Parameter Matching Design of Proton Exchange Membrane Fuel Cell System

Lin Sun, Binbin Sun*, Tianqi Gu, Pengwei Wang, Wentao Li

Abstract—**PEMFC is a complex electromechanical heating system with multi-component coupling and multi-parameter constraints. The parameter matching degree of each subsystem has an important impact on the dynamic and economy of the system. In order to develop PEMFC that meets the requirements of design performance indicators. This paper first establishes a fuel cell performance simulation platform including reactor, cathode system, anode system, hydrothermal management system and other modules based on electric power, thermodynamics and other theories. On this basis, according to the requirements of fuel cell performance design indicators, the parameters of each subsystem are analyzed and designed, and the matching and selection of core components are completed. The research results show that the maximum efficiency of the fuel cell system is 61.5% on the premise of meeting the requirements of 35kw rated power and dynamic performance design index. Under UDDS cycle conditions, the maximum efficiency of the fuel cell system is 50.34%, the average efficiency is 47.96%, and the hydrogen consumption under circulating conditions is 0.33kg, which meets the requirements of design performance indicators.**

Index Terms—**PEMFC, system modeling, parameter design, analysis of performance**

I. INTRODUCTION

PEMFC has the advantages of high efficiency and zero emissions, and is considered an effective solution for automotive energy power [1]. In particular, fuel cells have made significant progress in terms of durability, power density and cost in recent years. Major automobile manufacturers around the world have also listed fuel cell vehicles as a key development direction and have begun to launch relevant vehicle products [2]. Therefore, it is of great significance to study and design a high-efficiency proton exchange membrane fuel cell system to promote the technological progress of the automotive industry [3].

PEMFC is a highly integrated system with complex components, divided into two components: fuel cell stack and auxiliary system [4]. The auxiliary system can be divided into multiple subsystems, each of which is composed of multiple components [5]. PEMFC is a typical complex electromechanical heating system with multi-component coupling and multi-parameter constraints. The parameter matching degree of each subsystem has an important impact on the dynamic and economy of the system [6].

At present, PEMFC modeling methods mainly have empirical methods [7,8]. The empirical modeling process is relatively simple. There is no need to consider the internal reaction mechanism of the fuel cell. You only need to carry out a large number of experiments on the selected fuel cell. According to the experimental data, the external characteristic curve fitting equation of the fuel cell is obtained, and the fuel cell is described [9]. This kind of method can usually better reflect the performance of the selected fuel cell, but other types of fuel cells cannot be well described. At the same time, the empirical modeling method is better than the inability to represent the internal reaction of the battery, which is not conducive to the parameter design of the fuel cell system.

Reasonable design of fuel cell stack and accessories is the prerequisite for the efficient operation of the fuel cell system. It mainly designs, optimizes parameters and selects the core components according to the requirements of the performance design index of the fuel cell system [10,11]. At present, the parameter matching method of the proton exchange membrane fuel cell system can be summarized as follows: according to the requirements of the dynamic performance index of the system, the characteristic parameters range of the key components of the system are calculated and determined and simulated, and then the system parameters are selected based on the verification results [12]. However, because the economic factors of the fuel cell system are not considered, this method will affect the battery efficiency characteristics and hydrogen consumption.

In summary, it is designed to design high-efficiency PEMFC. This paper first uses a more complex mechanism to establish a PEMFC performance analysis model including fuel cell stack, cathode system, anode system and other modules. Furthermore, considering the requirements of fuel cell dynamic and economic performance design indexes, the parameters of core components such as PEMFC reactor, cathode system and anode system are designed. Finally, the

Manuscript received September 10, 2022; revised December 20, 2023. This work was supported in part by the Major Innovation Projects in Shandong under Grant 2020CXGC010405 and 2020CXGC010406， the Innovation team project of "Qing-Chuang science and technology plan" of colleges and universities in Shandong Province 2021KJ083, the National Natural Science Foundation Project of China under Grant 52102465, the Postdoctoral Science Foundation of China and Shandong under Grant 2020M680091 and 202003042.

