis cells (SOEC) can be used for efficient hydrogen production. However, the SOEC needs both high-temperature steam and hydrogen as feed gas. This paper proposed a new system that combines a solar thermochemical reactor and SOEC together. The simulation results indicate that although the combined system can avoid additional hydrogen sources, it also lowers the hydrogen yield by 61.41% due to the discontinuous H_2O/H_2 supply. Multiple solar reactors can provide mixed H_2O/H_2 alternatively thus extending the gas feeding period for SOEC. A combined system with double reactors can increase the hydrogen yield by 94.67% compared with a single-reactor SOEC system. Compared with the traditional SOEC system, the single-reactor SOEC system and double-reactor SOEC system can save heating electricity by 25.69% and 42.2% respectively.

Keywords: solar thermochemical, combined system, solid oxide electrolysis, solar fuel

NONMENCLATURE

Abbreviations	
SOEC	Solid oxide electrolysis cells
PEC	Photoelectrochemical
Symbols	
N	Diffusion flux
R	Reaction rates
E	Electrical potential
T	Temperature
P	Pressure

1. INTRODUCTION

Compared with other hydrogen production methods such as photoelectrochemical (PEC), Solid oxide electrolysis cells (SOEC) feature high efficiency and high conversion ratio. However, High-temperature steam source and additional hydrogen source are essential for operating solid oxide electrolysis cells (SOEC) normally. Instead of providing steam and hydrogen using fossil fuel, this paper proposed a new system that combines a solar thermochemical reactor and SOEC together.

2. SOEC SYSTEMS USING CONCENTRATED SOLAR POWER

An experimental platform has been built in the Institute of Electrical Engineering, Chinese Academy of Sciences (IEECAS) to generate high-temperature steam for SOEC using concentrated solar power. Figure 1 is the photo of the platform. A 30-unit stack is used in the concentrated solar SOEC system. In the case of testing stack V-I curve, the peak electrolysis power and hydrogen yield can reach 5kW and 23.5 slpm, respectively. The tests prove that the constructed concentrated solar SOEC system is feasible for producing hydrogen.

Fig. 1 The photo of the concentrated solar SOEC system

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Using concentrated solar power to provide SOEC with high-temperature steam still needs an additional hydrogen source. Thus a new system as shown in Fig. 2 is proposed to utilize a solar thermochemical (STC) reactor to provide SOEC system with both high-temperature steam and hydrogen. In the reduction step, the oxide materials are reduced. The exit N_2/O_2 enters the anode side of the stack after passing the anode gas preheater. In the oxidation step, the reduced materials capture the O^{2-} from H_2O and produce H_2. The mixed N_2/H_2O is used as the feed gas for the solar reactor. The exit $N_2/H_2O/H_2$ is vented into the cathode side of the stack and further converted into mixed gas with more hydrogen proportion by electrolysis.

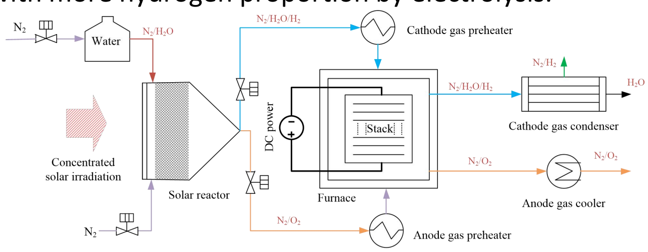

Fig. 2 The combined STC-SOEC system diagram

3. MODELING OF THE STC-SOEC SYSTEM

In this paper, $NiFe_2O_4$ supported on porous ceramics of ZrO_2 is chosen as the redox material [1]. The reactant constants for reduction and oxidation reactions can be found in the literature [2].

The porous ceramic is divided into N elements along the flow direction. The diffusion flux of the gas at the wall is considered equal to the reaction rate:

$$\begin{cases} N_{i,H_2O} \cdot a_V = -R_{ox,i} \\ N_{i,H_2} = -N_{i,H_2O} \end{cases} \tag{1}$$

The reaction rates are calculated according to the literature [3]. The solid phase conservation of $NiFe_2O_4$ in element *i* is listed as:

$$\psi \frac{df_i}{dt} = R_{ox,i} - R_{red,i} \tag{2}$$

The one-dimensional energy conservation equations for solid and gas are omitted here.

