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-30℃ COLD START STRATEGY OF DESIGNED FUEL CELL SYSTEM

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Abstract: Proton exchange membrane fuel cells (PEMFCs) are considered one of the most promising alternative power sources for future vehicles due to their high energy conversion efficiency, zero pollution, and wide availability of fuel sources. Enhancing the low-temperature start-up capability of fuel cell systems is crucial for their widespread commercial application in the future. However, current experimental research findings are primarily based on single fuel cells or low-power stacks, with very limited studies on the impact of cold start on high-power systems. This leads to a significant gap between current scientific research and practical application, and the relevant results cannot be directly applied to actual systems. Therefore, research on low-temperature cold start of high-power fuel cells is of great significance. In this study, a 130kW fuel cell system was designed, and AVL Cruise M software was used to model and simulate the low-temperature cold start process of the fuel cell. By studying the start-up current loading strategies and the effects of operating parameters on fuel cell performance changes under -30℃ experimental conditions, key information reflecting the state changes within the fuel cell stack was obtained. Based on this, a low-temperature cold start loading strategy corresponding to the specific temperature was proposed.
Keywords: PEMFC; -30℃ cold start; Cruise M simulation; Loading strategy

1 INTRODUCTION

With the increasing severity of environmental pollution and energy crises, countries have successively taken measures to accelerate the development of clean and renewable energy sources, reduce the combustion of fossil fuels, and urgently seek new alternative clean energy sources. Proton exchange membrane fuel cells (PEMFCs), as one of the best applications of hydrogen energy, have attracted widespread attention. PEMFCs are characterized by their high energy density, environmental friendliness, noise-free operation, and clean efficiency.In recent years, significant breakthroughs have been made in the development of related materials and core components. However, the issue of cold start at low temperatures remains a major constraint on their commercialization and practical application.

PEMFCs initially contain liquid water, and liquid water is also generated during the cyclic operation process. When accumulated liquid water freezes in low-temperature environments (<0℃), it can lead to several critical issues. The freezing of water can cover the gas diffusion layer with ice, preventing gases from reaching the surface of the catalyst layer and severely affecting gas transport. Ice formation in the catalyst layer can cover the reactive sites, reducing the electrochemical reaction active area. Additionally, freezing can cause localized stress on key materials and components within the fuel cell stack, damaging the cell's structural organization and causing permanent damage to the proton exchange membrane. Volume changes caused by freeze-thaw cycles can also lead to cracking in the catalyst layer, significantly affecting the performance of the fuel cell stack. These factors collectively result in a substantial decrease in the rate of electrochemical reactions, leading to cold start failure of PEMFCs at low temperatures and negatively impacting the lifespan and performance of the battery. Therefore, avoiding the extensive freezing of water during the low-temperature cold start process of PEMFCs is crucial for enhancing the performance of fuel cell systems.

Currently, both domestic and international research has been conducted on the cold start of fuel cells.

Regarding self-startup, various studies have explored different approaches to enhance the self-startup capabilities of fuel cells. In terms of constant-current self-startup, Zang compared the cold start performance of fuel cells under different current densities and proposed a boundary current density range for successful cold start at different temperatures [1]. In terms of variable-current self-startup, Gwak et al. achieved rapid cold start of the fuel cell by controlling the operating current during the cold start process [2]. Lei compared the effects of different current loading methods, such as constant current and linearly increasing current, on the cold start performance of fuel cells [3-4] . It was found that the cold start performance of fuel cells using variable current startup methods is significantly better than that of other startup methods.

Regarding assisted startup, in terms of coolant circulation heating, Ríos achieved successful cold start of the fuel cell at -30℃ by heating the coolant [5]. Luo et al. studied the cold start issue of fuel cell vehicles with a coolant preheating strategy and realized successful cold start of the fuel cell at -30℃ through coolant-assisted heating [6].

Regarding the loading strategy, Li et al. found that performing a large step load under a low current severely disrupts the uniformity of the cell voltage in the stack [7]. The impact of the loading magnitude on voltage uniformity is greater than that of the loading frequency. Migliardini et al. utilized a 6kW fuel cell stack to investigate the voltage uniformity under different constant loading and unloading rates [8].

