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Exergy analysis of a novel integrated polymer electrolyte membrane fuel cell test system

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ABSTRACT

To address the problems of low performance efficiency and high energy consumption of conventional fuel cell test systems, this study proposes a novel fuel cell test system. This test system integrates hydrogen circulation and recovery preheating, and uses a condenser to collect water generated from the stack, realizing the integrated gas-heat-water utilization of the system. The thermodynamic model of the system is also established, and the performance of the two systems are compared and evaluated using exergy analysis. The exergy loss distribution of each auxiliary component in the system as well as the net power, parasitic power, and exergy efficiency of the system are determined. The results show that the fuel cell stack, exhaust gas emission and bubble humidifiers are the locations with the largest losses in both systems, and the performance of the stack and the waste heat recovery of exhaust gas the system should be improved. When the systems are operating at 1A/cm2, the exergy loss of the novel system is 96kW, which is 28% lower than the conventional system, the net power output of the system is 80kW, which is 19% higher than conventional system, and the exergy efficiency of the system is 39%, which is 32% higher than the conventional system, while saving 309kg of humidified water per hour. Therefore, the proposed novel system can significantly improve the system performance and overall operating efficiency. The analysis of the two systems can provide a novel direction for further performance improvement of the fuel cell test system.

Keywords: PEMFC test system, Thermodynamic model, Exergy analysis, Exergy loss, System effificiency

1. INTRODUCTION

As a clean, flexible and application scenario-rich secondary energy source, hydrogen energy will play an important role in human society's efforts to combat climate change and build a decarbonized society. Thus it is an important alternative to fossil energy to achieve carbon neutrality[1]. Proton exchange membrane fuel cells (PEMFC) are an important type of technology to utilize hydrogen energy efficiently. It has been widely used in portable, vehicle-mounted and stationary power generation applications due to its advantages of energy saving, fast start-up, low or zero emissions, low noise and a high power density. Fuel cell test systems are essential equipment in the process of fuel cell performance testing and evaluation, and play an important role in promoting fuel cell development. Similar to fuel cell vehicle power systems, fuel cell test systems require a large amount of auxiliary equipment, such as pumps, humidifiers and heat exchangers. They generate a large amount of parasitic power during system operation, reducing the net power output of the system, which in turn limits the further improvement of the PEMFC test system efficiency. Under these conditions, any improvement in the efficiency of the PEMFC test system will help accelerate the commercialization of the fuel cell system[2].

The schematic diagram of the conventional fuel cell test system is shown in Figure 1, which is divided into an air subsystem, a hydrogen subsystem, a thermal management subsystem, and a hydration subsystem for humidification.The piping of the air subsystem is shown in blue and consists of an air compressor station (AC), mass flow controller (MFC), cathode gas heater (CHE), cathode bubble humidifier (CBH), and cathode backpressure valve (BPV). The ambient air is compressed at the AC and then enters the test system.

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The inlet gas flow to the stack is controlled by the MFC. The inlet gas is preheated by the CHE. After preheating, it enters the CBH for humidification to improve the proton conductivity of the proton exchange membrane. The unreacted gas enters the BPV for gas pressure control at the stack inlet and finally is discharged directly to atmosphere.The hydrogen subsystem piping, shown as red lines in Figure 1, consists of a mass flow controller (MFC), an anode gas heater (AHE), an anode bubble humidifier (ABH), and a cathode back pressure valve (BPV). The hydrogen gas supply is provided by a high-pressure hydrogen cylinder set. The workflow is identical to that of the air system.The piping of the thermal management subsystem is shown as the black line in Figure 1. It consists mainly of the water pump (WP1) and the cooling system heat exchange (CSHE). The coolant enters the stack and absorb the heat generated by the stack to increase temperature. the high temperature then coolant enters the CSHE to dissipate the heat to reach the required operating temperature of the stack and finally enters the stack again. The temperature difference between the inlet and outlet of the reactor is controlled by the speed of the pump. The piping of the hydration subsystem for humidification is shown as the green line in Figure 1. It is controlled by the main solenoid valve (WRSV). The humidifier of the test system requires constant water replenishment, which depends on the operating power of the fuel cell and the humidification demand.

