Optimization Design of Operating Parameters for Proton Exchange Membrane Fuel Cell

Mengxue Xie, Binbin Sun, Di Huang, Pengwei Wang and Wentao Li

Abstract—**The power outputs and hydrogen consumption of PEMFC are affected by its core operating parameters such as operating pressure, operating temperature and cathode stoichiometric ratio. In order to develop a high efficiency PEMFC, this paper first analyzes and designs a comprehensive optimization objective that takes into account both the power output and hydrogen consumption of the PEMFC. Based on the orthogonal experiment and significance analysis, a multi-factor and multi-level orthogonal experiment table for the optimization variables was designed subsequently, the PEMFC performance optimization variables were determined. Finally, the performance of PEMFC before and after optimization is analyzed and compared. The results indicate that working pressure, working temperature, cathode stoichiometric ratio and anode stoichiometric ratio are significant factors affecting the performance optimization of PEMFC. Under the step loading current of 80 A, 150 A, 130 A, 160 A, 230 A, 200 A and 250 A, the net output power of the optimized PEMFC increased by 1.32%, 2.55%, 3.30%, 3.71%, 9.47%, 7.57% and 10.55% respectively. The average hydrogen consumption rate decreased by 3.87% under the whole step loading current. The total hydrogen consumption is reduced by 2.37%. Under actual road conditions, the maximum efficiency and average efficiency of the optimized PEMFC are increased by 3.81% and 6.07%, respectively, and the hydrogen consumption is reduced by 2.61%.**

Index Terms—**operating parameters, orthogonal experiment, PEMFC, performance optimization**

I. INTRODUCTION

UNDER the common vision of global carbon neutrality, with the proposal of major "dual carbon" strategies such as China and the European Union, electrification has become an important carrier for the automotive industry to achieve low-carbon goals, and also an important direction for the world automotive industry to develop towards high quality [1-3]. The development of zero-carbon emission PEMFC vehicles is the highland of technological competition in the automotive industry and a core measure to implement the "dual carbon" strategy in the automotive industry [4-5]. However, high hydrogen consumption and high cost are still the common crucial problems of PEMFC vehicles [6-7]. Concentrating on the energy efficiency optimization of PEMFC, it is of great practical significance to enhance the PEMFC operation effectiveness and decrease hydrogen consumption, which will foster the rapid and sustainable development of the PEMFC automotive industry [8-9].

At present, there are three methods to improve the efficiency of PEMFC [10]. The first method is parameter design and matching selection of the core components of PEMFC. Specifically, corresponding to the performance development requirements of PEMFC, the parameter matching design and component selection of PEMFC stack, the cathode system, the anode system, water and heat management system and other core components are carried out [11-12]. The second method is the optimization design of the critical operational parameters of PEMFC, the core assumption of which is to optimize the cathode stoichiometric ratio, anode stoichiometric ratio, humidity and other parameters of the PEMFC under the premise of satisfying the power performance requirements of the PEMFC, so as to determine the optimal economic operational parameters [13-14]. The third method is to design a reasonable hybrid energy system and energy management strategy to achieve efficient control of PEMFC in vehicle applications [15-19].

Among the above three methods, the first method is primarily used in the early phase of PEMFC development, and the economic performance optimization range will be confined by the performance design index of PEMFC [20]. The third method is applied in the later phase of PEMFC development. The economic performance optimization of PEMFC will be impacted by the design index of vehicle performance, energy and power system performance [21]. The second method, which is used in the middle phase of PEMFC development, plays a linking role in the entire phase of PEMFC performance development and optimization, and has an significant effect on PEMFC performance [22].

At present, concentrating on the optimization design of critical operational parameters of PEMFC, relevant scholars have conducted out relevant research from the operational parameters of PEMFC such as working pressure, cathodic stoichiometric ratio, humidity and so on, and attained

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satisfactory economic optimization results [23-26]. Nevertheless, in general, there are still several unsolved issues about the optimization design of vital operating parameters of PEMFC. First, contemporary research predominantly gives priority to single parameter analysis and optimization. However, the power output and hydrogen consumption of PEMFC are impacted by its core functional parameters such as working pressure, operating temperature and cathode stoichiometric ratio, which is a classic problem of multi-component coupling and multi-parameter interaction [27-29]. Second, the significance of the effects of multiple operating parameters on PEMFC performance is still unpredictable, and the sensitivity of parameters requires to be further studied. Thirdly, it is essential to design a suitable optimization algorithm for the nonlinear optimization problem of PEMFC with multi-objective, multi-variable and multi-constraint.

In summary, in order to clarify the significance of the influence of different operating parameters on PEMFC, determine the sensitive parameters that impact PEMFC performance, and design the mathematical model of PEMFC performance optimization, firstly, the first part of this paper studies and determines the performance optimization objectives of PEMFC. The significance analysis of PEMFC performance optimization variables is discussed in detail in the second section. In the third part of this paper, the nonlinear optimization algorithm of PEMFC performance is designed. Finally, the fourth part analyzes the optimization results in detail.

II. Optimization objective design

Hydrogen consumption is an important economic indicator of PEMFC, and reducing hydrogen consumption can enhance the economic performance of fuel cells. Therefore, hydrogen consumption is selected as the first objective of optimization design in this research. In addition, the PEMFC is comprised of a stack and an auxiliary system. The air compressor, cooling water pump, hydrogen circulating pump and other components in the auxiliary system all have parasitic power problems. The net output power of PEMFC is the difference between the total power generated by the stack and the parasitic power of the auxiliary system. Expanding the net output power can improve the efficiency and power performance of the battery. The net output power of PEMFC indirectly reflects its economic and dynamic performance, so it is selected as another optimization objective in this paper. The PEMFC output power model can be expressed as:

$$W = W_{\text{stack}} - W_{\text{aux}} \tag{1}$$

Here, W_{stack} indicates the PEMFC output power, W_{aux} indicates the stack output power and indicates the total power of the auxiliary system.