Lin Sun is a graduate student of School of Transportation and Vehicle Engineering, Shandong University of Technology, Zibo, 255000 PR China. (e-mail: sl15692335337@163.com)

Binbin Sun is a Professor of School of Transportation and Vehicle Engineering, Shandong University of Technology, Zibo, 255000 PR China. (corresponding author to provide phone: 86-13708941464; e-mail: sunbin_sdut@126.com)

Tianqi Gu is a graduate student of School of Transportation and Vehicle Engineering, Shandong University of Technology, Zibo, 255000 PR China. (e-mail: tianqi.gu@outlook.com).

Pengwei Wang is a Professor of School of Transportation and Vehicle Engineering, Shandong University of Technology, Zibo, 255000 PR China. (e-mail: wpwk16@163.com)

Wentao Li is a Professor of School of Transportation and Vehicle Engineering, Shandong University of Technology, Zibo, 255000 PR China. (e-mail: liwentao1213@163.com)

performance of the designed PEMFC is verified.

II. PEMFC SYSTEM MODELING

A. fuel cell stack modeling

Fuel cell stack models include voltage models, cathode channel models, anode channel models and membrane hydration models. Taking the voltage model as an example, this paper discusses the reactor modeling method. Among them, dynamic voltage characteristics are used for voltage modeling. As shown in Figure 1, it is the equivalent circuit of the battery. During the fuel cell reaction, electrons and hydrogen ions will be produced. The former mainly exist in the anode and cathode, and the latter mainly exist in the electrolyte. A charge layer similar to the capacitor is formed between the cathode and the electrolyte. The above capacitance characteristics make that when the current of the fuel cell changes suddenly, the voltage will not change immediately with the change of the current, but has a certain hysteresis for the change of the current.

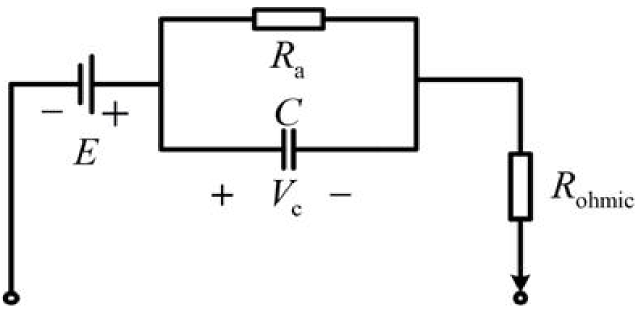


Fig. 1 Equivalent circuit diagram of fuel cell

The dynamic characteristics of fuel cells can be expressed by the following formula.

$$\frac{\mathrm{d}u_a}{\mathrm{d}t} = \frac{I}{C} - \frac{u_a}{\tau} \tag{1}$$

In the formula, u_a represents the total polarization overvoltage, which is the sum of activated overvoltage and concentration overvoltage. I indicates the current, and C is the equivalent capacitance capacity, τ indicating the time constant.

$$R_a = \frac{V_{act} + V_{conc}}{I} \tag{2}$$

$$\tau = CR_a = C\left(\frac{V_{act} + V_{conc}}{I}\right) \tag{3}$$

In the formula, R_a is the equivalent resistance, V_{act} is the activated polarization voltage, and V_{conc} is the concentration polarization voltage.

B. Cathode subsystem modeling

The cathode system model includes air compressor model, intercooler model, humidifier model and counterbalance valve model. This paper takes the air compressor model as an example to introduce the modeling method. The air compressor inputs compressed air for the fuel cell stack, and the inlet is ambient pressure. The air compressor pressure is controlled by motor speed. The dynamic model of the air compressor can be derived as follows:

$$J_{cp}\frac{\mathrm{d}\omega_{cp}}{\mathrm{d}t} = \tau_{cm} - \tau_{cp} \tag{4}$$

In the formula, J_{cp} represents the rotation inertia of the air compressor, ω_{cp} the angular velocity of the air compressor, τ_{cm} is the torque of the motor, and τ_{cp} is the torque of the air compressor.