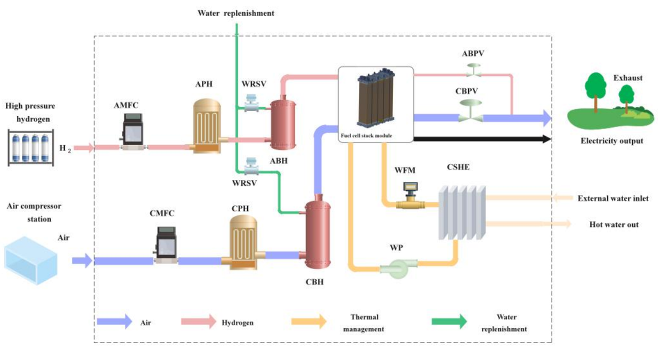

Fig 1 Schematic of the conventional PEMFC test system

Due to the conventional test system exhaust gas using the direct exhaust method, it not only causes the loss of hydrogen energy, but also has the safety risk. While the water produced by the electric reactor is not collected and utilized. Also air preheating is done by conventional external electric heating, and the tail gas energy is not effectively utilized. This results in a limited net power output of the conventional PEM fuel test system and a low overall performance efficiency of the system. In this paper, the performance of the PEMFC test system is evaluated by exergy analysis. Exergy analysis is an method based on the second law of thermodynamics, which considers all parameters or components of the entire system and can determine the loss of available energy as well as the cause, location, and true magnitude of the exergy loss[3-4].

Researchers have conducted extensive and detailed studies on the energy and exergy analysis of fuel cell systems in various fields, analyzing the impact of the exergy losses of the stack and various auxiliary components of the system on the system[5-6]. However, most of the current studies have focused on fuel cell power systems or combined heat and power systems, while the introduction of fuel cell test system applications is lacking. Meanwhile, the performance analysis of different components of the system lacks the coupling analysis modeling between each component, thus making the overall improvement and optimization of the fuel cell system difficult. The main objectives of this paper are (1) to propose a novel PEMFC test system, which can realize the integrated heat-gas-water utilization; (2) to establish a complete thermodynamic coupling model of the PEMFC test system, fully considering the thermodynamic processes of each auxiliary component and connected parts in the system; and (3) To reveal the exergy loss distribution of the test system, analyze and compare the performance of the two systems, and make suggestions for the optimization of the system.

2. SYSTEM LAYOUT

The schematic diagram of the novel fuel cell test system is shown in Figure 2, which can realize the comprehensive utilization of gas-heat-water.

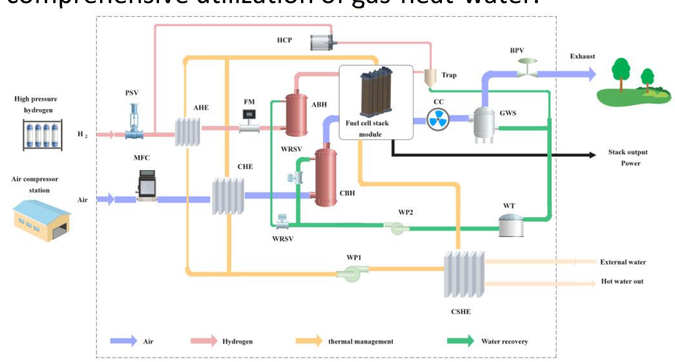

Fig 2 Schematic of the novel PEMFC test system

The air subsystem adds a condenser (CC) and a gas-water separator (GWS) to collect and utilize the water in the exhaust gas. The hydrogen subsystem introduces a hydrogen circulation pump (HCP) to recycle the unreacted hydrogen, and the liquid water is collected through a trap before the hydrogen enters HCP. In the thermal management subsystem, air and gas preheaters

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(AHE and CHE) are added. The high temperature cooling water is divided into two circuits to preheat the air and hydrogen inlets respectively. In the water recovery subsystem, the liquid water flows from the hydrogen trap and the GWS and is first collected in the water tank (WT) and then redistributed according to the different humidification needs of the humidifier.

