

and resource required for electrolysis. SOEC produces hydrogen and oxygen through electrolysis. The heat exchanger is used to collect the waste heat of high temperature gas at the outlet of the electrolytic cell. This system adds solar optical elements on the basis of the original high-temperature SOEC hydrogen production system. The innovation is that the hydrogen, oxygen and water vapor from the SOEC will release heat in the heat exchanger to cool down, and then enter the second heat exchanger to release the waste heat. The separated water and make-up water are heated in the double heat exchangers and the heat collector and then enter the electrolytic cell. Such staged heating and exothermic design can more thoroughly utilize the residual heat of the mixed gas to make the water vapor participating in the reaction have a higher temperature.

2.2 Empirical models

2.2.1 Electrochemical analysis of electrolytic cell

Assuming that the electrolysis process is reversible, the voltage applied on the electrode can be solved by the Nernst equation. According to the empirical formula, it can also be calculated as follows:

$$U_{rev} = -2.8993 \times 10^{-4} T + 1.2099 \quad (1)$$

Where T is the absolute temperature of the reaction process.

Nernst voltage U_{Nernst} is expressed as follows:

$$U_{Nernst} = U_{rev} + \frac{RT}{zF} \ln \left(\frac{p_{H_2} \sqrt{p_{O_2}}}{p_{H_2O}} \right) \quad (2)$$

Where, z is the number of transmitted electrons (2 in water electrolysis), and F is the Faraday constant. p is the partial pressure.

The actual battery voltage is affected by many different overpotentials and is higher than the reversible voltage so that resistance can be overcome. It is expressed as:

$$U_{cell} = U_{Nernst} + U_{con,c} + U_{con,a} + U_{act,a} + U_{ohm} \quad (3)$$

Where, $U_{con,c}$, $U_{con,a}$, $U_{act,c}$, $U_{act,a}$, U_{ohm} are the cathodic concentration overpotential, anode concentration overpotential, cathode activation overpotential, anode activation overpotential and electrolyte ohmic overpotential, respectively.

The hydrogen production rate (\dot{m}_{H_2}) on a single cell can be calculated according to the electron transfer rate obtained from the current density on the basis of Faraday's law. It is described as :

$$\dot{m}_{H_2} = \frac{N_{cell} \times J \times A_{cell} \times M_{H_2}}{2F} \quad (4)$$

Where, U_{cell} is the actual voltage, J is the current density, A_{cell} is the effective area of the battery, and N_{cell} is the number of batteries.

The efficiency of solid oxide cell is given as :

$$\eta_{SOEC} = \frac{\dot{m}_{H_2} \times LHV_{H_2}}{P_{st} + P_{pump} + P_{cell}} \quad (5)$$

In the formula, the low calorific value of hydrogen (LHV_{H_2}) is 120210kJ/ kg, and P_{st} and P_{pump} are the demand of reactor power and pump power respectively. Other parameters are cited from [3].

2.2.2 Photovoltaic cell and solar thermal system

Photovoltaic power output depends on the solar radiation intensity, the temperature of photovoltaic modules, the solar incident angle and the loading angle of photovoltaic panels. In order to predict the actual energy output, the most widely used five parameter model and solving method proposed by Zhang et al. [4] can be employed. The results are reliable and have higher accuracy. The parameters of adopted solar cell includes $P = 250W$, $V_{oc} = 33.1398V$, $I_{sc} = 9.2914A$, $I_m = 8.4717A$, $V_m = 25.2173V$. The obtained results are $I_{pv} = 9.2984A$, $I_0 = 729.52nA$, $R_s = 0.339 \Omega$, $R_p = 446.46 \Omega$, and $n = 1.1791$.

For the calculation of solar thermal system, the water in the pipe flows axially, regardless of the fine radial movement. The pressure exerted on the fluid in various states is equal on all cross sections and the influence of gravity can be ignored for the horizontal heat pipe. Since the inlet and outlet temperatures are known, the total heat received by the fluid can be obtained, and then the inner pipe wall temperature can be calculated according to the average temperature. According to the relevant design and research, the outer wall temperature can be taken as 30 °C and the average air temperature outside the tube can be taken as 20 °C [5, 6]. The inner diameter, outer diameter and length of the endothermic tube are 55mm, 70mm and 98.5m respectively. The heat flux of forced convection in the tube, the air convection heat flux, the outward radiation heat flux, and the total absorbed heat flux of the collector can be calculated according to the heat transfer theory. Thus, based on the actual absorbed solar radiation intensity, the efficiency can be obtained consequently.