The output power of PEMFC stack is a function of the number of cells and the product of stack voltage and current. The parasitic power of the auxiliary system can be determined by the damaged power of the energy-consuming components such as the air compressor, cooling water pump, hydrogen circulating pump and radiator in each subsystem.

$$\begin{cases} W_{\text{stack}} = n_{\text{cell}} IV \\ W_{\text{aux}} = W_{\text{comp}} + W_{\text{water}} + W_{\text{hcp}} + W_{\text{rad}} \end{cases} \tag{2}$$

According to the hydrogen mass flow into and out of the stack, the hydrogen consumption model of the PEMFC can be derived.

$$\omega = \int_0^t \left(m_{\text{H}_2,\text{in}} - m_{\text{H}_2,\text{out}} \right) \text{d}t \tag{3}$$

Where ω represents the hydrogen gas consumption of the fuel cell system, t represents the simulation time, $m_{\text{h}_2,\text{in}}$ and $m_{\text{H}_2,\text{out}}$ represent the hydrogen mass flow into and out of the stack, respectively.

When optimizing the PEMFC, the optimization objective design principle is to minimize the hydrogen consumption of the PEMFC within the given calculation time under the premise of maximizing the net power output of the PEMFC.

$$\begin{cases} \text{Max}(W) = f_1(x) \\ \text{Min}(\omega) = f_2(x) \end{cases} \tag{4}$$

The constraints are as follows:

$$\text{la}_i \le x_i \le \text{ua}_i \ \left(i = 1, 2, \cdots, n \right) \tag{5}$$

Where, x_i is the function variable in the form of parameter vector; ua_i and la_i represent the function variable of maximum and minimum values; i is the number of function variables.

III. Significance analysis and design of optimization variables

PEMFC is a classic nonlinear system with multi-variable input and multi-parameter constraints. It is impossible to attain global optimization by optimizing a single variable or a single subsystem of PEMFC. The operational parameters of PEMFC, such as working temperature, pressure, gas humidity and so on, all have an influence on its output performance. Therefore, different operating parameters will have different degrees of influence on the optimization goal. If all parameters are optimized in a unified way, the efficiency and reliability of optimization will be influenced. Therefore, in this paper, the significance analysis of parameters is carried out first in the design of optimization variables. The optimization efficiency can be improved by determining the influence of different parameters on the optimization target and removing the parameters with relatively insignificant influence.

In order to analyze the effects of many operational parameters on PEMFC more comprehensively, six optimization variables of PEMFC, involving working pressure, working temperature, cathode stoichiometric ratio, anode stoichiometric ratio, cathode gas relative humidity and anode gas relative humidity, were selected for comparative analysis. Three level values were selected for each optimization variable, and level values selected were within the working range during the operation of the PEMFC. An orthogonal experiment of 6 factors and 3 levels was established as shown in Table 1.

On the basis of Table 1, according to the orthogonal experiment method, the $L_{27}(3^6)$ orthogonal experiment table as shown in Table 2 is established. Where L represents the orthogonal test table. The *27* represents the number of rows in the orthogonal test table, and each row represents an experimental condition under different operating parameters. The *3* indicates the number of horizontal values. The *6* represents the number of columns in the orthogonal test table, which is also the number of optimization variables.

Table I, Optimization variables and horizontal values

Serial number	Optimization variable	Units	Level value 1	Level value 2	Level value 3
1	work pressure（P）	bar	1	2	3
2	operating temperature（T）	K	1	2	3
3	cathode stoichiometric ratio（S_{ca}）		333	353	373
4	anode stoichiometric ratio（S_{an}）		1	2	3
5	cathode relative humidity（RH_{ca}）	%	1	2	3
6	anode relative humidity（RH_{an}）	%	80	90	100

Table II, Orthogonal experimental design

Serial number	P	T	S_{ca}	S_{an}	RH_{ca}	RH_{an}
1	1	333	1	1	80	80
2	1	333	1	1	90	90
3	1	333	1	1	100	100
4	1	353	2	2	80	80
5	1	353	2	2	90	90
6	1	353	2	2	100	100
7	1	373	3	3	80	80
8	1	373	3	3	90	90
9	1	373	3	3	100	80
10	2	333	2	3	80	90
11	2	333	2	3	90	100
12	2	333	2	3	100	80
13	2	353	3	1	80	90
14	2	353	3	1	90	100
15	2	353	3	1	100	80
16	2	373	1	2	80	90
17	2	373	1	2	90	100
18	2	373	1	2	100	80
19	3	333	3	2	80	100
20	3	333	3	2	90	80
21	3	333	3	2	100	90
22	3	353	1	3	80	100
23	3	353	1	3	90	80
24	3	353	1	3	100	90
25	3	373	2	1	80	100
26	3	373	2	1	90	80
27	3	373	2	1	100	90

The orthogonal experimental data shown in Table 3 can be obtained according to the different working conditions designed in Table 2 of the orthogonal experiment and in combination with the PEMFC performance analysis platform shown in Figure 4. In general, hydrogen consumption decreases with the decrease of net output power under different test conditions. The main reason is that the decrease in net output power indirectly reflects the increase in parasitic power, which in turn affects the PEMFC hydrogen consumption. According to the data in Table 3, based on the significance analysis method, the sum of squares of deviations 'SS' of each optimization variable can be calculated and determined. On this basis, the influence proportion table of each optimization variable can be obtained as shown in Table 4. According to this table, the significant degree of the influence of each optimization variable on the optimization objective can be analyzed.