3. MODEL

3.1 *Fuel cell Stack Modeling*

The fuel cell stack model uses the model proposed by Gimba[7]. The output voltages are:

$$V_{\text{cell}} = V_{rev} - V_{act} - V_{ohm} - V_{conc} \quad (1)$$

where V_{rev} is the fuel cell voltage output value predicted by thermodynamic theory, V_{act} is the activation loss voltage drop of the fuel cell, V_{ohm} is the ohmic loss voltage drop of the fuel cell, and V_{conc} is the concentration loss voltage drop of the fuel cell.

3.2 *Molar flow rate of reactants, products and make-up water*

The molar flow rate of inlet and outlet reactants and water produced by the stack in the fuel cell system can be calculated by the following equations:

air inlet molar flow rate:

$$n_{in}^{Air} = \frac{I \cdot StoA \cdot N}{4F \cdot 0.21} = 1.19 StoA \cdot \frac{IN}{F} \quad (2)$$

hydrogen inlet molar flow rate:

$$n_{in}^{H_2} = \frac{I \cdot StoH \cdot N}{2F} = 0.5 StoH \cdot \frac{IN}{F} \quad (3)$$

air outlet molar flow rate:

$$n_{out}^{Air} = (1.19 StoA - 0.25)\frac{IN}{F} \quad (4)$$

hydrogen outlet molar flow rate:

$$n_{out}^{H_2} = (0.5 StoH - 0.5)\frac{IN}{F} \quad (5)$$

where *StoA* and *StoH* are the stoichiometric ratios of air and hydrogen respectively. *F* is the Faraday constant and *F*=96485C/mol. *I* represents the fuel cell operating current. *N* is the number of single cell of the stack

The molar flow rate of humidifiers refill water:

$$n_{in}^{H_2O} = \frac{RH \cdot P_{in}^{Sat}}{P_{in} - RH \cdot P_{in}^{sat}} \cdot n_{in} \quad (6)$$

where: *RH*, P_{in}, p_{in}^{sat} and n_{in} are the corresponding saturated vapor pressure and inlet molarity at gas inlet humidity demand, inlet pressure and inlet temperature, respectively.

3.3 *Parasitic power of system*

3.3.1 Hydrogen circulation pump

The unreacted hydrogen is recycled through a hydrogen circulation pump, with the gas outlet pressure being the stack inlet pressure. The power of the hydrogen cycle compressor can be expressed as:

$$W_{hc} = \frac{n_{out}^{H_2} C_{pH_2} T_{sout}}{\eta_{hc}} .[(\frac{p_{a,in}}{p_{a,out}})^{\frac{r-1}{r}} - 1] \quad (7)$$

where C_{pH2} is the molar specific heat capacity of hydrogen, T_{sout} is the hydrogen temperature at the outlet of the stack, η_{hc} is the hydrogen circulation pump operating efficiency, $P_{a,out}$ is the pressure of circulating hydrogen at the outlet of the stack, and r is the hydrogen adiabatic coefficient.

3.3.2 Bubble humidifier

The humidification of the gas in the fuel cell system is realized through the bubble humidifier. Liquid water becomes saturated vapor needs to absorb a lot of energy which is mainly provided by the heater in the humidifier, so the power consumption of the humidifier can be obtained as follows:

$$W_{bh} = n_{in}^{H_2O} H_{vb} \quad (8)$$

where H_{vb} is the latent heat of vaporization of water.

3.3.3 Water pump

The thermal management subsystem and the water recovery subsystem are driven by pumps for cooling water circulation and make-up water.

The power consumption of the water pump of :

$$W_{wps} = n_s \frac{p_{in-}p_{out}}{\rho \eta_{wp}} \quad (9)$$

where P_{in} and P_{out} are the cooling water into and out of the pump pressure respectively, n_s is the molar flow rate of liquid water, ρ is the density of water, and η_{wp} is the pump operating efficiency.