According to the motor efficiency and the compression efficiency of the air compressor, the total efficiency of the air compressor can be calculated.

$$\eta_T = \eta_{cm} \cdot \eta_{cp} \tag{5}$$

The output power of the air compressor can be derived according to the torque and angular speed of the air compressor.

$$W_{comp} = \tau_{cp}\omega_{cp} \tag{6}$$

According to the MAP diagram of the air compressor, the flow rate, rotation speed and compression ratio of the air compressor can be calculated by checking the table.

$$m_{cp} = f\left(\omega_{cp}, \lambda_{comp}\right) \tag{7}$$

C. Anode subsystem modeling

The anode system model includes the hydrogen circulation pump model and the pressure regulator model. This paper takes the hydrogen circulation pump model as an example to introduce its modeling method. The hydrogen circulation pump is connected to the anode outlet of the fuel cell stack. Assuming that the gas entering the hydrogen, circulation pump is consistent with the anode outlet gas, and the inlet pressure is equal to the anode outlet pressure, the mass flow rate of the hydrogen circulating pump can be derived.

$$m_{Hcp} = m_{bl}\frac{\sqrt{T_{Hcp}/T_{ref}}}{P_{Hcp}/P_{ref}} \tag{8}$$

In the formula, m_{Hcp} represents the mass flow rate at the outlet of the hydrogen circulating pump, m_{bl} is the mass flow rate of the circulating pump under standard conditions, T_{Hcp} is the gas temperature entering the circulating pump, T_{ref} is the reference temperature, P_{Hcp} is the gas pressure entering the hydrogen circulating pump, and P_{ref} is the reference pressure.

The rotation angular velocity of the hydrogen circulation pump is modified according to the standard condition value.

$$\omega_{Hcp} = \frac{\omega_{bl}}{\sqrt{T_{Hcp}/T_{ref}}} \tag{9}$$

In the formula, ω_{Hcp} represents the rotation angular speed of the circulating pump and ω_{bl} is the rotational angular speed of the circulating pump under standard conditions.

D. Heat and water management subsystem modeling

The Heat and water management subsystem includes the radiator model, the cooling pump model and the thermostat model. This paper takes the radiator model as an example and introduces its modeling method. The radiator distributes the heat carried through the cooling water into the environment. According to the basic laws of thermodynamics, the temperature of the cooling water at the outlet of the radiator can be derived.

$$\frac{\mathrm{d}T_{\mathrm{rad,out}}}{\mathrm{d}t}=\frac{m_{\mathrm{cw}}c_{\mathrm{water}}\left(T_{\mathrm{rad,in}}-k_{\mathrm{rad}}T_{\mathrm{rad,out}}\right)-Q_{\mathrm{rad,amb}}}{\rho_{\mathrm{water}}V_{\mathrm{rad}}} \tag{10}$$

In the formula, $T_{\mathrm{rad,in}}$、$T_{\mathrm{rad,out}}$ represents the inlet and outlet temperature of the radiator, m_{cw} represents the mass flow of cooling water, k_{rad} represents the heat transfer coefficient, $Q_{\mathrm{rad,amb}}$ represents the heat dissipation capacity of the cooling fan, and V_{rad} represents the volume of the radiator.

The radiator mainly relies on the cooling fan to exchange heat with the environment. The cooling fan improves the heat dissipation efficiency by accelerating the airflow on the surface of the radiator. The heat dissipation of the cooling fan can be deduced as:

$$Q_{\mathrm{rad,amb}}=A_{\mathrm{rad}}h_{\mathrm{rad}}\left(T_{\mathrm{rad,in}}-T_{\mathrm{amb}}\right) \tag{11}$$

In the formula, A_{rad} represents the heat dissipation area of the radiator, and h_{rad} represents the transfer coefficient of the cooling fan.

Heatsink Power Dissipation Power is a function of parameters such as efficiency, fan transfer coefficient。

$$W_{\mathrm{rad}}=\frac{\rho_{\mathrm{Air}}\eta_{\mathrm{fan}}h_{\mathrm{rad}}m_{\mathrm{amb}}^{3}}{2\pi^{3}r^{6}} \tag{12}$$

In the formula, η_{fan} represents the mechanical efficiency of the radiator fan, and r represents the radius of the radiator fan blade。

III. PEMFC SYSTEM PARAMETER DESIGN

As shown in Table 1, the developed fuel cell performance index parameters are given. In this paper, according to the design requirements in the table, the parameters of the battery stack, the core components of the cathode subsystem, the core components of the anode subsystem, and the core components of the water and heat management subsystem are designed.