Table III, Orthogonal table test results

Serial number	Set system power /kW	hydrogen consumption /g	Serial number	Set system power /kW	hydrogen consumption /g
1	47.94	95.98	15	39.58	83.85
2	47.98	93.54	16	43.98	85.31
3	48.00	92.60	17	44.00	84.70
4	44.90	90.79	18	43.99	84.94
5	44.98	88.74	19	29.84	84.80
6	45.02	88.13	20	29.73	85.34
7	40.30	93.66	21	29.92	84.44
8	40.47	92.20	22	39.57	87.65
9	40.47	92.20	23	39.51	88.28
10	40.3	88.39	24	39.61	87.24
11	40.41	87.35	25	36.25	79.00
12	40.36	87.76	26	36.22	79.27
13	39.53	84.26	27	36.28	78.83
14	39.61	83.57			

Based on the significant calculation results in Table 4, for the net output power of PEMFC, the influence of working pressure is the highest, accounting for 47.43%, which is a significant parameter. Cathode stoichiometric ratio takes second place, accounting for 38.73% percent respectively, which is a significant parameter. The total influence proportion of the other four parameters is 13.84%, which is relatively insignificant. The influence of the relative humidity of cathode and anode gas on the net output power and efficiency of PEMFC is extremely small, which is a non-significant parameter. The main reason is that the net output power of PEMFC is closely associated to the output power of the stack and the parasitic power of the auxiliary system. The parasitic power of the air compressor accounts for the highest proportion of total power consumption. Therefore, the larger working pressure and cathode stoichiometric ratio will raise the power consumption of the air compressor and reduce the net output power of the system.

For the hydrogen consumption of PEMFC, the influence of working pressure on it is 47.99%, which is a significant parameter. The working temperature, the cathode stoichiometric ratio and the anode stoichiometric ratio each account for about 16%, which are significant parameters. The effects of the relative humidity of the cathode gas and the relative humidity of the anode gas on hydrogen consumption are about 1% respectively, which are non-significant parameters. The results illustrate that hydrogen loss can be reduced by increasing the system pressure and temperature properly. Increasing a certain cathode stoichiometric ratio can increase the concentration of reactants, improve the reaction rate, make the hydrogen fuel react fully, and reduce the waste of hydrogen. Increasing the stoichiometric ratio of the anode can also accelerate the reaction rate, but excessive hydrogen supply will cause the waste of hydrogen.

Table IV, Degree of influence of optimization variables on optimization objectives

Optimization variables	net system power /kW		hydrogen consumption /g	
	SS	proportion /%	SS	proportion /%
P	284.513	47.43	207.376	47.99
T	57.246	9.54	68.452	15.84
S_{ca}	232.35	38.73	66.004	15.27
S_{an}	25.473	4.25	77.397	17.91
RH_{ca}	0.153	0.03	6.826	1.58
RH_{an}	0.166	0.03	6.067	1.40
Total	599.901	100	432.122	100

In summary, in order to take into account the optimization efficiency and optimization results, this paper selects four operating parameters as the optimization variables: working pressure, working temperature, cathode stoichiometric ratio and anode stoichiometric ratio. The relative humidity of the cathode gas and the relative humidity of the anode gas, which will have little effect on the optimization goal, are maintained at a stable value, and both are maintained at 90%. The minimum values of working pressure, working temperature, cathode stoichiometric ratio and anode stoichiometric ratio are set to 1, 333, 1 and 1, respectively. Its maximum values are set to 3, 373, 3 and 3, respectively.

IV. Optimization Method Design

According to the data in Table 3, it can be determined that as the net output power decreases, the hydrogen consumption also decreases. However, the optimization objective designed above requires that the net output power should be as large as possible and the hydrogen consumption should be as small as possible, which is contradictory. Therefore, the compromise solution can only be chosen from the optimal solution set. In order to solve the nonlinear optimization problem of PEMFC with multi-objective, multi-variable and multi-constraint, NSGA-II is selected in this paper. The algorithm design idea is shown in Figure 2.

First, the population size, mutation probability, and crossover probability are initialized, and the appropriate function values for generating the population are calculated. The individual of the population is the optimization variable value, and the appropriate function value is the optimization target value. During the calculation, the fuel cell system model is invoked to assign the population individuals to the model, and the appropriate function values are obtained after the model simulation. After the non-dominated sorting, the algorithm selects, crosses and mutates the individuals in the population to generate a new generation of sub-populations. The sub-population is combined with the parent population to generate a new population. The non-dominated sorting is performed again to calculate the crowding degree, and the appropriate individuals are selected to generate a new parent population. The above process is repeated until the maximum number of iterations is reached, and finally the Pareto front is output.

