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Development of Hydrogen Circulation System Test Platform for High-Power Fuel Cell

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Abstract. The increasing demand for high-power fuel cell system pushes the improvements of each subsystem, and hydrogen circulation system is one of the key subsystems. Therefore, it is necessary to establish a test platform for hydrogen circulation subsystem with complete testing capabilities and reliability. However, the research on the hydrogen circulation system test system is obviously lagging, especially in the performance test of the core components of the hydrogen circulation pump and the ejector. This paper adopts the modular design idea, develops a complete and reliable comprehensive performance test platform for hydrogen circulation system, designs the corresponding closed-loop control strategy of pressure and temperature, and finally conducts test verification.

Keywords. High-power fuel cell, hydrogen circulation system, ejector, hydrogen circulation pump, test platform.

1. Introduction

As a promising power source for automotive application, proton exchange membrane fuel cell (PEMFC) attracts much attention, and many governments and automobile enterprises pay a lot of efforts to promote its commercialization [1]. Under the environment of energy transformation, to promote the commercialization of fuel cells, high-power fuel cells are becoming the development focus of China's fuel cell industry. The recirculation mode for PEMFC stack is proved to be beneficial [2], the demand of the fuel cell system for hydrogen intake and circulation is greatly increased, and the design requirements of the hydrogen circulation system are higher. Therefore, it is necessary to develop a hydrogen circulation system test platform for high-power fuel cell to meet the performance test requirements of key components such as hydrogen circulation pump and ejector.

There are two types of hydrogen circulation system test platform, the first one is the system-level test with the participation of stack. Nikiforow K [3] has carried out the pulling load experiment of proton exchange membrane fuel cell (PEMFC) system with 5 kW power. The experiment shows that the hydrogen circulation system based on ejector can meet the demand of hydrogen supply in the pulling load process, and the

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response speed of stack power is mainly limited by the response speed of air side. Liu Y [4] tested the performance attenuation characteristics of single-chip PEMFC on 850E test platform. The other is test platform without stack. Wang et al. [5] designed and developed a performance test platform for the ejector. By means of buffer tank and proportional valve, the stack's reaction consumption of hydrogen was simulated, and the cycle performance of the ejector was tested. Nikiforow K [6] designed a hydrogen ejector for the hydrogen cycle system of 5 kW power PEMFC, and test the hydrogen ejector by test platform, and verified the emission performance of the hydrogen ejector under different pressure drop of the induction loop, different inlet pressure and different hydrogen humidity. Hwang J [7] established a three-dimensional CFD model of ejector and carried out numerical simulation, and tested the performance of ejector on the test bench, and the experimental results show that the model accuracy of hydrogen ejector is high. Song Y [8] made the actual hydrogen ejector, and verified the accuracy of the model with the help of the test bench, and the relative error of the test data to the simulation data was within 7%, indicating that the CFD model had high accuracy. The following references can also be found for related bench testing [9-13].

The system-level test can obtain the performance of the hydrogen circulation system under actual working conditions, and maximize the matching between the hydrogen subsystem and proton exchange membrane fuel cell (PEMFC), but the cost is high; The disadvantage of the test platform is that the boundary conditions such as gas temperature and humidity cannot be completely consistent with the actual working conditions, but the system complexity and cost are low.

The test platform designed in this paper is a test platform without stack. It adopts modular design scheme and can test the performance of key components such as hydrogen circulation pump, ejector and water separator. At the same time, the test platform realizes the decoupling control of temperature and humidity, and can apply the closed-loop control strategy of temperature, humidity and pressure.

2. Demand Analysis

The basic function of the test platform is to monitor the running state of the whole system in real time, display the physical quantities of the corresponding monitoring points, control the state of each component, save, analyze and process the collected data, and at the same time ensure the normal operation of the system, timely judge the abnormal situation and quickly make corresponding safety protection measures.

According to the test requirements of hydrogen circulation pump, the test platform should have the test functions of map performance test and variable working condition durability test of hydrogen circulation pump. The pressure and temperature at the inlet of hydrogen circulation pump should be controllable and the flow rate should be measurable, and the pressure and temperature at the outlet should be controllable. For the performance test of ejector, it is necessary to test the ejector ratio under different workflow pressures and different drainage and outlet pressure differences, and it is necessary to control the pressure of ejector workflow path, measure the temperature and flow rate, control the pressure and temperature of drainage path, measure the flow rate, and control the outlet pressure and temperature of ejector. The test platform can also test the flow resistance and water separation efficiency of the water separator, and the flow rate and pressure at the inlet of the water separator needs to be controllable.

