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Juexiao Chen, Yinhao Yang, Chang Du, Ziheng Gu, Tiancai Ma

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Experimental study on cold start strategy of high-power fuel cell system

Juexiao Chen*, Yinhao Yang, Chang Du and Ziheng Gu

School of Automotive Studies,
Tongji University,
Shanghai, 201804, China
Email: chenjuexiao@tongji.edu.cn
Email: 3039822027@qq.com
Email: duchang@tongji.edu.cn
Email: 976850281@qq.com
*Corresponding author

Tiancai Ma

School of Automotive Studies,
Tongji University,
Shanghai, 201804, China
and
Carbon Neutrality Research Institute,
Tongji University,
Shanghai, 201804, China
Email: matiancai@tongji.edu.cn

Abstract: With the gradual popularisation of clean energy, proton exchange membrane fuel cells (PEMFCs) have received widespread attention as a good way to apply hydrogen energy. Freezing during start-up of fuel cells in low-temperature environment can cause a series of problems, such as clogging of porous electrodes, obstruction of reactant gas transport, etc. leading to the failure of fuel cell start. Therefore, it is of great research significance to improve the stability and speed of cold start of proton PEMFC without heat source assistance. However, at present, most experimental research on cold start of fuel cells is focused on single cell or low-power stack. In this study, we will conduct start experiments at -5°C ~ 25°C based on a 130 kW fuel cell power system. The results showed that with the current loading slope 3A/s, the cooling water pump speed 3,000 rpm, the minimum time for automatic purging 50 s, the maximum time for purging 500 s, the impedance real part threshold for purging 750 m Ω , and a manual purge of the air and hydrogen circuits performed before starting, the system used in the study can successfully start at -25°C and then run to a stable operating point.

Keywords: proton exchange membrane fuel cells; high-power fuel cell system; cold start strategy at -25°C .

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Biographical notes: Juexiao Chen is an Associate Professor at the School of Automotive Studies, Tongji University, focusing on research in fuel cells and automotive electronics.

Yinhao Yang is a Master's student at the School of Automotive Studies, Tongji University, working on the issue of fuel cell cold start in the research group.

Chang Du is a Doctoral student at the School of Automotive Studies, Tongji University, specialising in low-temperature cold start of fuel cells.

Ziheng Gu is a Doctoral student at the School of Automotive Studies, Tongji University, studying voltage consistency during the cold start of fuel cell systems.

Tiancai Ma is a Professor at the School of Automotive Studies, Tongji University, with years of experience in fuel cell development and testing.

1 Introduction

Proton exchange membrane fuel cells (PEMFCs) have many advantages, such as high-power density, high efficiency, and low emissions. And they have been developed rapidly and applied in various fields (Wang, 2015; Veziroglu and Macario, 2011). However, if the external temperature is below zero, the product water of PEMFC will change into ice and occupies the pores of the porous layers, obstructs the transportation of reactant gas and then causes start failure (Dursch et al., 2014; He et al., 2020); this has become a crucial factor hindering the commercialisation of PEMFC. The cold start of PEMFC involves starting the fuel cell from sub-zero temperature and running to operating temperature. During this period, the heat and ice generated by the fuel cell compete with each other. If the temperature of the fuel cell fails to rise above freezing point before the ice covers reaction zone, it will stop working and the cold start will fail. This will result in irreversible loss to components and performance of PEMFC, therefore it is necessary to study how to perform cold start successfully and minimise performance degradation and structural damage.

So far, in order to solve the problem of freezing during the cold start process of fuel cells, experimental studies have been conducted both domestically and internationally on the low-temperature cold start of PEMFCs, including research on start strategies, current loading methods, etc.

The cold start strategy of fuel cells is divided into self-start strategy and auxiliary-start strategy. The self-start strategy utilises the heat released by electro-chemical reaction inside the fuel cell for heating. Common self-start methods include constant current start and constant voltage start. The auxiliary-start strategy refers to the use of external heat sources to assist for achieving successful cold start. There are many ways to achieve external heat sources, including adding heaters, (e.g., PTC), circulating coolant heating, preheating gases, and reaction heating. The self-start strategy can avoid the complexity and power consumption caused by auxiliary heating system, which can also reduce time of cold start. The research on self-start strategy is as follows.