3.3.1 Condenser

The condenser uses air-cooled fan to condense and collect the liquid in the air exhaust. In order to realize the recycling of water in the system, the system needs to meet the condition that the amount of water recovered from the exhaust gas should be greater than the amount of water used for humidification, which is deduced from the literature[8].

$$P_{con}^{sat} \le \frac{0.5}{1.19 StoA - 0.25} P_{con} \quad (10)$$

$$P_{con}^{Sat} = -0.03089 + 0.02451 \exp(\frac{T_{con}}{26.3731}) \quad (11)$$

where P_{con} is the condenser outlet pressure, T_{con} is the temperature of the exhaust gas out of the condenser.

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The power consumption of this fan can be expressed as:

$$W_{fan} = n_{out}^{c} \cdot C_{pAir} \cdot (T_{sout} - T_{con}) \quad (12)$$

where n_{out}^{c} is the molar flow rate of air at the outlet of the stack, including air and water vapor, C_{pAir} indicates the molar specific heat capacity of air.

The total parasitic power of the system is the sum of the power of all the auxiliary components in the system, which can be expressed as :

$$W_p = W_{hc} + W_{bh} + W_{wpc} + W_{wps} + W_{fan} \quad (13)$$

The output power of the stack can be derived as:

$$W_{stack} = V_{cell} \cdot I \cdot N \quad (14)$$

The net power of the PEMFC system is equal to the output power of the fuel cell stack minus the parasitic power:

$$W_{net} = W_{stack} - W_p \quad (15)$$

3.4 *Theory Exergy theory*

The exergy of a substance can be generally divided into two parts: physical exergy and chemical exergy.

$$e = e_{ph} + e_{ch} \quad (16)$$

where e_{ph} and e_{ch} are physical exergy and chemical exergy respectively.

Physical exergy is related to the temperature and pressure of the reactants and products in a fuel cell system. Physical exergy is expressed as the difference between enthalpy and entropy, and the temperature and pressure in the standard state are T_0=298.15k and P_0=1bar, respectively. The general expression for physical exergy can be described as:

$$e_{ph} = (h - h_0) - T_0(s - s_0) \quad (17)$$

where h_0 and s_0 denote the specific enthalpy and entropy evaluated under standard conditions, respectively.

Chemical exergy is related to the deviation of the chemical composition of the system from the chemical composition of the environment. Chemical exergy considered in the analysis of this sysytem is the standard chemical exergy based on the standard conditions. The chemical exergy of the material flow is calculated using the following equation.

$$e_{ch} = (\sum x_i e_{ch,i} + RT_0 \cdot \sum x_i \ln x_i) \quad (18)$$

where x_i denotes the molar fraction of substance *i* in the mixture, $e_{ch,i}$ denotes the chemical exergy of substance *i* in the mixture, and *R* is the substance gas constant.

For the PEMFC system, the exergy balance equation can be developed.

$$n_{in}^{Air} e_{x,in}^{Air} + n_{in}^{H_2} e_{x,in}^{H_2} + n_{in}^{exW} e_{x,in}^{exW} - n_{out}^{Air} e_{x,out}^{Air} - n_{out}^{exW} e_{x,out}^{exW} - W_{net} - (1 - \frac{T_0}{T_{con}}) Q_{fan} - E_{x,cshe} - E_{x,system} = 0 \quad (19)$$

where n_{in}^{exW} and n_{out}^{exW} are the inlet and outlet molar flow rates of external cooling water respectively, Q_{fan} are the rate loss by the condensing fan to the environment, $E_{x,system}$ is the internal rate of exergy losses for the system, and $E_{x,cshe}$ is the rate of heat transfer exergy losses by the water-cooled heat exchangers to the external cooling water, which can be obtained according to the following formula:

$$E_{x,cshe} = T_0 Q \frac{T_{ave,h} - T_{ave,c}}{T_{ave,h} \cdot T_{ave,c}} \quad (20)$$

where $T_{ave,h}$ and $T_{ave,c}$ are the average heat transfer temperature of the cooling water entering the hot and cold side of the water-cooled heat exchanger respectively, *Q* is the heat transfer from the hot side of the water-cooled heat exchanger.