To meet the above functions, the test platform is divided into the following modules: gas supply module, humidification module, circulation module, back pressure module, liquid water injection and collection module, nitrogen purging module, electrical module and software module. The relationship between modules is shown in figure 1.

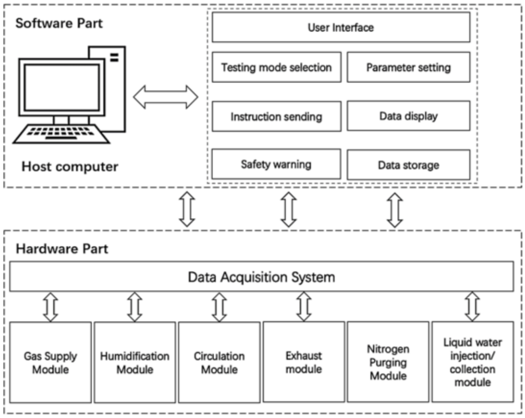

Figure 1. Relationship diagram of each module.

3. Hardware Design

The test platform adopts modular design idea, and the hardware part mainly includes gas supply module, humidification module, circulation module, back pressure module, nitrogen purging module, liquid water injection and collection module and data acquisition device.

3.1. Gas Supply Module

The gas supply module simulates the intake and recycling paths of the fuel cell hydrogen system. It is mainly used to realize the functions of gas flow detection and pressure control, and can automatically cut off the gas supply in case of emergency. The gas supply path is divided into two inlet branches, and one branch is used as ejector jet path; The other branch is used as the ejector drainage path and the inlet path of hydrogen circulation pump. This path is divided into two branches of dry and wet gas. The difference is that one branch does not pass through the humidifying tank, the other one passes through it, and then the two branches merge. The relative humidity of the circulating gas is controlled by controlling the mixing ratio of dry and wet gas and humidifying temperature. The gas supply module is shown in figure 2.

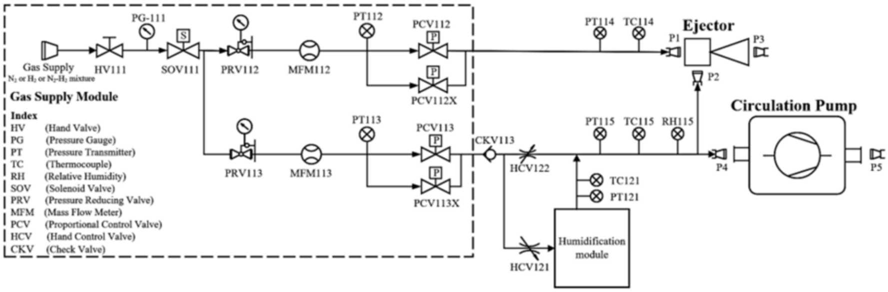

Figure 2. Schematic diagram of gas supply module.

The test gas mainly comes from the high purity hydrogen in the hydrogen storage tank, but the pressure in the hydrogen storage tank is too high to be directly used. Therefore, it is necessary to reduce the pressure through the pressure reducing valve. At the same time, according to the test requirements, it is necessary to install a proportional valve after the pressure reducing valve. Using two proportional valves in parallel can increase the accuracy of pressure control.

3.2. Humidification Module

The humidification module is humidified by bubbling method, which mainly realizes the function of humidifying and warming gas. This module includes automatic water supply and drainage function. The water in the humidifying tank is heated by two heaters to form two circulating waterways, to heat and humidify the gas. After passing through the humidification module, the gas will be humidified into wet gas with 100% relative humidity. By controlling the mixing ratio of dry gas and wet gas, the relative humidity of the gas can be adjusted, thus avoiding the long-term change of the water temperature in the tank and making up for the long-term change of the water temperature in bubbling humidification. Schematic diagram of humidification module is shown in figure 3.