A. fuel cell stack parameter design

This paper takes the proton exchange membrane as an example to introduce the design method of the key parameters of electric propulsion. The normal working voltage of a single fuel cell is 0.6 ~ 0.7 V。 The fuel cell stack is composed of a plurality of single cells, and the output voltage of the stack is the product of the single cell voltage and the number of cells. When the fuel cell operates under rated conditions, the stack voltage is the product of the single cell voltage and the number of cells. According to the output voltage of the single cell, the number of single cells can be calculated to be 265.63, and the result is 266 after rounding.

$$V_{\mathrm{stack,rated}}=n_{\mathrm{cell}}V_{\mathrm{cell}} \tag{13}$$

In the formula, $V_{\mathrm{stack,rated}}$ represents the rated voltage of the stack, n_{cell} represents the number of single cells, and V_{cell} represents the voltage of the single cell.

The proton exchange membrane is the core component of the PEMFC stack and plays an important role in the performance of the stack. Among them, the size of the membrane area is an important parameter in the design of the stack, which can be determined according to the relationship between the rated power of the battery and the current density and voltage of the battery. According to formula 14, it can be calculated that the area of the proton exchange membrane is 300 cm^2, and the rated voltage of the stack output under the rated power is 300 A.

Tab. 1 Fuel cell parameter index requirements

Parameter	Parameter values	Parameter	Parameter values
Rated system power/kW	30	Stack rated power/V	170
Working pressure/bar	0 ~ 3	Admissible voltage difference between anode and cathode/bar	0.2
Hydrogen consumption in cycling condition /g	≤75	Maximum admissible intake temperature/K	333
UDDS maximum efficiency of circulating system /%	≥ 50	Maximum allowable pressure drops of humidifier/bar	0.2
UDDS average efficiency of circulating system /%	≥ 40	Nominal current density/A·cm^{-2}	1.00

$$P_{\mathrm{stack,rated}}=n_{\mathrm{cell}}V_{\mathrm{cell}}iA \tag{14}$$

In the formula, $P_{\mathrm{stack,rated}}$ represents the rated power of the stack, i represents the current density of the stack, and A represents the area of the exchange membrane.

B. Parameter design of cathode core components

This paper takes the air compressor as an example to introduce the parameter design method of the cathode core components. The air flow provided by the air compressor should be higher than the air flow required when the fuel cell outputs maximum power. Therefore, the maximum flow output of the air compressor should satisfy the following formula:

$$m_{\text{comp,out}} = \frac{S_{O_2} M_{\text{Air}}}{y_{O_2} 4F} I \; n_{\text{cell}} \tag{15}$$

In the formula, $m_{\text{comp,out}}$ represents the air mass flow rate output by the air compressor, S_{O_2} represents the air stoichiometric ratio, M_{Air} represents the air molar mass, y_{O_2} represents the oxygen mole fraction, F represents the Faraday constant, and I represents the stack output current.

When air is fed into the stack, the typical stoichiometric ratio is 2 ~ 3. In order to prevent the selected air compressor from not meeting the actual application, the value is 3. Then, the outlet mass flow of the air compressor can be determined to be $m_{\text{comp,out}} \geq 86\text{g} \cdot s^{-1}$.

Another important parameter of an air compressor is the compression ratio. According to the maximum flow rate of the air compressor calculated before, the pressure drops of the air passing through the intercooler and humidifier is estimated, and the working pressure of the electric reactor is added to calculate the pressure required by the air compressor.

$$P_{\text{comp,out}} = P_{\text{coller,down}} + P_{\text{hum,down}} + P_{\text{stack}} \tag{16}$$

In the formula, $P_{\text{comp,out}}$ represents the output air pressure of the air compressor, $P_{\text{coller,down}}$ is the pressure drop of the air through the intercooler, $P_{\text{hum,down}}$ is the pressure drop of the air through the humidifier, and P_{stack} is the operation of the stack.