However, current experimental research findings are primarily based on single fuel cells or low-power stacks. There is a significant lack of studies on the impact of cold start and the coupling of multiple parameters on cold start in high-power systems. This has led to a considerable gap between the current scientific research and practical application, and the relevant results cannot be directly applied to the cold start performance evaluation and design of actual fuel cell systems. Therefore, this research will design a high-power fuel cell power system (130kW) and determine the effects of different loading methods and other parameter conditions on the cold start performance of fuel cells through experiments and simulations. Based on these findings, the startup strategy will be optimized.

2 DESIGN OF A FUEL CELL SYSTEM

Achieving low-temperature cold start of fuel cell systems is extremely important for their widespread application. In actual experimental testing, proton exchange membrane fuel cell (PEMFC) stacks exhibit a series of significant characteristics. First, PEMFCs have a large number of signals to be collected, requiring real-time monitoring and recording of numerous parameters to ensure stable system operation and performance evaluation. Second, control signals need to be fast and precise, as any slight delay or error can affect the performance and safety of the fuel cell. Additionally, the controlled components need to have rapid response capabilities to adapt to complex operating conditions and strong anti-interference capabilities to ensure stable operation in various complex environments.

During the development of fuel cell systems, the system design phase is crucial. It is necessary to ensure that the hardware and software performance can meet the high requirements of the fuel cell system and have good real-time capabilities to complete complex calculations and control tasks in a short time. This study employs a high-power fuel cell stack (comprising 418 single cells) to conduct low-temperature cold start experiments, and the relevant systems have been designed and constructed as shown in Figure 1, including the hydrogen supply system, the air supply system, the thermal management system, and the electrical and control system.

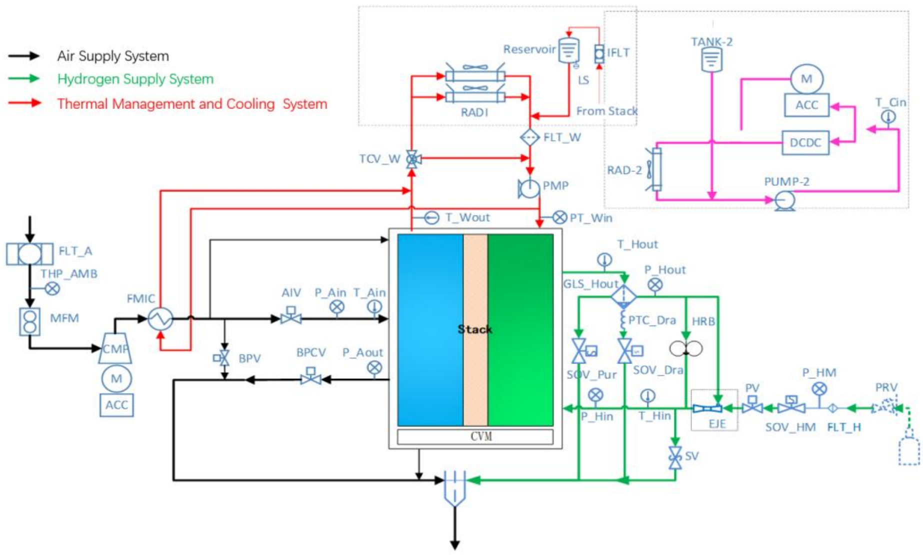

Figure 1 Schematic Diagram of the 130kW Fuel Cell System

2.1 The Air Supply System

The air supply system mainly consisting of an air filter, an integrated ambient temperature, humidity, and pressure sensor, an air mass flow meter, an air compressor, an intercooler, an air intake valve, and a backpressure valve. During normal operation of the fuel cell stack, air passes through the air filter and is compressed into high-temperature, high-pressure gas by the air compressor. It then enters the fuel cell stack after being cooled by the intercooler, providing the cathode of the stack with the oxidant.