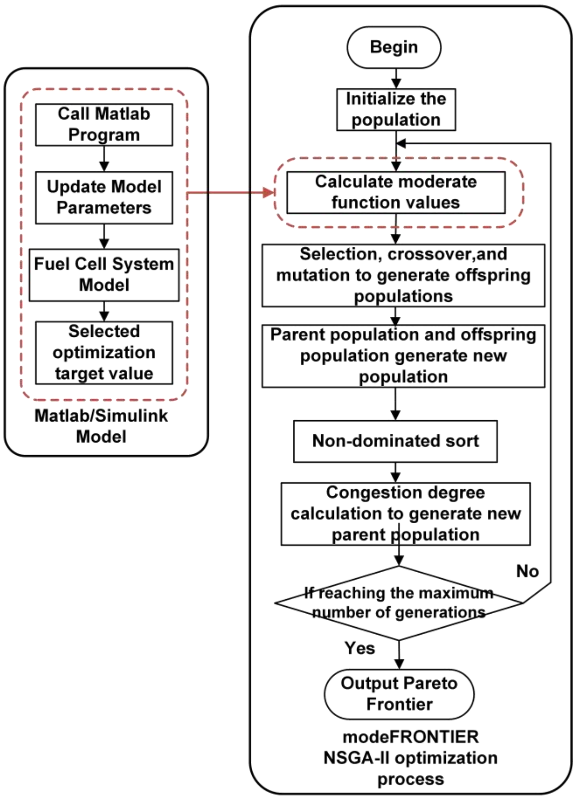


Fig 1, Fuel cell system optimization process

V. Analysis of Optimization Results

Figure 2 shows the Pareto front distribution at the rated condition of the PEMFC. Each point in the graph is the optimal solution, and these points form the optimal solution set.

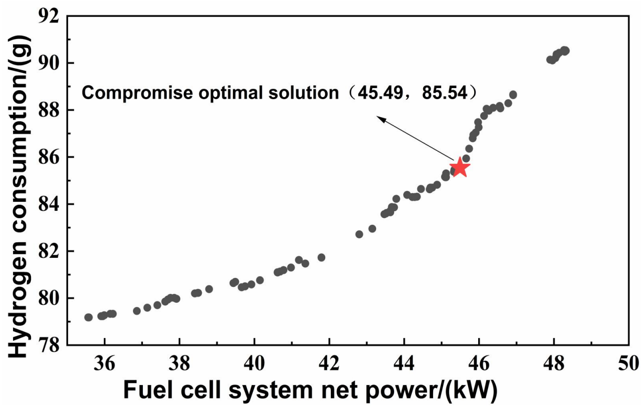


Fig 2, Pareto front distribution of objective optimization under rated working conditions

As the net power of the system increases, hydrogen consumption also increases. Therefore, it is unrealistic to satisfy the minimal hydrogen consumption and the maximum net power output at the same time, only a compromise solution can be selected from the optimal set of solutions. The compromise solution is selected according to the principle of minimum distance compromise, that is, the compromise solution selected from the optimal solution set should satisfy the minimum comparative distance from the ideal solution.

$$S=\sqrt{\left(\frac{P-\dot{P}}{\dot{P}}\right)^2+\left(\frac{H-\dot{H}}{\dot{H}}\right)^2} \tag{6}$$

Where, S represents the compromise indicator; $(\dot{P},\dot{H})$ represents the ideal solution and (P,H) represents any Pareto front upper solution.

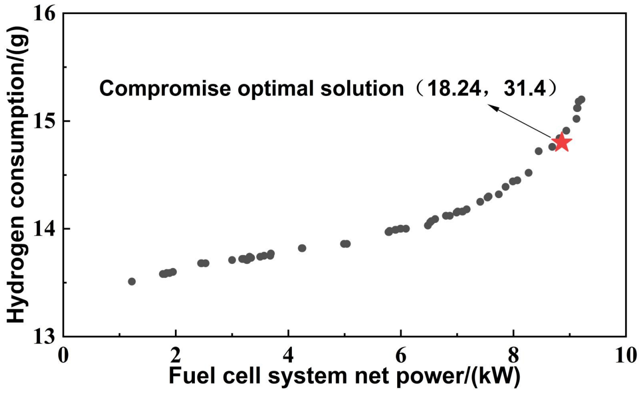
The ideal solution $\dot{P}$ is the optimal solution with the optimization objective of minimum hydrogen consumption, that is, the minimum hydrogen consumption is 79.18 g when the output power is 35.56 kW. The value of $\dot{H}$ is the optimal solution when the maximum net output power is taken as the optimization objective, that is, when the hydrogen consumption is 90.52 g, the maximum net output power is 48.32 kW. In this case, the ideal solution is set to (48.32, 79.18). The compromise solution at rated condition can then be derived as (45.49, 85.54).

Table 5 displays the comparison results of PEMFC before and after optimization under rated conditions. The results demonstrate that the net power of the optimized PEMFC increases by 12.3% out from 40.49 kW to 45.49 kW under the rated condition. The hydrogen consumption decreased by 2.2% from 87.45 g to 85.54 g in 100 s. The main reason is that both the working pressure and the cathode stoichiometric ratio are decreased after the optimization. On the premise that the output performance of the PEMFC is not decreased, lowering the working pressure and the cathode stoichiometric ratio can reduce the power consumption of the air compressor, reduce the power consumption of an auxiliary system and increase the net output power of the system. After optimization, the working temperature of the stack and the stoichiometric ratio of the anode are increased, which promotes the internal reaction, ensures the hydrogen required for the reaction, improves the output performance of the reactor, and reduces the amount of hydrogen required to output the same power.