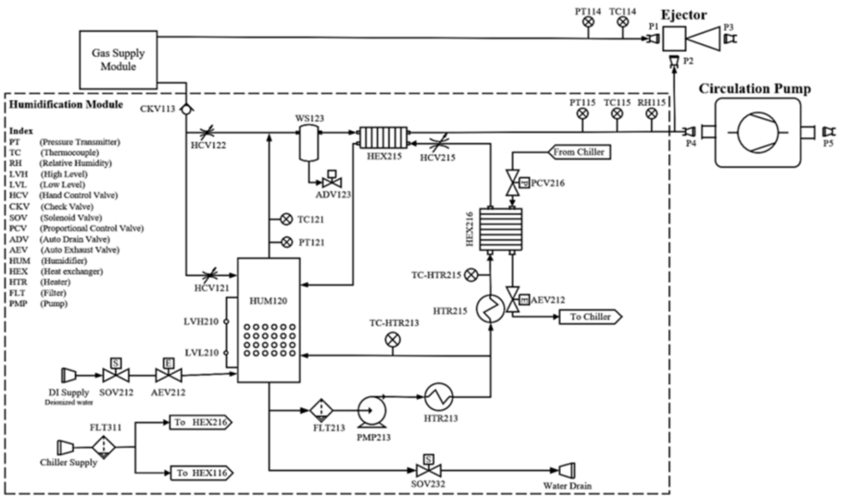

Figure 3. Schematic diagram of humidification module.

Humidifying tank size design should be moderate, too big is not conducive to the layout of test platform, and the temperature adjustment is slow due to too much water. However, it is necessary to meet the requirement of the maximum humidification amount of gas, so that the residence time of gas in humidified water is long enough to achieve complete water saturation in the gas, and it is convenient to accurately control the relative humidity of gas. The test platform uses high purity hydrogen, which can be regarded as the moisture content of hydrogen before humidification $d_1 = 0$. Assuming that after passing through the humidifier, the temperature $T = 70℃$, pressure $P = 0.15MPa$ and relative humidity $R_H = 100\%$ ， take the saturated vapor pressure $P_{sat} = 0.0311MPa$, the moisture content of each 1kg of hydrogen entering the hydrogen circulation pump can be obtained as follows：

$$d_2 = \frac{M_{H_2O}}{M_{H_2}} \cdot \frac{P_{H_2O}}{P - P_{H_2O}} \tag{1}$$

M_{H_2O} is the molar mass of water with a value of 18g/mol; M_{H_2} is the molar mass of hydrogen with a value of 2g/mol; P_{H_2O} is the partial pressure of water vapor in the gas in MPa.

Defined by relative humidity are:

$$R_H = \frac{P_{H_2O}}{P_{sat}} \tag{2}$$

Combining formulas (1) and (2) yields:

$$d_2 = \frac{M_{H_2O}}{M_{H_2}} \cdot \frac{R_H \cdot P_{sat}}{P - R_H \cdot P_{sat}} \tag{3}$$

Substituting the data, it can be obtained $d_2 = 2.35$kg that the required humidification amount per 1kg of hydrogen is $\Delta d = d_2 - d_1 = 2.35kg$. The maximum volume flow rate of hydrogen on the platform is $V_{H_2} = 2000L/min$, and take the density of dry hydrogen as $\rho_{H_2} = 0.089kg/m^3$, then can know that the mass flow rate of hydrogen is $W_{H_2} = V_{H_2} \times 10^{-3} \times 60 \times \rho_{H_2} = 10.68kg/h$, so the total humidification amount of hydrogen is $W_{H_2O} = W_{H_2} \times \Delta d = 25.1kg/h$. According to the above calculation, the water consumption of humidifier can be obtained, and the water supply circuit of humidification module can be designed with a certain margin.

3.3. Circulation Module

To simulate the consumption of anode gas in the stack and the circulation of gas during the actual operation of the fuel cell system, and to reduce the use of gas during the durability test of the hydrogen circulation pump on the test platform, a circulation module was designed. The circulation module mainly includes buffer tank, heat exchanger and automatic regulating valve. The buffer tank is used to simulate the anode chamber of the stack, the proportional valve of the heat exchanger is used for controlling the temperature of the circulating gas. The schematic diagram is shown in figure 4.

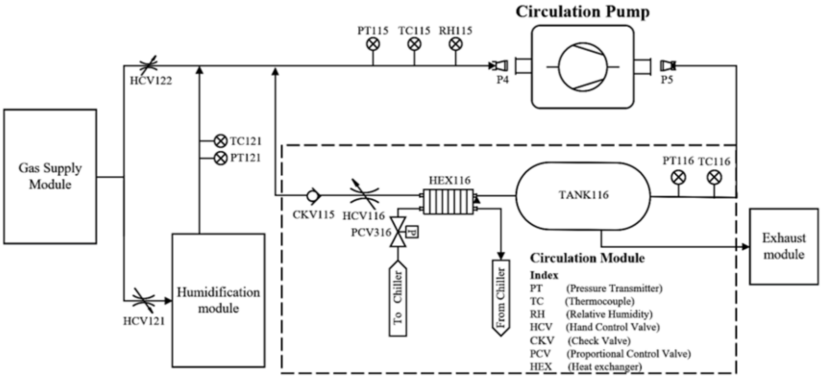

Figure 4. Schematic diagram of circulation module.