The air filter selected is the Xuanke Hydrogen FC120 fuel cell cathode air filter. Xuanke Hydrogen's FC series fuel cell cathode air filters are safe, reliable, and available in a wide range of specifications. They are chemically adsorptive filter materials specifically developed for Chinese fuel cell systems, achieving an optimal balance between the filtration of harmful gases such as sulfur dioxide and nitrogen oxides, and dust particles. The product features high dust capacity, high adsorption efficiency, and simple, flexible installation methods.

The Xuanke Hydrogen FC120 fuel cell cathode air filter is suitable for fuel cell stacks ranging from 50 to 130 kW, with a rated flow rate of 720 slpm, which meets the requirements of this fuel cell stack. The detailed parameters are shown in the table. The air mass flow meter is used to monitor the air flow in the air path, thereby controlling the flow of the air compressor. The BOSCH 0281006270 model is selected, with an input voltage of 6–17 V and a rated flow rate of 640 kg/h (with a measuring range of -60 to 800 kg/h). The pressure drop is 12 kPa, and it is equipped with an NTC.

The integrated ambient temperature, humidity, and pressure sensor is used to detect the temperature, humidity, and pressure of the air at the air intake of the fuel cell stack. The Wuxi Shengbang ST8251-1BBA1 type temperature, humidity, and pressure integrated sensor is selected, and its product characteristics are shown in Table 1. The air compressor is a crucial component of the air supply system, providing the necessary air pressure and flow rate for the fuel cell stack. The Haidowell HEC30 air compressor is selected for this purpose. It features a maximum motor power of 30 kW, a maximum flow rate of 180 g/s, a maximum pressure ratio of 3.3, and a maximum rotational speed of 120,000 revolutions per minute.

Table 1 Product Characteristics of Integrated Sensor

Characteristic	Range
Temperature Measurement Range	-40℃~125℃
Relative Humidity Output	0%RH~100%RH
Pressure Measurement Range	20kPa(A)~300kPa(A)

2.2 The Hydrogen Supply System

The hydrogen supply system includes components such as hydrogen storage cylinders, pressure-reducing valves, medium-pressure solenoid valves, hydrogen recirculation pumps, drain valves, and proportional valves. The hydrogen exhaust valve selected is the ASCO X256548494 with a 2.0 mm orifice. This valve has a Kv value of 0.129, the maximum hydrogen exhaust flow rate is 233.3 slpm.

It is estimated that the anode chamber volume of a 418-cell stack is approximately 1.672 L. From this, it can be inferred that opening this hydrogen exhaust valve for 0.43 seconds each time would be sufficient to replace the gas inside the chamber once, meeting the usage requirements. The drain valve selected is the ASCO X986542315 with a 3.5 mm orifice.

The medium-pressure solenoid valve is defined as the switch between the first-stage pressure reduction of hydrogen and the proportional valve. The model selected is the Zhejiang Hongsheng HONGSHGN-FSV-1. The role of the proportional valve is to provide the hydrogen pressure and flow rate required for the normal operation of the fuel cell stack. The proportional valve chosen is the Weifu WHI22.

The purpose of the hydrogen recirculation pump is to improve the utilization rate of hydrogen and increase the hydrogen flow rate, thereby enhancing the water drainage efficiency.

The medium-pressure sensor is used to detect the pressure after the pressure-reducing valve. The model selected is the Sensata 32CP42-01-ENV, with a pressure range of 0.1-2.0 MPa(A) and an operating temperature of -40℃ to +125℃. The low-pressure sensor is used to detect the hydrogen pressure from the proportional valve outlet to the fuel cell stack inlet. The model selected is the Sensata 30CP42-06-ENV, with an operating pressure of 50–300 kPa(A). The rated hydrogen inlet pressure of the fuel cell stack is 266.30 kPa(A), which meets the usage requirements. The hydrogen inlet and outlet temperature sensors are used to detect the temperature of the hydrogen at the inlet and outlet of the fuel cell stack. The model selected is the Qufu Tianbo Fuel Cell Temperature Sensor 1927, with an operating temperature range of -40℃ to 140℃. The water separator is used to separate liquid water from the wet hydrogen at the anode to prevent liquid water from entering the anode of the fuel cell stack and causing anode flooding. The model selected is the Suzhou Ruidu HWS120-WC gas-water separator. The safety valve is used to release pressure when the pressure after the proportional valve is too high, thus protecting the fuel cell stack. The safety valve is a purely mechanical device. Based on experience, the set pressure = the rated hydrogen absolute pressure of the fuel cell stack × 1.1. Calculations show that the inlet pressure of the fuel cell stack should not exceed 2.926 bar (2.66 × 1.1). The Zhejiang Hongsheng HSXYF-121L meets this requirement. The hydrogen recirculation pump selected is the Suzhou Ruidu WDE-C008-H hydrogen recirculation pump, with its specific performance parameters shown in Table 2.