The stack is composed of 30 cells. The voltage of single cell is calculated as [4]:

$$\begin{aligned} V_{cell} &= E_{eq,i} + \eta_{conc,c,i} + \eta_{conc,a,i} \\ &+ \eta_{act,c,i} + \eta_{act,a,i} + \eta_{ohmic,i} \end{aligned} \tag{3}$$

Where $E_{eq,i}$ is calculated using Nernst equation.

The concentration overpotential is calculated as:

$$\begin{cases} \eta_{conc,c,i} = \dfrac{RT}{2F} \ln\left[\dfrac{P^I_{H_2,i} P^0_{H_2O,i}}{P^0_{H_2,i} P^I_{H_2O,i}}\right] \\ \eta_{conc,a,i} = \dfrac{RT}{2F} \ln\left[\left(\dfrac{P^I_{O_2,i}}{P^0_{O_2,i}}\right)^{0.5}\right] \end{cases} \tag{4}$$

The activation overpotential of both electrodes are calculated using Butler-Volmer equation. The ohmic overpotential is only considered for the electrolyte.

4. RESULTS AND DISCUSSION

4.1 Solar reactor performance

Figure 3 depicts the outlet hydrogen and oxygen molar flow rates from the solar reactor under multiple thermochemical cycles. Totally 8 cycles are conducted. The rest 7 cycles except the first one have almost the same molar flow rates for hydrogen and oxygen. The first cycle differed a lot from the others because the initial conditions such as temperature and reactant proportion are not the same as the other cycles.

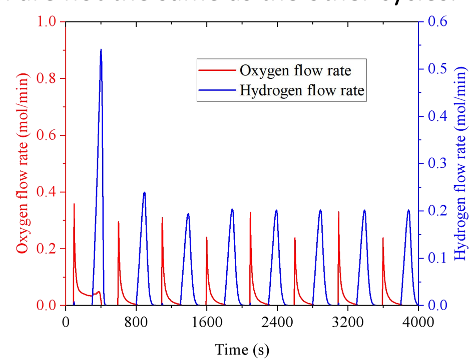

Fig. 3 The outlet hydrogen and oxygen flow rates from the solar reactor

4.2 Performance of the STC-SOEC system

Figure 4 depicts the outlet hydrogen and oxygen molar flow rates of the STC-SOEC system. The peak hydrogen flow rate is 2.5 times larger than that of only using the solar reactor due to the contribution of SOEC electrolysis.

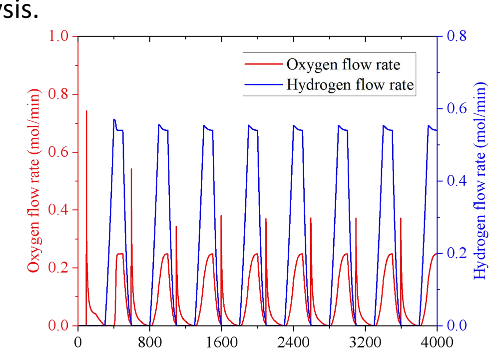

Fig. 4 The outlet hydrogen and oxygen molar flow rates of the STC-SOEC system

A single SOEC system operation case is studied to explore the effect of a discontinuous supply of steam on hydrogen production. Compared with a single SOEC system, the hydrogen yield of the STC-SOEC system decreased by 61.41%. A double-solar-thermochemical-reactor-SOEC (DSTC-SOEC) system is proposed to fix the discontinuous steam supply problem. Two solar reactors are used to provide the SOEC with steam and hydrogen alternatively. The outlet hydrogen and oxygen flow rates of the DSTC-SOEC system are depicted in Fig. 5. Although the hydrogen flow rate still fluctuated, the cycle number increased and the hydrogen flow rate is always beyond 0.1 mol/min. The hydrogen production in the same period increased by 94.67% compared with the STC-SOEC system. The results prove that deploying multiple solar reactors can increase the hydrogen yield of the STC-SOEC system effectively.