3.4. Exhaust Module

The exhaust module mainly discharges the gas in the pipeline, which is used to simulate the consumption of anode gas in the operation of the stack, adjust the back pressure of the outlet gas, and is equipped with an electromagnetic valve to simulate the pulse discharge of the drainage electromagnetic valve during the operation. The schematic diagram of the exhaust module is shown in figure 5.

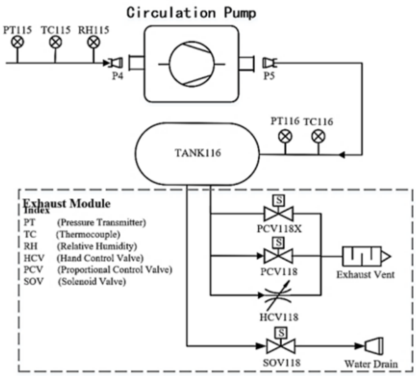

Figure 5. Schematic diagram of exhaust module.

3.5. Nitrogen Purging Module

Safety is an important consideration in hydrogen testing. The function of the nitrogen purging module is mainly to purge the pipeline when the test platform conducts hydrogen test. When hydrogen leaks, it will automatically purge the hydrogen pipeline and equipment compartment, dilute the hydrogen, and prevent the accumulation of hydrogen and potential safety hazards. The nitrogen purging module mainly includes sensors, manual valves, electromagnetic valves, manual throttle valves, etc., and its configuration is equivalent to that of the gas supply module. The schematic diagram is shown in figure 6.

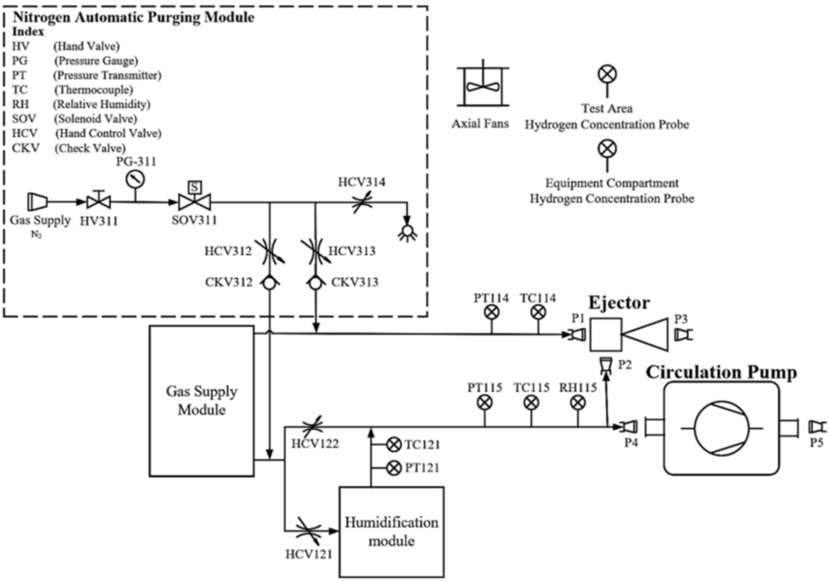

Figure 6. Schematic diagram of nitrogen purging module.

3.6. Liquid Water Injection Collection Module

The liquid water injection module can quantitatively and continuously inject liquid water into the pipeline during the operation of the hydrogen circulation pump and ejector, to observe the influence of liquid water on the performance, and can also be used for the separation efficiency test of the water separator. The module mainly includes a micro gear pump and a micro flowmeter, and the flow rate of injected liquid water is mainly realized by adjusting the rotation speed of the gear pump. The liquid water collection module is mainly used to weigh the separated liquid water when testing the water separator, which is used to test the water separation efficiency of the water separator. The electromagnetic valve controls the frequency of drainage, and the electronic scale detects the quality change of the collected liquid water in real time. The schematic diagram is shown in figure 7.