Table 2 Product Characteristics of HRP

Characteristic	Range/Value
Maximum Suction Pressure	230kPa(A)
Maximum Discharge Pressure	300kPa(A)
Pressure Ratio Range	1-1.2
Displacement	200CC
Maximum Volumetric Flow Rate	750L/min
Speed Range	500-700rpm

2.3 The Thermal Management System

The electrochemical reactions occurring inside the fuel cell stack generate heat. Excessive heat can cause the stack temperature to rise too high, leading to performance degradation of the stack components. In severe cases, it can reduce the service life of the stack. The primary function of the thermal management system is to maintain the thermal balance of the fuel cell system, dissipate the excess heat generated by the stack, ensure that the stack quickly reaches a suitable temperature, and prevent the stack from overheating.

The thermal management system mainly consists of a coolant pump, an expansion tank, a thermostat, and a radiator (with a cooling fan). The thermostat controls the large and small coolant circulation loops. When the stack temperature is low, the thermostat directs the coolant to flow within the small circulation loop. When the coolant temperature is high, the thermostat directs the coolant to flow through the radiator assembly for cooling, thereby maintaining the normal operating temperature of the stack.

The coolant pump controls the coolant flow rate by adjusting its speed to achieve temperature control, ensuring that the fuel cell system operates within an appropriate temperature range. The cooling fan transfers the heat from the coolant to the environment, reducing the coolant temperature. The cooling fan is required to have a high airflow rate, low noise, stepless speed control, and the ability to feedback its operating status.

The circulating water pump selected is the Beijing Ai'er LQY-P150 model pump. The ion filter is connected in series between the fuel cell stack coolant exhaust port and the expansion tank branch, and the I2M i10-3 ion filter is chosen. The temperature and pressure integrated sensor is used to detect the coolant temperature and pressure at the fuel cell stack inlet. Based on the detected data, the circulating water pump and fan are adjusted in speed to ensure that the fuel cell operates at the recommended working temperature and to maintain the coolant pressure within the normal range. The temperature and pressure integrated sensor selected is the Sensata 31CP02-03-ENV.

2.4 The Electrical and Control System

The function of the electrical and control system is to ensure that other systems can operate efficiently and in coordination, guaranteeing sufficient gas supply and appropriate working temperature, among other things. It is mainly composed of various types of sensors, flow meters, valve components, and so on.

3 COLD START SIMULATION AT -30℃

3.1 Model Assumption

To facilitate the calculations, the following assumptions are made for the PEMFC model to simplify the analysis within the stack:

1) All gases within the model are assumed to be ideal gases, and the influence of gravity is neglected.
2) The initial state of water generated by the electrochemical reaction is assumed to exist in the cathode catalyst layer in the form of membrane-bound water.
3) Only diffusion, heat transfer, and mass transfer in the direction perpendicular to the plane are considered.
4) Pressure variations within the fuel cell are ignored.
5) Liquid water and ice in the flow channels are neglected.
6) The heat exchange between the fuel cell stack and the external environment is assumed to be uniform, i.e., the phenomenon where the heat dissipation rate at the ends of the stack is much higher than other parts, leading to lower temperatures of the end cells in the stack, is ignored.

3.2 Model Construction

The relevant parameters of the fuel cell stack are shown in Table 3. Based on the software AVL Cruise M, a cold start simulation model that reflects the internal state of the PEMFC is established, and its structure is shown in Figure 2.