The maximum pressure drop of the intercooler is 10 kPa, the maximum pressure drop of the humidifier is 20 kPa, and the working pressure of the high-pressure fuel cell system stack is usually about 200 kPa, where the working pressure of the stack is 220 kPa. The outlet pressure of the air compressor can then be determined to be $P_{\text{comp,out}} \geq 250$ kPa.

Air compressor compression ratio is a function of inlet and outlet pressure. Since the source of the air entering the air compressor is the surrounding environment, the inlet pressure of the air compressor is taken as the surrounding environment pressure, and the standard atmospheric pressure is taken as the inlet pressure, and the calculation is determined as $\lambda_{\text{comp}} = 2.47$.

$$\lambda_{\text{comp}} = \frac{P_{\text{comp,out}}}{P_{\text{comp,in}}} \tag{17}$$

In the formula, λ_{comp} represents the compression ratio of the air compressor; $P_{\text{comp,out}}$ represents the air pressure (kPa) entering the air compressor.

Outside the rated operating point, it is generally necessary to consider the overloaded operating point and leave a margin for the maximum operating point, which is generally designed according to 110 % kW, at this time, $m_{\text{comp,out}} = 95g \cdot s^{-1}, \lambda_{\text{comp}} = 2.7$.

C. Anodic core component parameter design

This paper takes the hydrogen circulating pump as an example to introduce the parameter design method of the anode core components. The hydrogen flow rate that the hydrogen circulation pump can deliver is greater than the amount of hydrogen remaining after the fuel cell reaction is completed. The hydrogen mass flow required by the fuel cell at rated power is:

$$m_{H_2,\text{in}} = \frac{S_{H_2} M_{H_2}}{2F} I n_{\text{cell}} \tag{18}$$

In the formula, $m_{H_2,\text{in}}$ represents the mass flow rate of hydrogen into the reactor, S_{H_2} represents the stoichiometric ratio of hydrogen, and M_{H_2} represents the molecular weight of hydrogen.

Taking the hydrogen stoichiometric ratio as 3, the calculated hydrogen mass flow at the stack inlet is 2.5 g·s $^{-1}$. When the fuel cell works at rated power, the required hydrogen flow is the maximum flow required by the system. The hydrogen circulating pump needs to deliver the maximum hydrogen mass flow can be derived from the remaining hydrogen flow at the anode outlet of the stack.

$$m_{H_2,\text{cycle}} = m_{H_2,\text{out}} = \left(S_{H_2} - 1\right)\frac{M_{H_2}}{2F} I n_{\text{cell}} \tag{19}$$

In the formula, $m_{H_2,\text{cycle}}$ represents the hydrogen mass flow that the hydrogen circulation pump needs to circulate, and $m_{H_2,\text{out}}$ represents the hydrogen mass flow at the anode outlet of the stack.

D.Parameter design of core components of hydrothermal management system

This paper takes the radiator as an example to introduce the parameter design method of the core components of the water heat management system. The heat generation of the fuel cell system mainly includes two parts, one is the heat generated by the compressed air, and the other is the heat generated by the internal reaction of the stack, both of which require cooling water for heat dissipation. The heat generated by the stack is equal to the difference between the total energy produced by the reaction and the electrical energy of the stack.

$$Q_{\text{stack}} = P_{\text{stack}}\left(\frac{V_{\text{refer}}}{V_{\text{cell}}} - 1\right) \tag{20}$$

In the formula, Q_{stack} represents the heating power of the stack, P_{stack} represents the power of the stack, V_{refer} represents the theoretical voltage of the single cell, and V_{cell} represents the actual voltage of the single cell.

The heat dissipation forms mainly include cooling water heat dissipation, stack heat radiation and reaction generated water vaporization heat dissipation. The water generated by the reaction inside the stack will take away part of the heat when it flows out of the stack, and the heat dissipated is small and can be ignored. The heat radiated by the stack to the surrounding environment is also small and negligible, and it is considered that all the heat generated by the stack is taken out by the cooling water. The heat that the radiator needs to dissipate, such as the heat generated by the stack, and the heat that the intercooler needs to cool.

$$Q_{\text{rad}} = Q_{\text{water}} = Q_{\text{stack}} + Q_{\text{cooler}} \tag{21}$$

In the formula, Q_{rad} represents the heat dissipation power of the radiator, and Q_{water} represents the heat dissipation power of the cooling water.