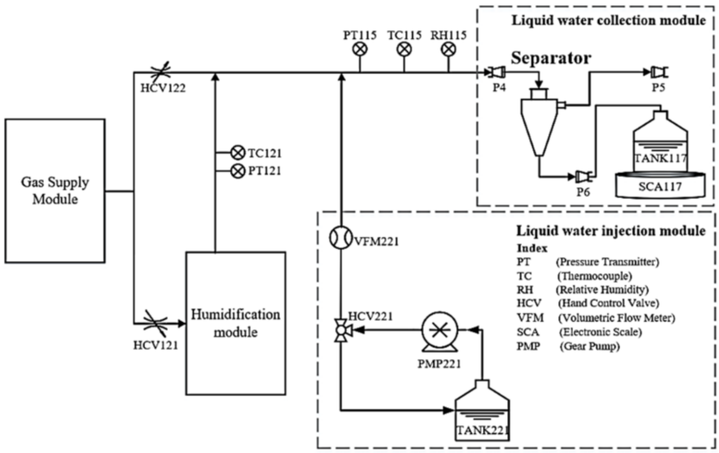

Figure 7. Schematic diagram of liquid water injection collection module.

3.7. Data Acquisition Device

The whole data acquisition process consists of five parts: original signal, sensor, signal conditioning equipment, data acquisition equipment and host computer. The original signal and sensor determine the signal type, and signal conditioning and conversion between analog and digital signal is achieved by selecting different modules of the programmable logic controller (PLC), and different transmission channels should be selected for different signals.

Combined with the design principle of each module mentioned above, the statistics of signal types of the test platform are shown in the following table.

Table 1. Statistics of basic signal types of test platform

Channel type	Related instruments	Total points
AI	Pressure sensor, temperature sensor, hydrogen concentration sensor, electromagnetic valve, micro flowmeter	18
AO	Electromagnetic valve, gear pump	5
DI	Emergency stop button, phase sequence detection, power regulator, liquid level sensor and feedback contact.	9
DO	Electromagnetic valve power supply, 380V power supply, tower lamp	13
RS485	Mass flowmeter, humidity sensor, temperature controller, power regulator, electric measuring instrument, electronic scale	9

Select Siemens S7-1200 series PLC. Configure the modules corresponding to PLC according to table 1. According to the system I/O point requirements and monitoring performance requirements, CPU 1215C DC/DC/DC is selected as the MCU of the bottom control unit of the system; In order to collect the analog signal of the temperature sensor, it is necessary to configure the temperature acquisition module of PLC and select SM1231 TC module; The remaining 13 AI signals, select two SM1231 AI modules; Select SM 1232 AQ module to collect four AO signals; Select SM 1223 DC/RLY module for DI/DO signal; Choose CM 1241 RS422/485 module for signals communicated by RS485. The detailed PLC module configuration and corresponding channel characteristics is shown in table 2.

Table 2. Parameters of PLC module of test platform

PLC	Channel Characteristics	quantity
CM 1241 RS422/485	Communication module with RS422/RS485 interface; 9-pin D-sub socket	2
CPU1215C DC/DC/DC	PROFINET interface 1, DI 14/DQ 10, AI 2/AQ 2, HSC 6, POT/PWM 4	1
SM 1223 DC/RLY	DI 16/DQ 16	1
SM 1231 AI	8 AI, current signal	1
SM 1231 AI	8 AI, channel 0~5: current signal, channel 6/7: voltage signal	1
SM 1232 AQ	4 AQ, current signal	1
SM 1231 TC	8 AI， TC	1

4. Software Design

4.1. PLC Software Design

Write PLC control program based on TIA Portal V16. PLC is the control core of the whole bottom control unit, which is responsible for the conversion between signal conditioning and analog digital quantity, as well as the automatic control of flow, temperature and pressure of the test platform. The original signal is processed by PLC and transmitted to the host computer, and the signal parameter instructions returned by the host computer are processed by PLC to control the operation of the corresponding actuators. PLC and LabVIEW monitoring program of the host computer carry out real-time data interaction to complete the whole test process control.