Table 3 The Parameters of The Fuel Cell Stack

Parameter	Value
Number of Cell	418
Reaction Active Area	330cm2
Thickness of Membrane	8μm
Thickness of Bipolar Plate	2mm
Flow Channel Cross-section	1mm2
Flow Channel Length	500mm

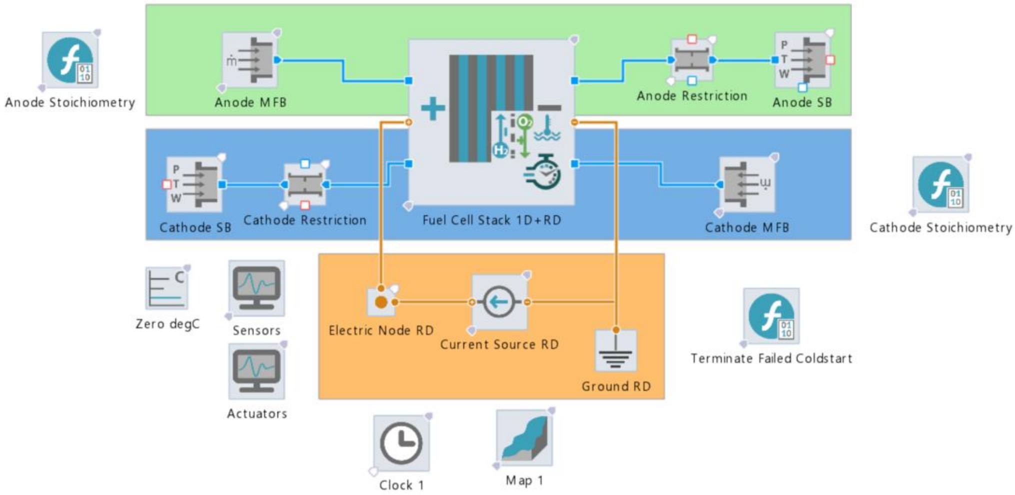

Figure 2 The Model of the 130kW Fuel Cell System

3.3 Simulation Result

Figure 3 illustrates the current loading process in the simulation, which is designed to closely match the experimental loading curve.

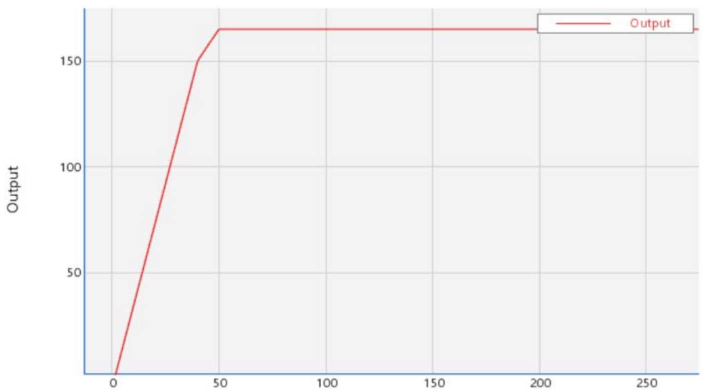

Figure 3 Current Loading in Simulation

The cell voltage variation after simulation is shown in Figure 4. Since the simulation is conducted on the cell stack model, while the experiment is performed on the entire system, there is inevitably some deviation. Additionally, the voltage fluctuations in the simulation are relatively large. Therefore, only a qualitative analysis can be made based on this simulation. It can be observed that the battery voltage slightly drops after startup and then stabilizes after a period of fluctuation. The fact that the voltage does not drop to 0V indicates that the cold start is successful.