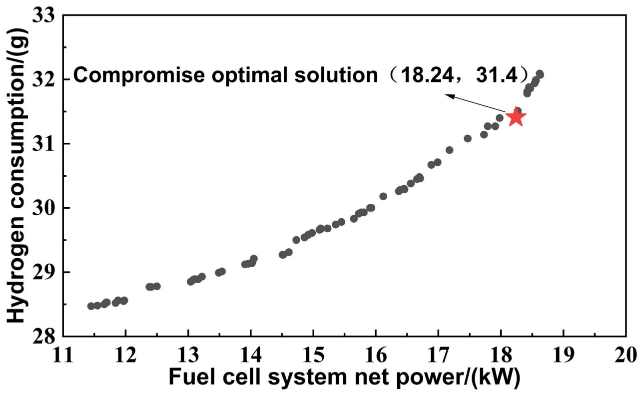
Table V, Comparison before and after model optimization under rated working conditions

	P /bar	T /K	S_{ca}	S_{an}	net system power /kW	hydrogen consumption /g
Pre-optimization model	2.06	357	2.5	1.2	40.12	87.45
Post-optimization model	1.76	362	1.87	1.76	44.49	85.54

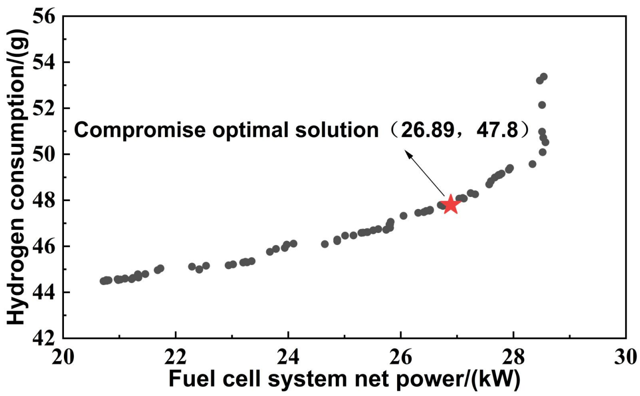
Figure 3 shows the compromise optimal solution of PEMFC with the stack output power of 10 kW, 20 kW, 30 kW and 40 kW. The performance changes of PEMFC before and after optimization were obtained with the optimal operating parameters determined as shown in Table 6 and Table 7. The results illustrate that the optimized operating parameters, such as operating pressure, working temperature, cathode stoichiometric ratio and anode stoichiometric ratio, can decrease the hydrogen consumption of PEMFC and boost the net output power of PEMFC at a given stack output power.



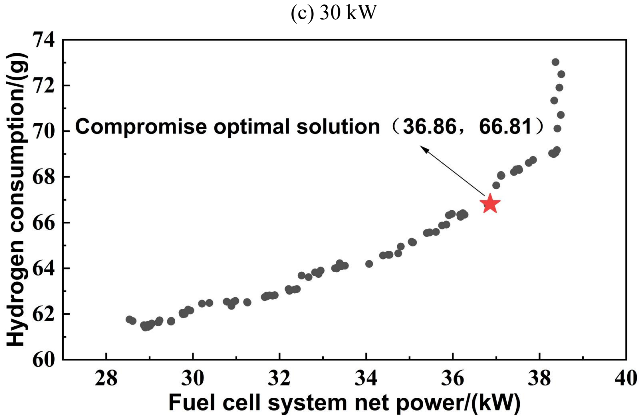
(a) 10 kW



(b) 20 kW



(c) 30 kW



(d) 40 kW

Fig 3, Pareto front distribution of objective optimization under different working conditions

Specifically, hydrogen consumption is reduced under the above different test conditions. The net output power has increased.

Table VI, Model parameters before optimization

stack power /kW	P/bar	T/K	S_{ca}	S_{an}	net system power /kW	hydrogen consumption /g
10	1.19	349.4	2.5	1.2	8.81	16.51
20	1.40	352.7	2.5	1.2	17.77	34.79
30	1.62	355.5	2.5	1.2	25.93	50.16
40	1.84	356.3	2.5	1.2	33.58	68.64

Table VII, Model parameters after optimization

stack power /kW	P/bar	T/K	S_{ca}	S_{an}	net system power /kW	hydrogen consumption /g
10	1.19	356.6	1.21	1.21	8.86	14.80
20	1.29	357.4	1.38	1.23	18.24	31.40
30	1.55	358.0	1.49	1.44	26.89	47.80
40	1.61	359.4	1.62	1.67	36.86	66.81

VI. PERFORMANCE ANALYSIS AND VERIFICATION

The PEMFC and PEMFC bus performance test platforms are shown in Figure 4. The PEMFC performance test platform can be controlled by host computer to set the operating parameters of PEMFC under different operating conditions such as loading current, operating pressure, operating temperature, cathode stoichiometric ratio, so as to obtain the performance of PEMFC under different operating parameters. The energy system of PEMFC bus is comprised of lithium battery and PEMFC, and the power distribution of lithium battery and PEMFC can be controlled under actual operating conditions through the set vehicle energy management strategy. On this basis, the performance parameters of PEMFC such as power, efficiency and hydrogen consumption can be obtained through the data acquisition system.

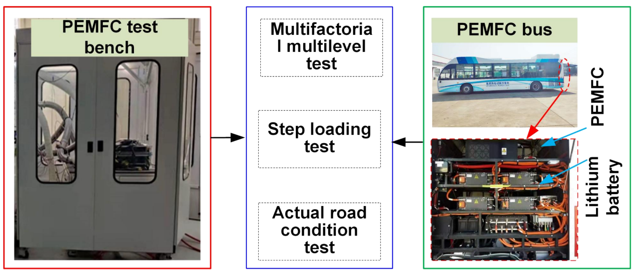
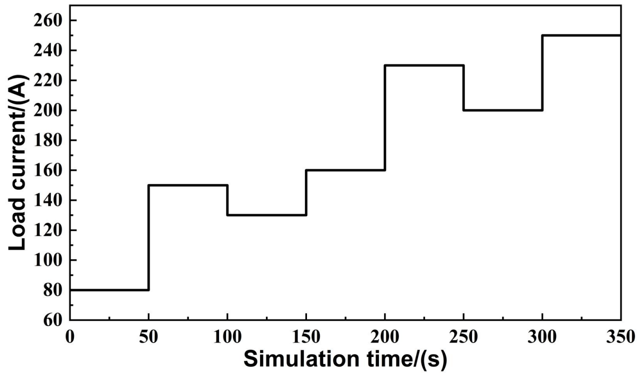