PLC adopts modular programming idea, and the program is divided into signal processing module, data interaction module, fault processing module and automatic control module. Among them, the automatic control module is the focus of research. The test platform needs to realize the automatic control of pressure, temperature and flow, and the automatic control algorithm is realized in PLC. The fuzzy adaptive PID algorithm is used to realize the closed-loop control of pressure and temperature, and the measured actual value is compared with the set value to get the real-time error and error change rate [14]. The fuzzy rules are used for fuzzy reasoning, and the fuzzy rule table is queried for parameter adjustment to meet the requirements of error and error change rate at different times for parameter self-tuning [15]. The fuzzy rule table is shown in table 3. The pressure control is mainly realized by adjusting the opening of the corresponding proportional valve, and the temperature control is realized by adjusting the temperature of the thermostat and the opening of the proportional valve. The pressure control block diagram is shown in figure 8.

Table 3. Fuzzy rule table

	U	EC						
		NB	NM	NS	ZO	PS	PM	PB
	NB	PB	PB	PB	PB	PM	ZO	ZO
	NM	PB	PB	PB	PM	PM	ZO	ZO
	NS	PB	PM	PM	PS	ZO	NS	NM
E	ZO	PM	PM	PS	ZO	NS	NM	NM
	PS	PS	PS	ZO	NM	NM	NM	NB
	PM	ZO	ZO	ZO	NM	NB	NB	NB
	PB	ZO	NS	NB	NB	NB	NB	NB

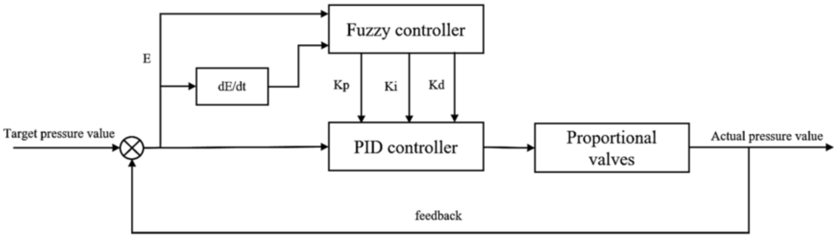

Figure 8. Pressure control block diagram.

4.2. PC Software Design

The host computer software of the test platform is developed based on LabVIEW, and the user interface is shown in figure 9. The host computer unit uses the I/O Server of LabVIEW DSC module and the standard Modbus TCP/IP communication protocol of PLC to realize the communication between the host computer and PLC in the form of shared variables and complete the data interaction.

The user interface of the host computer can be divided into five functional areas: test mode selection area, test function selection area, fault status display area, test mode operation area and other functional areas.

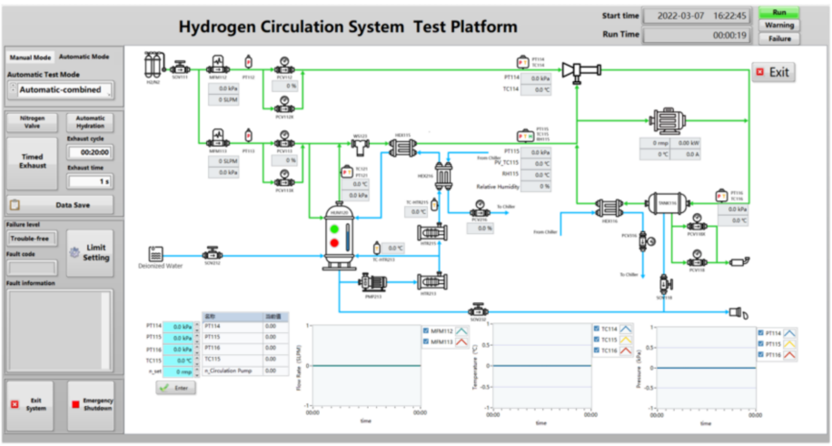

Figure 9. User interface of test platform.

The test mode selection area can switch between manual test mode and automatic test mode. In the manual test mode, all parameters and valve switches need to be set manually. Correspondingly, in automatic mode, after manually setting a few necessary parameters, the test can run automatically. Under the two test modes, seven test modes can be selected according to the different parts to be tested. After manual or automatic test is selected, the specific test mode can be selected in this area, and the selected operation interface will be loaded in the test mode operation area on the right side of the interface.

Some general functions are placed in the test selection area, including nitrogen valve, automatic water replenishment, timing exhaust and data saving functions. Click the corresponding function buttons according to the actual needs, and the corresponding functions will be executed after clicking.