Then it can be deduced that the heat dissipation power of the radiator is 52.89 kW. Considering the design redundancy, take the cooling power as 56 kW.

The air specific heat capacity is 1.047 $kJ \cdot kg^{-1} \cdot K^{-1}$, the air temperature difference before and after the radiator is 15 K, and the air volume flow is calculated to be 2.53 $m^3 \cdot s^{-1}$. The air volume flow is the radiator area and the radiator fan. By multiplying the provided wind speed to determine the maximum wind speed of the radiator fan, the heat dissipation area of the radiator can be calculated.

$$V_{Air} = \frac{Q_{rad}}{c_{Air} \cdot \rho_{Air} \cdot \Delta t_{Air}} \tag{22}$$

In the formula, V_{Air} represents the volume flow of air entering the radiator, c_{Air} represents the specific heat capacity of the air, and Δt_{Air} represents the air temperature difference before and after the radiator.

IV. PERFORMANCE ANALYSIS

As shown in Figure 2, in order to analyze the power and economy of the designed fuel cell, the design loading current is increased from 80 A to 250 A, the total loading time is 350 s, and the time interval of each step load current is 50 s. The current values in different stages are 80 A, 150 A, 130 A, 160 A, 230 A, 200 A, and 250 A, respectively. Figure 3 shows the output power of the fuel cell stack and system. The results show that with the increase of the loading current, the output power of the fuel cell stack and the output power of the system both increase, the rated power of the stack is not less than 35kw, and the rated power of the system is not less than 30kw. However, due to parasitic power problems in accessories such as air compressors and cooling water pumps, the output power of the system is less than the output power of the stack.