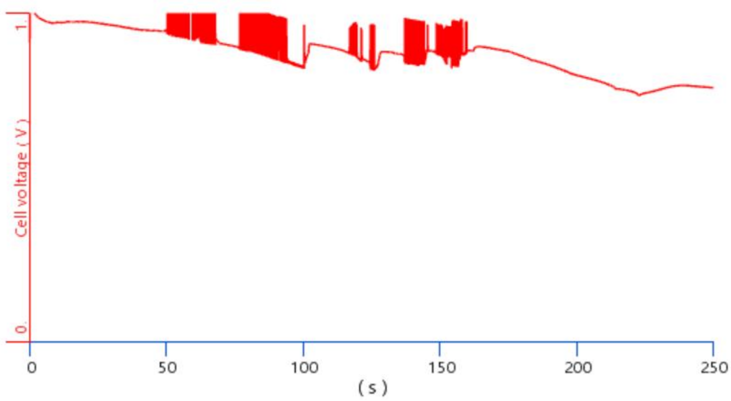

Figure 4 Cell Voltage during Simulation

4 COLD START EXPERIMENT AT -30℃

4.1 Experimental Procedure

The cold start experimental procedure is as follows:

1) Set the environmental chamber to a specific temperature and place the fuel cell system inside for more than 12 hours.
2) After the temperature stabilization is complete, turn on the electronic load and open the hydrogen inlet valve. Check for any hydrogen leaks at the valve.
3) Once all preparations are complete, send a cold start command to the fuel cell system. The control unit will perform a self-check on the system, verifying the communication status of system components such as the air compressor, hydrogen recirculation pump, and water pump to ensure they are operating normally. Then, the cold start program will be executed, and the system will begin loading. During the warm-up process, as the coolant temperature increases, the system power will gradually rise to the set power level.
4) After the system has operated stably at the set power for a period of time, the shutdown procedure will be executed. Subsequently, the stack load will decrease to idle load, and the purging program will start to expel any residual water.
5) Once the purging is complete, turn off the electronic load and stabilize the system at the set temperature for another 12 hours until the next cold start experiment begins.

4.2 Experimental Result

The Voltage and Current Curve, Coolant Temperature Curve, Voltage Range Curve during startup at -30℃ is shown in Figure 5. As can be seen from Figure 5, the use of a continuous loading strategy allows the system to successfully cold start at -30℃. The current is loaded from 0A to approximately 150A within 40 seconds at a rate of 3.75A/s. During this period, the temperature of the stack's coolant outlet rises steadily and exceeds 0℃, with a temperature increase rate of 0.73℃/s. During the loading process, the average voltage of the stack and the minimum voltage of the single cell decrease. Once the coolant temperature exceeds 0℃, the voltage begins to recover and continues to rise until the system operates stably. At this point, the difference between the average voltage and the minimum single cell voltage is negligible.

It can also be observed from the range chart that, at the initial stage of loading, the range begins to increase gradually, reaching a maximum of approximately 0.38V. After the coolant temperature exceeds 0℃, the range starts to decrease. When the system operates stably, the range is essentially zero, indicating good consistency of the stack and good system output performance.

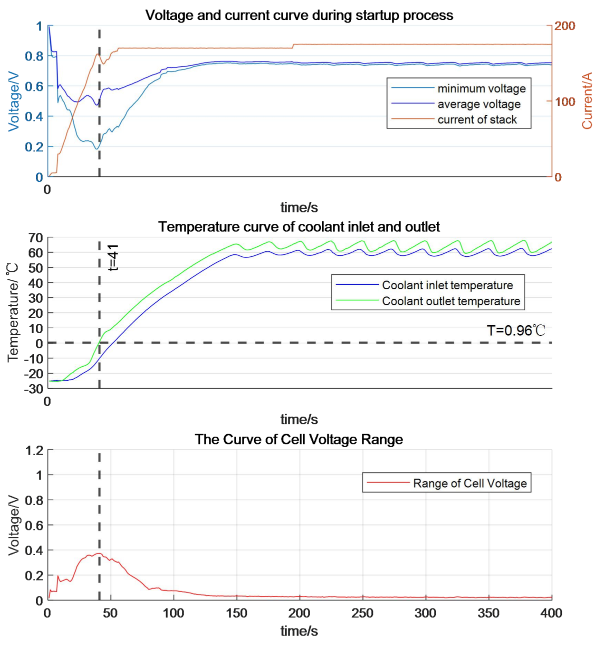

Figure 5 The Voltage and Current Curve, Coolant Temperature Curve, Voltage Range Curve during startup at -30℃

The voltage distribution of individual cells at a current of 175A is shown in Figure 6. It can be seen that in the initial stage of current loading, the voltage of the lowest single cell drops rapidly, but it does not fall below the protection threshold. During the fast continuous loading period, the coolant temperature rises at a relatively high rate. About 41 seconds after loading, the coolant outlet temperature of the cell stack exceeds 0℃. The drop in the lowest voltage and average voltage continues until this time. After that, the coolant temperature continues to rise, while the lowest voltage and average voltage begin to recover. When the coolant temperature rises to about 50℃, the lowest voltage and average voltage return to a stable level, with little difference between the two.