The fault status display area is used to display the fault level, fault code and fault details. Users can click the "Limit Setting" button to enter the fault information page and set the upper and lower limits of the alarm. After setting, click "Return to Main Interface" to return to the main operation interface. DTC was defined before the fault program was written. The test platform needs to monitor the relevant hardware state, temperature, pressure, flow rate, hydrogen concentration and liquid level state of humidification tank of the test system in real time. In case of abnormal working conditions such as hardware fault, pressure temperature and hydrogen concentration exceeding the limit, a warning will be given to the user to indicate the specific abnormal situation. The software will execute the relevant protection flow procedures, and then the test can be conducted again after troubleshooting. The fault level is defined as four levels, and the specific definitions are shown in table 4.

Table 4. Definition of Fault Level

Fault level	Fault type	Equipment action	Three-color lamp state	Recovery condition	User permission
0	-	-	green	-	-
1	warning	Self-recovery	yellow	Automatic recovery	adjustable
2	Alarming	Stop test, don't stop electricity	red buzzer	Artificial restoration	Partially adjustable
3	Emergency Stop	Emergency, power failure	red buzzer	Power-down restart	No adjustable

The test operation area is divided into parameter setting area and data display area. The parameter setting area is used to set parameters and send them to PLC. The data display area includes data display in panel, system diagram and chart. The data display in the panel contains the important parameters of the test, and only shows the value of the current moment; The data display in the system diagram marks the relevant parameters in the designated position of the system diagram, and the data is comprehensive and intuitive; The data display in the chart shows the change trend of related parameters with time. Other functional areas include functions such as exiting the system, emergency stop, time display and software status monitoring.

5. Test Verification

According to the system architecture design of the test platform, a test platform for hydrogen circulation system is built, with the overall structure as shown in figure 10. The whole test platform can be divided into two areas, one is the test area and the other is the equipment area. Electrical related components are centrally arranged on the left side of the platform, and water-gas pipelines are centrally arranged on the right side of the test platform, with internal water and electricity separated to prevent electrical flooding; Heat preservation treatment is carried out in the pipeline involving the temperature control part or the pipeline through which wet gas flows to prevent condensation or scalding; Mechanical layout adopts modular internal structure, which is convenient for upgrading and maintenance.

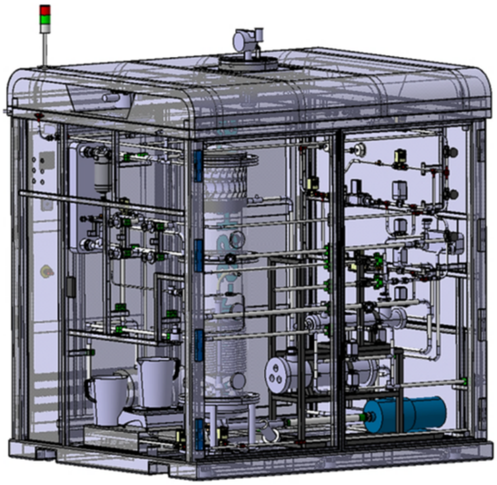

Figure 10. Appearance design of test platform

To verify the working effect of the designed test platform, according to the working conditions of the tested parts, it is necessary to accurately control the temperature, pressure and other parameters at the set values, and verify the rapidity and accuracy of the closed-loop control strategy of the test platform. Taking the performance test of circulating pump as an example, compressed air is used instead of hydrogen. The inlet pressure of circulating pump PT115 is set to 220kPa, the outlet pressure PT116 is set to 240kPa, and the inlet temperature TC115 is set to 75℃, and the corresponding change curve is recorded. As shown in figure 11, within the sampling time, the test system as a whole can respond quickly according to the pressure set value, the pressure response time can be controlled within 15 s, the pressure overshoot is less than 3 kPa, and the difference between the pressure response value and the set value after stabilization is ≤1 kPa, which indicates that the pressure closed-loop control effect of the test platform is good.