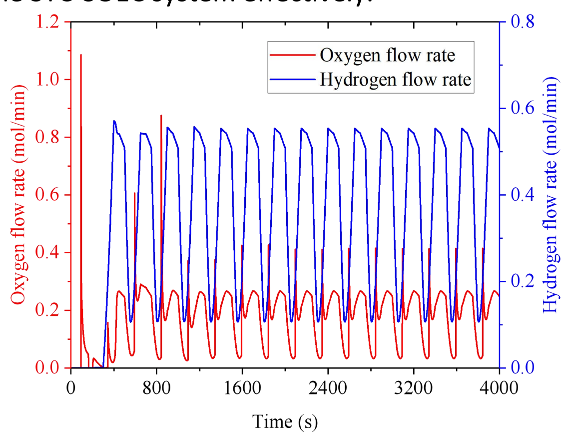

Fig. 5 The outlet hydrogen and oxygen molar flow rates of the DSTC-SOEC system

4.3 Heating Electricity comparison

The outlet gas temperature of the solar reactor is larger than 1200K and can be used to heat the pipes and equipment of the hydrogen production system. Thus, the electricity consumed for system heating is compared for SOEC, STC-SOEC and DSTC-SOEC systems. Figure 6 indicates that the heating electricity of the STC-SOEC system is 25.69% lower than that of the SOEC system while the DSTC-SOEC can save the heating electricity by 42.2% compared with the SOEC system. The advantage of DSTC-SOEC in saving heating electricity also implies the importance of providing gas continuously. The outlet gas temperature is actually beyond the operating temperature of the SOEC system. However, the gas flow rate in this simulation is so small that the gas temperature decreased significantly during the transport process. Increasing the flow rate can further save or even eliminate the heating electricity consumption. One should also note that overheating SOEC may cause damage of SOEC sealing parts.

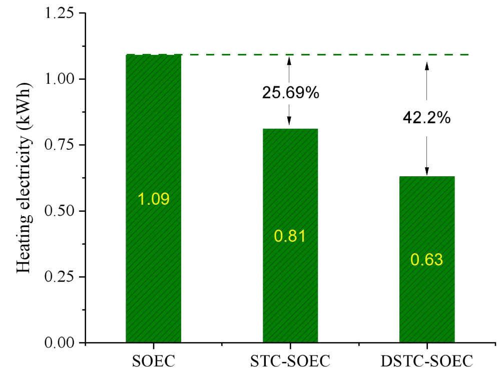

Fig. 6 The comparison of heating electricity among different systems

5. CONCLUSION

A new system combing the solar thermochemical reactor and SOEC is introduced in this paper. The solar reactor can provide SOEC with high-temperature steam and hydrogen using concentrated solar power. The simulation results indicate that although the combined system can avoid additional hydrogen sources, it also lowers the hydrogen yield by 61.41% due to the discontinuous H2O/H2 supply. Multiple solar reactors can provide mixed H2O/H2 alternatively thus extending the gas feeding period for SOEC. The DSTC-SOEC system can increase the hydrogen yield by 94.67% compared with the STC-SOEC system. The electricity consumed for heating is also compared among different systems. Compared with the traditional SOEC system, the STC-SOEC system and DSTC-SOEC system can save heating electricity by 25.69% and 42.2% respectively.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

REFERENCE

[1] Zoller S. A 50 kW Solar Thermochemical Reactor for Syngas Production Utilizing Porous Ceria Structures [D]; ETH Zurich, 2020.

[2] Villafán-Vidales H. I., Abanades S., Caliot C., et al. Heat transfer simulation in a thermochemical solar reactor based on a volumetric porous receiver [J]. Applied Thermal Engineering, 2011, 31(16): 3377-3386.

[3] Agrafiotis C. C., Pagkoura C., Lorentzou S., et al. Hydrogen production in solar reactors [J]. Catalysis Today, 2007, 127(1): 265-277.

[4] Ni M., Leung M. K. H., Leung D. Y. C. Parametric study of solid oxide steam electrolyzer for hydrogen production [J]. International Journal of Hydrogen Energy, 2007, 32(13): 2305-2313.