It can also be seen from the voltage difference graph of individual cells that before the coolant temperature rises to 0℃, the voltage difference gradually increases, but it does not exceed 0.4V. After the coolant temperature rises to 0℃, the voltage difference gradually decreases until it reaches zero. Both the voltage difference graph and the individual cell voltage graph show good voltage consistency of the cell stack.

The impedance variation during the shutdown and purge process after operation is shown in Figure 7. The purge process lasts for about 200 seconds, with the highest purge impedance reaching 1082 mΩ.

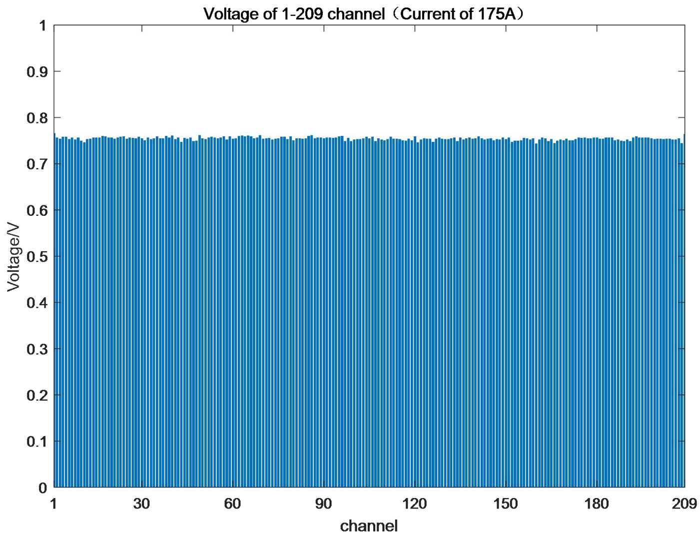

Figure 6 The Voltage and Current Curve, Coolant Temperature Curve, Voltage Range Curve during startup at -30℃

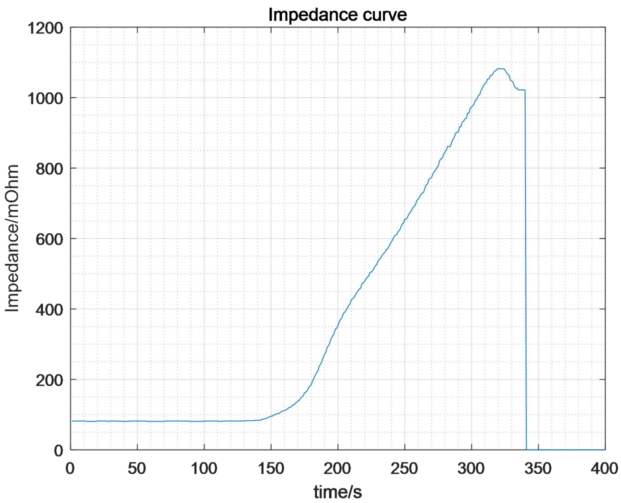

Figure 7 The Voltage and Current Curve, Coolant Temperature Curve, Voltage Range Curve during startup at -30℃

5 CONCLUSION

This paper designs a fuel cell integrated system for low-temperature cold start and verifies the correctness and effectiveness of the startup strategy used in this paper through simulation and experiments. The results show that rapid continuous loading at a rate of 3.75A/s is conducive to heat generation in the stack and the increase in coolant temperature, and enables successful cold start at -30℃. Of course, there are also shortcomings in this paper. For example, the subsequent simulation analysis can be more quantitative rather than limited to qualitative analysis.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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