The exergy efficiency is defined as the ratio of the net output power of the system to the input exergy of the system and can be expressed as:

$$\eta_{exergy} = \frac{W_{net}}{E_{x,in}} \times 100\% \quad (21)$$

4. RESULTS AND DISCUSS

The design and operating parameters of the core components of the fuel cell test system are shown in the table 1. Under the current operating conditions, the exergy loss of each component of the different systems can be obtained by exergy analysis.

Table 1 Basic design and operating parameters of system

Components	Parameters	Values
High-pressure hydrogen	Outlet Pressure	10.0 bar
Air compressor	Outlet Pressure	4.0 bar
Fell cell stack	Number	300
	Effective working area	400 cm2
	Current density	1.0 A/cm2
	Average cell voltage	0.659 V
	StoA/StoH	2.0/1.2
	Relative humidity	100%
	Inlet temperature	343.15 K
	Inlet pressure	3.0 bar
	Temperature difference	5 K

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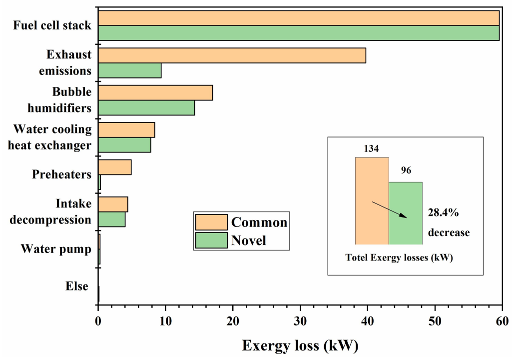

Fig 3 Exergy loss distribution of the same components for different types of systems

Fig. 3 shows the exergy loss of the same components in two different systems, where the novel system has a exergy loss of 96kW, which is 28.4% lower compared to the conventional system. Fig 3 clearly shows that the largest exergy loss in both systems are generated in the fuel cell stack, both have the same value, accounting for 44.3% and 62.3% of the total exergy losses in the respective systems, which is caused by the irreversibility of the chemical reaction, so improving the performance of the fuel cell stack is the key to the optimization of the PEMFC system. Secondly, the exhaust gas in the conventional system contains unreacted hydrogen, which is directly discharged into the environment. So the chemical exergy carried by the hydrogen is not fully utilized, causing 29.6% of the total exergy loss. While the novel system adopts the hydrogen circulation pump to recycle the unreacted gas, and the exergy loss is reduced by 76.5%, but the large amount of heat carried by the exhaust gas is still not fully utilized, so it is important to find an effective method to recover and utilize the waste heat of the exhaust gas. In addition, the cooling systems in both systems use water-cooled heat exchangers, and there is heat transfer exergy loss in the process of water-cooled heat exchange, and under the same ambient temperature and heat transfer, the greater the heat transfer temperature difference, the greater the heat transfer exergy loss. And when the external cooling water average heat transfer temperature is certain, reduce the system operating temperature can reduce the heat transfer heat loss. Since part of the heat of the novel system is used for preheating, the heat transfer temperature difference of the novel system is low compared with the conventional system, so the heat transfer exergy loss is reduced by 7.1%. Finally, the preheating of air and hydrogen in the novel system uses the heat absorbed from the reactor by the cooling system, which can save 4.9 kW compared with the conventional system using electric heating. Therefore, the exergy losses of the system can be significantly reduced by using the novel system.

Fig 4 shows the performance of the different systems at different current densities. The stack output power and the system parasitic power gradually increase with the increase of current density, while the system net output power first increases, then slowly increases to the maximum value and then starts to gradually decrease. The maximum net power of both systems reaches the maximum at 1.4A/cm^2 , which is 72.4kW and 62.4kW respectively, with a net power increase of about 13.8%. The overall parasitic power of the conventional system is larger than that of the novel system, and the greater the current density, the greater the increase. Therefore, the net power output of the novel system is higher than that of the conventional system with the same power output of the stack. When the system is operated under the parameters of Table 1, the novel system uses the cooling water at the outlet of the stack to preheat the gas, which can replace the electric heating preheat and save 4.9kW of energy consumption, and the humidifier make-up water is the high-temperature liquid water collected from the tail gas, which can save 2.3kW of energy consumption of humidifier heating compared with the cold water make-up water of the conventional system. Therefore, the novel system can significantly reduce energy consumption and increase the net power output of the system.