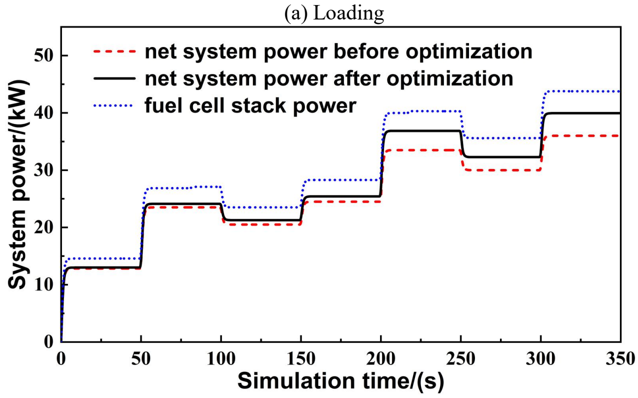
Fig 4, Fuel cell performance test platform

Figure 5 displays the PEMFC power output characteristics under different step loading currents. The total time of step load current is 350 s, and the time interval of each step load current is 50 s. The magnitude of the step loading current is 80 A, 150 A, 130 A, 160 A, 230 A, 200 A and 250 A at different time intervals. The results demonstrate that the net output power of PEMFC is increased by 1.32%, 2.55%, 3.30%, 3.71%, 9.47%, 7.57% and 10.55% respectively. The net power output of PEMFC increases by an average of 5.49% over the entire load range. The main reason is shown in Figure 5, where the parasitic power of the optimized auxiliary system is reduced at different step currents, resulting in an increase in the net output power of the PEMFC.

Overall, the difference in net output power before and after PEMFC optimization is minor at low loading current. With the increase of the loading current, the optimized net output power increases significantly. The main reason is that, as shown in Figure 5, at low step loading currents, the parasitic power of the auxiliary system itself is relatively small, which limits the optimization of the parasitic power. Therefore, the reduced power loss of the optimized auxiliary system is also smaller. With the increase of the step loading current, the ratio of the parasitic power of the auxiliary system to the overall power increases gradually. Therefore, the proportion of the parasitic power of the auxiliary system that can be reduced is also increased, and the power consumption is significantly reduced after optimization.



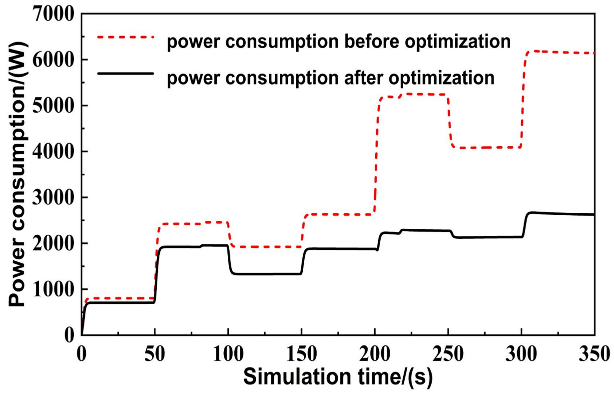
(a) Loading



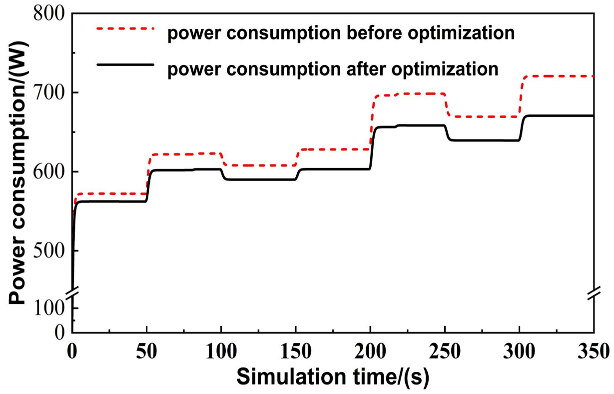
(b) PEMFC output power characteristics

Fig 5, PEMFC output characteristics under different loading currents

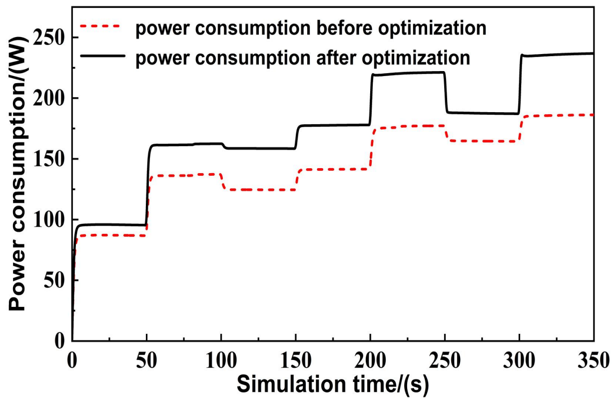
As shown in Figure 6 and Table 8, the parasitic power variation of the auxiliary system before and after PEMFC optimization is given. The results reveal that the parasitic power of the air compressor is the largest, while the parasitic power of the hydrogen circulating pump is the lowest. In the entire loading range, the parasitic power of air compressor, cooling water pump and radiator of the optimized PEMFC decreases by an average of 36.19%, 4.15% and 19.76%, respectively. Among them, the reduction of the parasitic power of the air compressor is the largest. The difference is that the parasitic power of the optimized PEMFC hydrogen circulating pump is increased, and the average power loss is increased by 20.99%. The main reason is that for the air compressor, the air excess coefficient before PEMFC optimization is a fixed value, while the air excess coefficient after optimization is reduced, thus reducing the parasitic power of the air compressor.