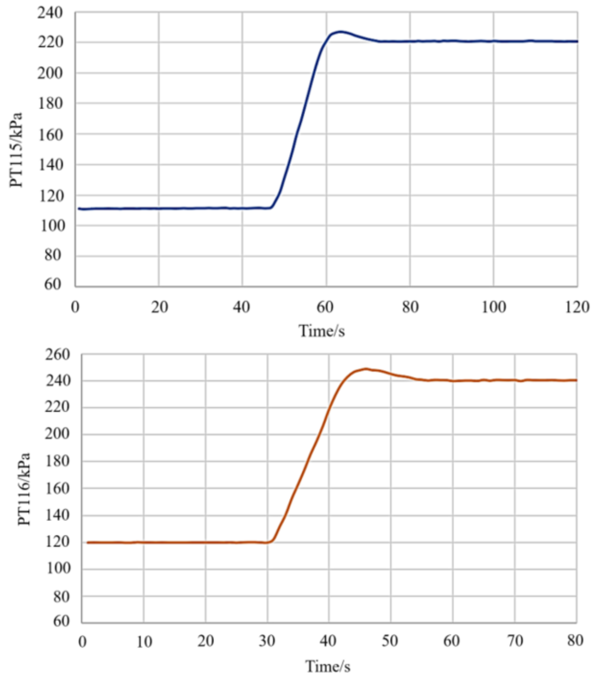

Figure 11. Pressure change curve.

To verify the performance test function of the test platform, the ejector performance test, circulating pump performance test and water separator flow resistance test were carried out with this test platform. The dry hydrogen and wet hydrogen were tested respectively. Under the same jet pressure and jet flow rate, the change rate of ejector ratio under different pressure differences was obtained by controlling the drainage pressure and outlet pressure. The experimental ejector performance curve is shown in figure 12. The map diagram of the circulating pump for testing the saturated wet gas and dry gas at 60°C at the circulating pump limit speed of 5000rpm is shown in figure 13. The water flow resistance test curve of the water separator is shown in figure 14. The corresponding performance test verifies that the test platform has the function of comprehensive performance test of hydrogen circulation system. Compared with the single function test platform, the test range is wide and the function is more comprehensive.

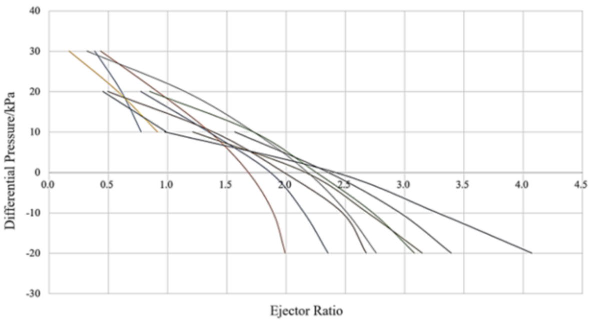

Figure 12. Performance test of ejector.

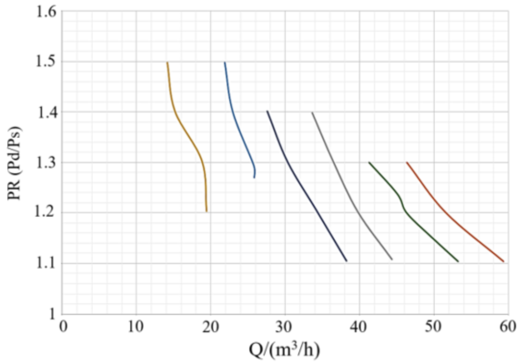

Figure 13. Performance test of circulating pump.

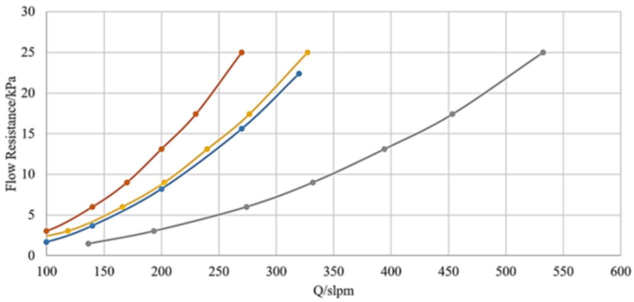

Figure 14. Flow resistance test of water separator

6. Conclusion

The purpose of this paper is to develop a comprehensive test platform for hydrogen circulation subsystem, which can be used to test the performance of core components of hydrogen circulation subsystem, such as hydrogen circulation pump, ejector and water separator, to help the development of fuel cell industry. This paper analyzes the functional requirements of the test platform and designs its overall architecture. The structure of each module of the hardware part of the test platform is designed, and some modules are theoretically calculated to determine the working range. At the same time, the PLC module is selected based on the signal type analysis, and the hardware system of the test platform is built. The PLC internal control program is written, the data acquisition function is completed, the closed-loop control strategy of the pressure and temperature of the test platform is designed, and the control program is written to realize the automatic control of the pressure and temperature. At the same time, the host computer software of the test platform is designed and developed based on LabVIEW, and the user interface is designed according to the functions of the test platform. Through the design and validation process, the paper finally demonstrates the capabilities of the platform.

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