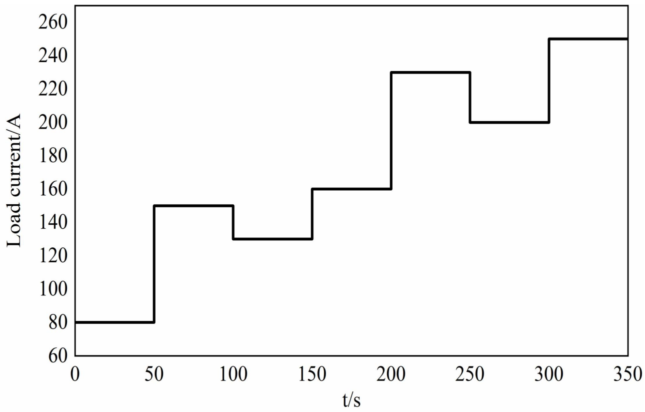


Fig. 2 Load current

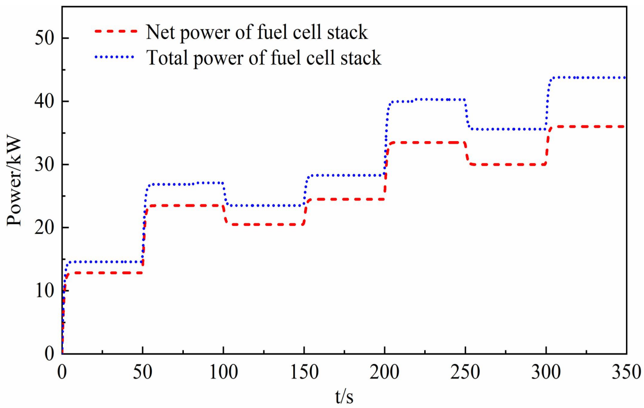
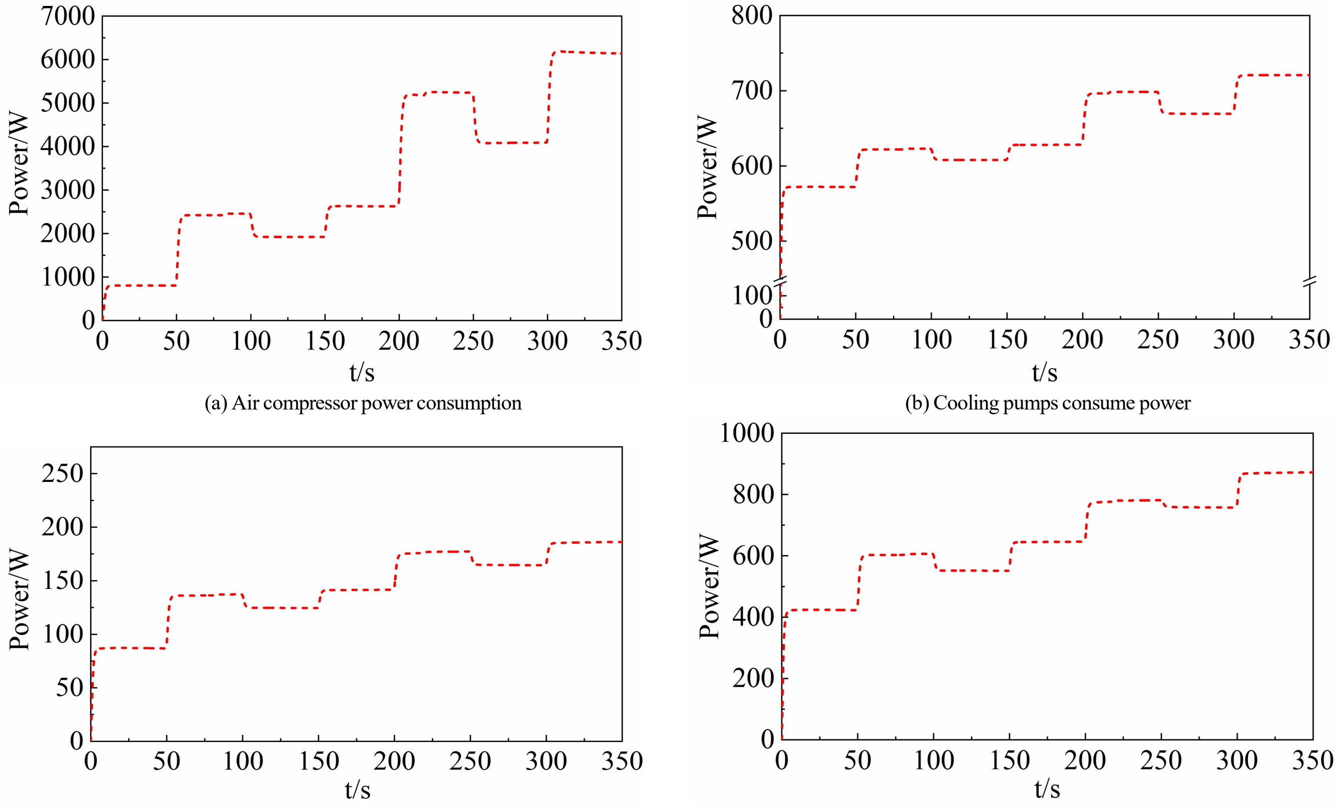


Fig. 3 Fuel cell output power

As shown in Figure 4, the power consumption of accessories such as fuel cell air compressor and cooling water pump is given. The research results show that with the increase of the loading current, the power consumption of the air compressor, cooling water pump, hydrogen circulation pump and radiator increase. The main reason is that with the increase of the loading current, the amount of air and hydrogen required by the fuel cell also increases, and the power consumed by the air compressor and the hydrogen circulation pump also increases accordingly. As the power of the fuel cell stack increases, the heat generated also increases, so the demand for the water flow of the cooling system and the heat dissipation of the radiator also increases, which in turn increases the power consumption of the cooling water pump and the radiator. Overall, the air compressor has the largest power loss, much higher than the other three components. The parasitic power of the hydrogen circulation pump is minimal.