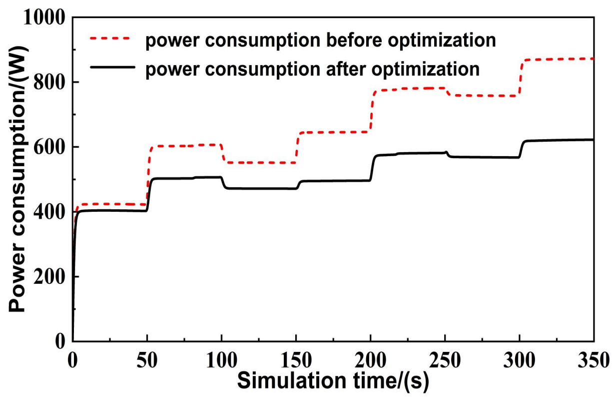
(a) Power consumption of air compressor



(b) Power consumption of cooling water pump



(c) Power consumption of hydrogen circulating pump



(d) Power consumption of radiator

Fig 6, Power consumption of different components

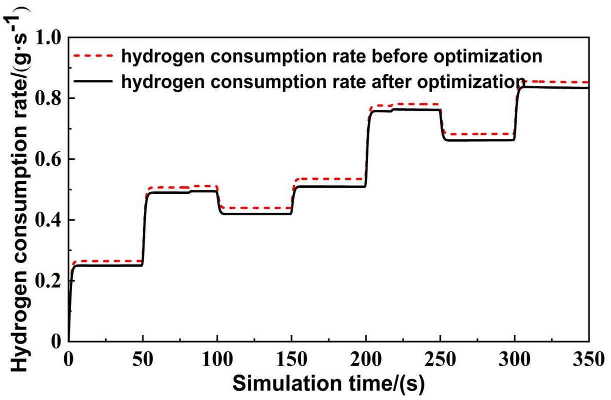
For the hydrogen circulating pump, the optimized hydrogen excess coefficient is increased. Therefore, the amount of hydrogen remaining after the reaction is increased, thereby increasing the power consumption of the hydrogen circulating pump.

Table VIII, Variation amplitude of parasitic power of auxiliary system before and after PEMFC optimization

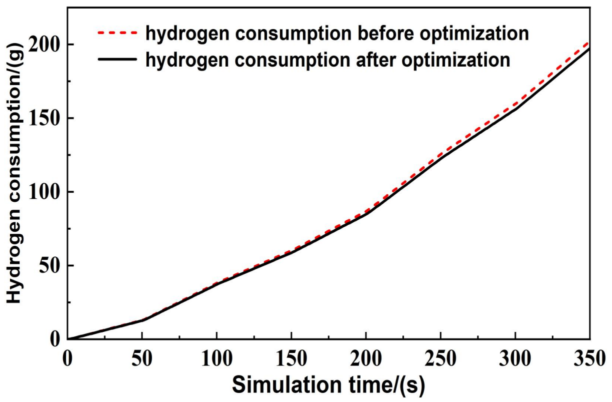
loading interval	component	parasitic power variation range/%	loading interval	component	parasitic power variation range /%
0-50	air compressor	-12.13	200-250	air compressor	-56.58
	cooling water pump	-1.75		cooling water pump	-5.73
	radiator	-4.72		radiator	-25.61
	hydrogen circulation pump	+9.97		hydrogen circulation pump	+24.79
50-100	air compressor	-20.40	250-300	air compressor	-47.79
	cooling water pump	-3.21		cooling water pump	-4.48
	radiator	-16.49		radiator	-25.07
	hydrogen circulation pump	+18.35		hydrogen circulation pump	+13.86
100-150	air compressor	-30.78	300-350	air compressor	-57.19
	cooling water pump	-2.96		cooling water pump	-6.94
	radiator	-14.53		radiator	-28.68
	hydrogen circulation pump	+27.26		hydrogen circulation pump	+27.05
150-200	air compressor	-28.45	350-400	air compressor	-36.19
	cooling water pump	-3.97		cooling water pump	-4.15
	radiator	-23.22		radiator	-19.76
	hydrogen circulation pump	+25.67		hydrogen circulation pump	+20.99

As shown in Figure 7, the variation of hydrogen consumption of PEMFC in the entire loading range is given. From the aspect of hydrogen consumption rate, compared with before optimization, the hydrogen consumption rate in different loading stages decreased by 6.04%, 3.55%, 4.77%, 4.86%, 2.43%, 3.22% and 2.23% respectively. The hydrogen consumption rate decreased by 3. 87% percent on average in the whole load range. The total hydrogen consumption is reduced by 2.37%. The primary reason is that the optimized PEMFC control parameters can effectively reduce the power loss of the auxiliary system, enhance operating efficiency and reduce hydrogen consumption.

As shown in Figure 8, the changes of the demanded power and component power of the fuel cell vehicle under current driving conditions are given. The rule-based energy management strategy is used between the lithium battery and the PEMFC, which will not be described in detail in this paper. The results demonstrate that the required power of the vehicle changes swiftly and fluctuates considerably under the actual driving conditions. The maximum demand power of the vehicle is 71.39 kW, and the maximum regenerative braking power is 23.04 kW. In the first 90 seconds of starting and start-up, the power required by the whole vehicle is provided by the lithium battery alone. After starting and starting up, when the power required by the whole vehicle increases suddenly, the required power is provided by PEMFC and lithium battery. When the required power of the whole vehicle is less than a certain value, the fuel cell maintains a stable output, and the generated excess energy charges the lithium battery. In the whole actual driving condition, the maximum power of PEMFC is 43.06 kW, and the maximum power of lithium battery is 38.25 kW.