The overall performance of the hydrogen production system can be evaluated via the total efficiency. It is defined as :

$$\eta_{overall} = \frac{\dot{m}_{H_2} \times LHV_{H_2}}{Q_{solar}} \quad (6)$$

Where, Q_{solar} is the solar radiation energy absorbed by the system.

3 Results and discussion

3.1 SOEC performance

The obtained main cell polarization with the varying current density is shown in Figure 2. It can be seen that the largest irreversible voltage loss of the cell is the activation over potential, followed by the ohmic over potential, and the smallest is the concentration over potential.

With the increase of current density, the irreversible loss increases, which leads to the decrease of energy efficiency. However, the hydrogen production rate is directly proportional to the current density. Therefore, in practical engineering application, we should make a trade-off between energy efficiency and hydrogen production rate. In the case of hydrogen production alone, energy efficiency can be biased. In the case that hydrogen production needs to be supplied to subsequent power generation and heating, hydrogen production rate can be biased. The previous results showed that the low hydrogen production rate caused by low current density will reduce the degradation rate of the battery and prolong the service life of the battery. Therefore, the design of the system should be considered between the efficiency, cost and hydrogen production rate.

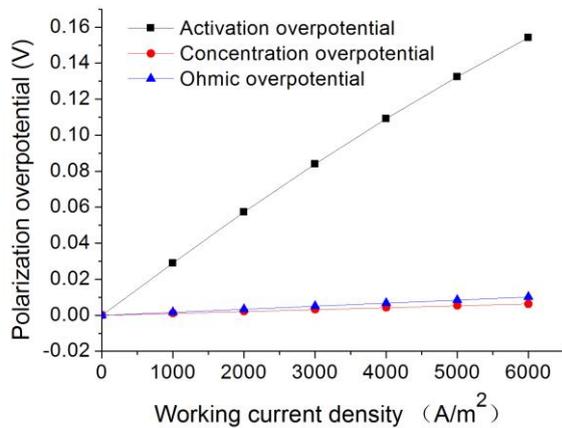


Fig. 2. Effect of current density change on cell polarization

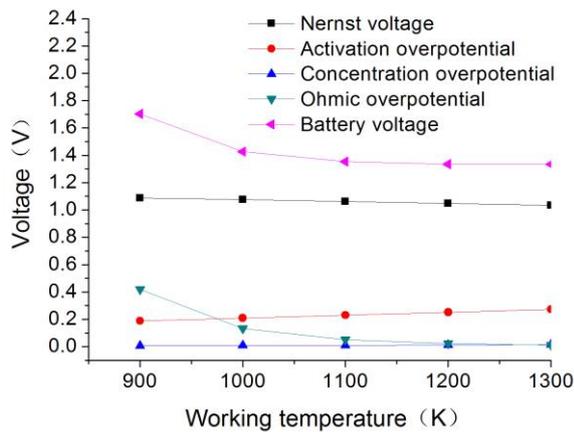


Fig. 3. Variation of different polarization overvoltage and battery voltage with operating temperature

Figure 3 shows the effects of operation temperature on polarization overpotential and battery voltage. It indicates that with the increase of temperature, Nernst voltage slightly decreases, activation overpotential slightly increases, concentration overpotential basically

remains unchanged, ohmic over potential greatly decreases in the range of 900-1100K, and then decreases slightly. The battery voltage also shows a downward trend, falling rapidly in the range of 900-1100K, and then slightly down.

3.2 System performance

Figure 4 shows the rate of consumed electric energy to thermal energy. It can be seen that the proportion of consumed electric energy and thermal energy decreases with the increase of temperature, and gradually changes to the equal value. Further analysis indicates that the electric energy consumed per unit hydrogen production in high temperature cell is less than that in low temperature cell, and the heat energy is more.

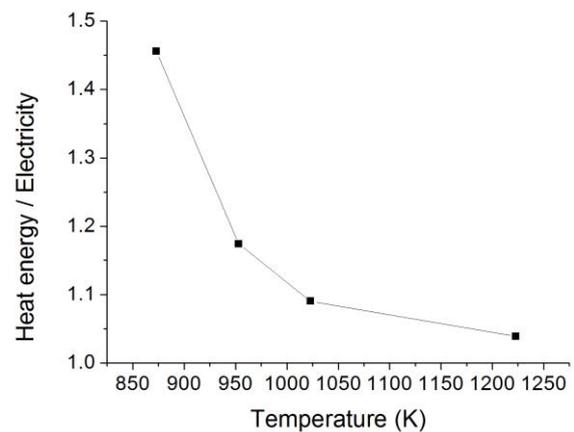


Fig. 4. Variation of power to heat consumption ratio with temperature

Figure 5 shows the variation of hydrogen production efficiency with current density. It can be seen that when SOEC is at 1223K high temperature, the energy efficiency of the system continues to increase with the current density, and it can reach about 80% hydrogen production efficiency at 12000 A/m², and then gradually decrease. When the temperature is 873K, the energy efficiency of the system begins to decrease when the current density is about 6000 A/m², and the maximum hydrogen production efficiency is about 62%.