(a) Air compressor power consumption

(b) Cooling pumps consume power

(c) Hydrogen circulating pumps consume power

(d) Heat sink consumption power

Fig. 4 Power consumption of different components

As shown in Figure 5, the hydrogen consumption rate of the fuel cell system under different loading currents is given. The results show that the hydrogen consumption rate is consistent with the changing trend of the fuel cell loading current. The first 50 s hydrogen consumption rate is 0.265 g·s-1, the 50 to 100 s hydrogen consumption rate is 0.507 g·s-1, the 100 to 150 s hydrogen consumption rate is 0.440 g·s-1, the 150 to 200 s hydrogen consumption rate is 0.535 g·s-1 The rate of hydrogen consumption is 0.535 g·s-1, the rate of hydrogen consumption from 200 to 250 s is 0.781 g·s-1, the rate of hydrogen consumption from 250 to 300 s is 0.683 g·s-1, the rate of hydrogen consumption from 300 to 350 s is0.853 g·s-1. Overall, the total hydrogen consumption is 202.13 g.

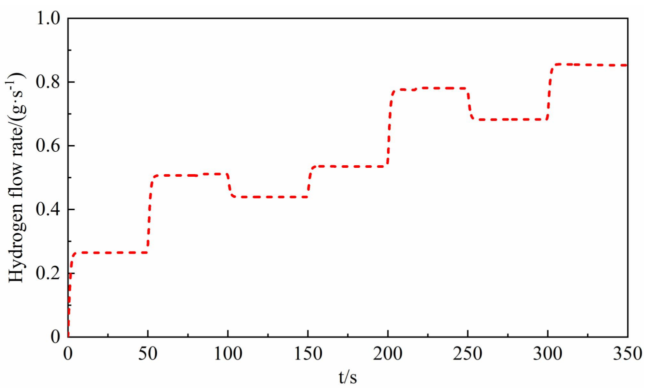


Fig. 5 Hydrogen consumption rate of fuel cell system

As shown in Figure 6, the efficiency curve of the fuel cell system under UDDS conditions is given. The research results show that under UDDS condition, the maximum output power of the fuel cell stack is 53.14kw, and the average output power is 17.13kw. The efficiency of the fuel system varies from 39.99 % ~50.34 %, the highest efficiency is 50.34 %, and the average efficiency is 47.96 %, all of which meet the design requirements. The hydrogen consumption under UDDS driving condition is 0.3291 kg.

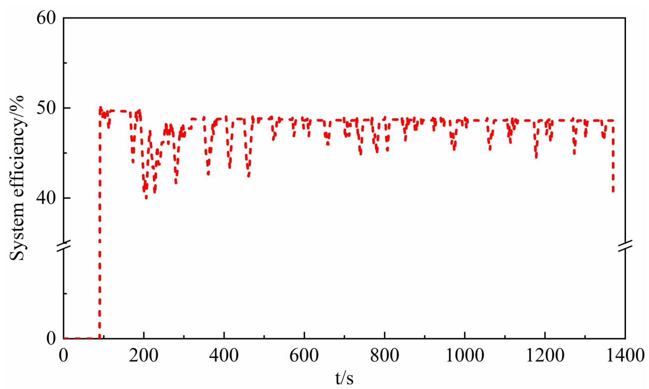


Fig. 6 Efficiency curve of fuel cell system

V.CONCLUSION

In order to develop high-efficiency PEMFC, this paper firstly based on the MATLAB/Simulink software platform, combined with the mechanism method, to model the selected components of the PEMFC system, mainly including the stack model and each subsystem model. The stack model includes voltage model, cathode and anode flow channel model, and membrane hydration model. The cathode system model includes air compressor, intercooler, humidifier and back pressure valve. The anode system model includes hydrogen circulation pump, pressure regulator Valves and other components. The water and heat management system analyze the heat balance, and the model includes components such as radiators, cooling water pumps, and thermostats. On this basis, the design and matching of core components such as PEMFC stack, cathode gas supply system, anode gas supply system and water heat management system are completed. Finally, the performance of the designed PEMFC is analyzed, and the results show that the maximum efficiency of the fuel cell system is 61.5% under the premise of meeting the design requirements of the 35kw rated power dynamic performance. Under the UDDS cycle condition, the maximum efficiency of the fuel cell system is 50.34%, the average efficiency is 47.96%, and the hydrogen consumption under the cycle condition is 0.33kg, which meets the design performance requirements.

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(1)Revised December 20, 2023.

(2)The corresponding author was changed from Mr. Sun Lin to Professor Sun Binbin.