(a) Hydrogen consumption rate



(b) Hydrogen consumption

Fig 7, Variation of hydrogen consumption in PEMFC

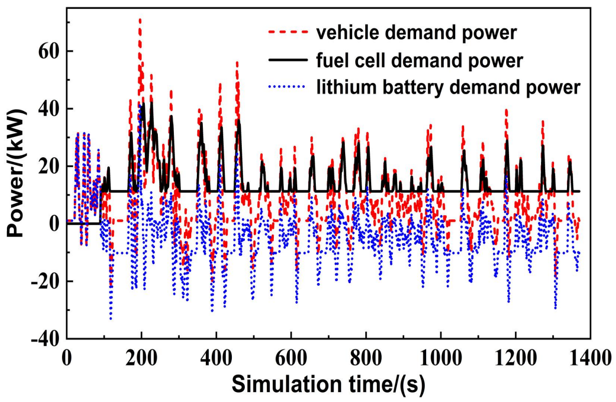
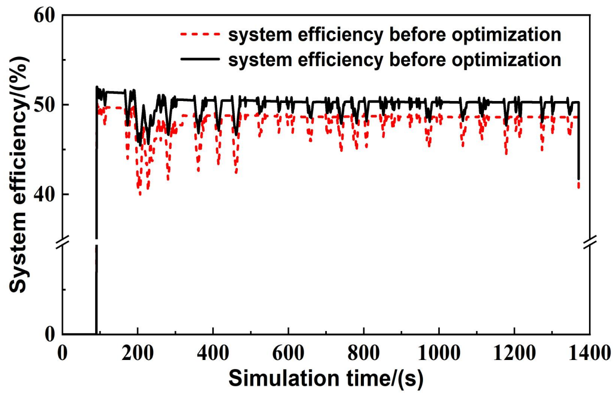
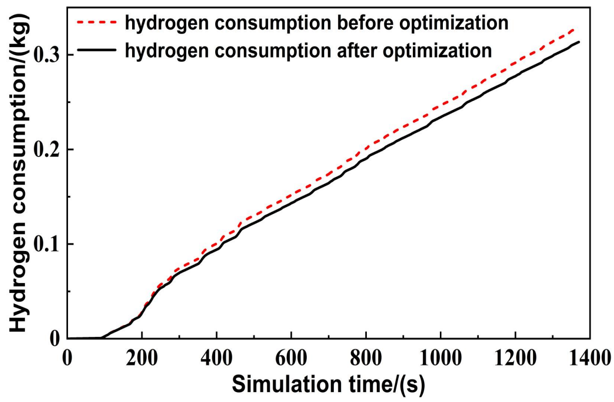


Fig 8, Power variation law of vehicle and components

As shown in Figure 9, the variation of PEMFC efficiency and hydrogen consumption before and after optimization under actual driving conditions is given. The results show that the efficiency of PEMFC before optimization varies from 39.99% to 50.34%, and the average efficiency is 47.96%. After optimization, the efficiency of PEMFC ranged from 45.45% to 52.26%, and the average efficiency was 50.87%. After optimization, the maximum efficiency and average efficiency of PEMFC increased by 3.81% and 6.07%, respectively. The hydrogen consumption of PEMFC before optimization is 0.3291 kg, and the hydrogen consumption of PEMFC after optimization is 0.3135 kg, which is reduced by 2.61%.



(a) PEMFC efficiency characteristic



(b) PEMFC hydrogen consumption

Fig 9, Economy of PEMFC under actual working condition

VII. CONCLUSION

(1) Based on orthogonal trial and significance analysis, it can be determined that operating pressure, operating temperature, cathode stoichiometric ratio and anode stoichiometric ratio have significant effects on the performance optimization of PEMFC. NSGA-II can solve complex multi-parameters and multi-objective nonlinear optimization problems. According to the minimum distance compromise principle, the contradiction between the power output and the hydrogen consumption of the PEMFC can be solved. Under the rated condition, the net output power of PEMFC increases by 9.82% and the hydrogen consumption decreases by 2.18% compared with the compromise solution selected from the Pareto solution set after optimization.

(2) In the whole step loading current range, the parasitic power of the air compressor is the largest, and the parasitic power of the hydrogen circulation pump is the smallest. After optimization, the average reduction of parasitic power of air compressor, cooling water pump and radiator of PEMFC is 36.19%, 4.15% and 19. 76%, respectively, and the parasitic power loss of hydrogen circulating pump

increases by 20.99%. The net power output of PEMFC increases by 5.49%, and the hydrogen consumption rate decreases by 3.87%. The total hydrogen consumption is decreased by 2.37%.

(3) Under actual driving conditions, the efficiency of PEMFC before optimization varies from 39.99% to 50.34%, and the average efficiency is 47.96%. After optimization, the efficiency of PEMFC ranged from 45.45% to 52.26%, and the average efficiency was 50.87%. After optimization, the maximum efficiency and average efficiency of PEMFC are improved by 3.81% and 6.07%, respectively. The hydrogen consumption of PEMFC before optimization is 0.3291 kg, and the hydrogen consumption of PEMFC after optimization is 0.3135 kg, which is reduced by 2.61%.

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