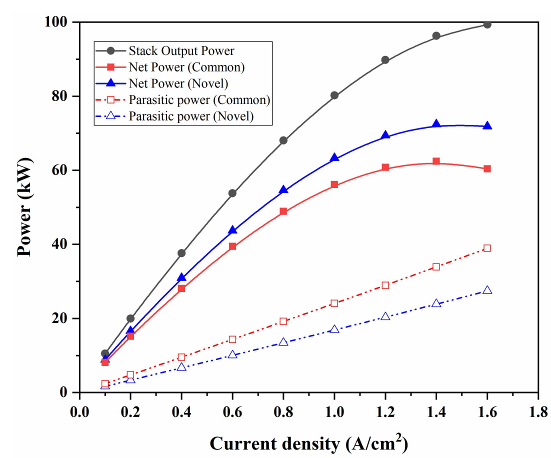

Fig 4 Variation trends of various power of the system with the stack current density

Fig 5 shows the change of the exergy efficiency of different systems at different current densities. In the Fig 5, both system exergy efficiencies decrease with the increase of current density, which is consistent with the polarization curve of fuel cell. The overall efficiency curve of the novel system is higher than that of the

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conventional system. Under the operating conditions of Table 1, the overall efficiency of the two systems is 29.0% and 38.9% respectively with an increase of 34.2%. This is because the net power of the novel system is larger than that of the conventional system at the same current density, and also the total exergy into the system is lower in the novel system due to the realization of hydrogen cycle. Therefore, in order to improve the system efficiency, the system parasitic power should be reduced and the recent utilization of hydrogen gas should be enhanced.

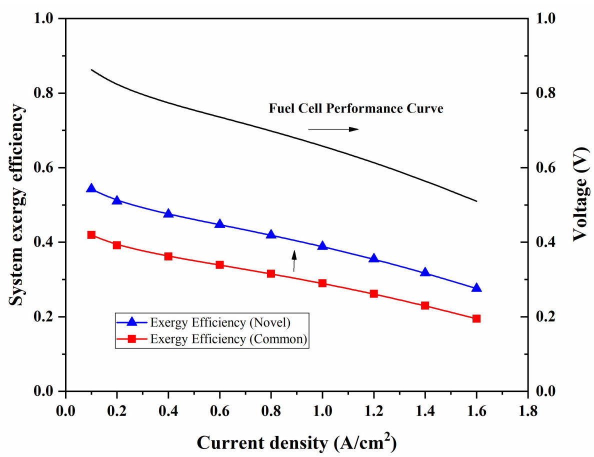

Fig 5 Variation trends of the system exergy efficiency and voltage with the stack current density

5. CONCLUSIONS

In this study, a novel fuel cell test system is proposed to address the shortcomings of the low performance efficiency of the conventional fuel cell test system, while a complete thermodynamic coupling model of the PEMFC test system is developed. The performance of the two test systems are compared and analyzed by exergy analysis. The main conclusions are as follows:

(1) The novel system can realize the efficient utilization of hydrogen circulation through the hydrogen circulation pump. The water generated by the stack can be separated and collected for gas humidification by using the condenser. In addition, the waste heat of the stack can be used to preheat the inlet gas of the system. The novel system can realize the comprehensive utilization of gas - heat - water.

(2) The stack, tail gas and bubble humidifiers are the three locations with the largest exergy loss of both systems. In order to improve the performance of the fuel cell test system, the performance of fuel cell stack and the heat recovery of tail gas should be improved.

(3) When the system is operated at 1A/cm^2 , the exergy loss, net output power, and exergy efficiency of the novel system are 96 kW, 80 kW, and 39%, respectively, which are 28% lower, 19% higher, and 32% higher than those of the conventional system. Therefore, the proposed novel system can significantly improve the system performance and overall exergy efficiency. The results provide some effective suggestions for the performance improvement of existing fuel cell test systems.

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