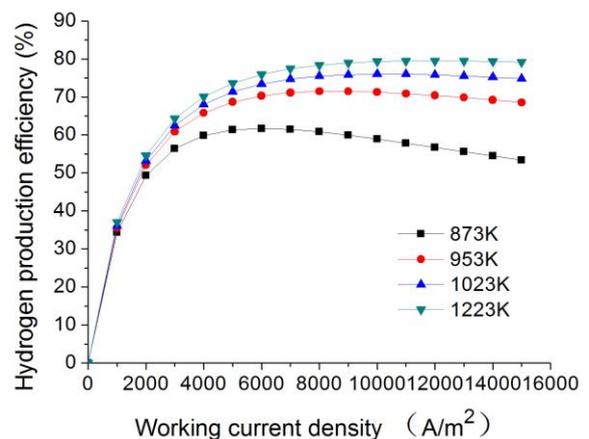


Fig. 5. Variation of hydrogen production efficiency with current density

The overall performance of the hybrid system is also evaluated based on three factors: the low heat value of hydrogen, the solar radiation energy absorbed and the hydrogen production rate in the solid oxide cell. By supposing that the operating pressure of the system is 5MPa, the temperature of the mixture at the outlet of the electrolytic cell is 950 °C [2, 3] and the working current density is 12000 A/m², the efficiency of solid oxide electrolyzer is 79.55%, and the efficiency of hydrogen production system based on PV/T technology is 34.08%. These value are almost the same as the results reported in the literature [3].

<i>rev</i>	reversible state
<i>Nernst</i>	open circuit voltage
<i>con,c</i>	cathode concentration polarization
<i>con,a</i>	anode concentration polarization
<i>act,c</i>	cathode activation polarization
<i>act,a</i>	anodic activation polarization
<i>ohm</i>	ohmic polarization
<i>cell</i>	electrolytic cell
<i>H₂</i>	hydrogen
<i>st</i>	stack
<i>pump</i>	pump
<i>SOEC</i>	solid oxide electrolysis cell
<i>overall</i>	total
<i>solar</i>	solar energy

4 Conclusions

In this work, the hydrogen production system based on PV/T technology and the traditional high-temperature SOEC technology is proposed. Multiple heat exchangers are added to make full use of solar thermal energy. Through the design and efficiency calculation of the system, the following conclusions are drawn:

(1) The activation, concentration and ohmic overpotential increase with the increase of current density. The activation overpotential is dominated in the irreversible voltage loss of the cell. The hydrogen production efficiency of SOEC increases with the increase of temperature and first increases and then decreases with the increase of current density.

(2) There is a trade-off between energy efficiency and hydrogen production rate in SOEC. With the increase of current density, the energy efficiency decreases and the hydrogen production rate increases. The rate of consumed electric energy to thermal energy decreases with the increase of temperature.

(3) The efficiency of the cell in the proposed system can be as high as 80% at a certain high temperature and current density. The total efficiency of the composite hydrogen production system is 34%, indicating the reliability and good performance of the proposed system.

Nomenclature

<i>R</i>	universal gas constant
<i>A</i>	area, m ²
<i>T</i>	temperature, °C
<i>P</i>	heating power, W
<i>Q</i>	heat quantity, kJ
<i>F</i>	the Faraday constant
<i>U</i>	voltage
<i>z</i>	number of transmitted electrons
<i>N</i>	number of batteries
<i>n</i>	diode parameter
<i>J</i>	current density
<i>\dot{m}_{H_2}</i>	rate of production
<i>LHV</i>	low calorific value
<i>Greek letters</i>	
η	efficiency
<i>Subscripts</i>	

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References

1. R. Ma, Plant Mainte Eng. **19**, 126-128 (2017)
2. S. Zhou, Y. Wang, T. Hu, Z. Deng, Academic meeting of China Society of Engineering Thermophysics, 196110, (2019)
3. D. Raheleh, M. Mehrpooya, Energy Convers. Manage. **176**, 73-94 (2018)
4. S. Zhang, D. Chen, In for Res. **44**, 39-43 (2018)
5. Q. Chou, SEU., 37-91 (2016)
6. B. Yang, TJU., 23-54 (2011)