Yan et al. (2006) used a current density of 100 mA/cm² and successfully start the single cell at -10°C, but the cold start failed when the starting current was increased to

200 mA/cm². Oszipok et al. (2006) conducted cold start experiments based on a 6-cell stack and found that the initial water content of the fuel cell should not be too low, otherwise the fuel cell will not be able to generate more heat during the cold start process. Jia et al. (2014) conducted a study on the cold start performance of a 2-cell stack and found that the fuel cell can successfully start at -5°C , and a higher initial water content helps to improve the cold start performance of PEMFC. Tajiri et al. (2006) conducted constant temperature cold start experiments on single cell, quantified the cold start performance using cumulative water production, and measured the output voltage changes of fuel cell at different starting current densities. The results indicate that a higher starting current density is more likely to cause fuel cell cold start failure. Lin et al. (2014) applied partition current monitoring technology to monitor the current density and temperature distribution during the cold start process of fuel cell single cell in real time, and they found that the self-start performance of fuel cells can be improved by reducing the initial current density. Lin et al. (2019) analysed the cold start characteristics and decay mechanism of a 5-cell stack at different temperatures, and found that the fuel cell had good cold start performance at -5°C and -10°C ; by reducing the starting voltage, a successful cold start at -15°C can be achieved; but the fuel cell failed to start at -20°C .

It can be seen that the current experimental research results are mainly based on single cell or low-power stacks, and there is little research on cold start strategies for high-power fuel cell systems. There are hundreds of single cells in high-power integrated fuel cell system. Due to the different positions of the single cells in the stack, their temperature field distribution, voltage distribution, and reaction gas distribution during cold start process will vary greatly. This leads to significant differences in the consistency between high-power systems and single cell or low-power systems, and the cold start characteristics may differ greatly. Therefore, research results on single cell or low-power systems cannot be directly applied to high-power systems. Therefore, it is necessary to design and develop a cold start scheme for high-power fuel cell systems and conduct cold start experiments on them.

In this study, we will perform cold start experiments at different low temperatures based on a 130 kW fuel cell system and a temperature-adjustably environmental chamber. By adjusting various operating parameters such as current loading slope and adjusting the purge strategy, we have successfully achieved cold start of high-power fuel cell systems at -25°C , and we also analysed the voltage and current change and voltage consistency during the start-up process. This is of great significance for the research of fuel cell cold start.

2 Experimental

2.1 Experimental setup

The experimental setup used in this study mainly consists of a temperature-adjustable environmental chamber and a 130 kW fuel cell integrated power system.

2.1.1 Environmental chamber

The physical image of the environmental chamber is shown as Figure 1. The environmental chamber is of good tightness and thermal insulation performance. The

temperature is adjustable between -35°C and 60°C . There are several cooling fans on the ceiling in the environmental chamber, as shown in Figure 2, which can be used to reduce the temperature inside the chamber. There are also hydrogen and air supply pipelines in the chamber to supply fresh reaction gases to the system. And there is an exhaust system in the chamber to discharge unreacted gases and generated water. Figure 3 shows the control interface of the chamber, which can adjust the temperature inside the chamber by inputting parameters and monitor relevant situations inside it.

Figure 1 Environment chamber (see online version for colours)



Figure 2 The cooling fan (see online version for colours)



Figure 3 Control interface of the chamber (see online version for colours)



Figure 4 The 130 kW fuel cell system (see online version for colours)



2.1.2 Fuel cell integrated system

As shown in Figure 4, the fuel cell system module consists of a stack, an air supply system, a low-pressure hydrogen supply system, DC/DC, and a cooling system (shared). Batteries are used for storing electrical energy in fuel cells. To achieve a net rated output power 130 kW of the fuel cell system, the rated output power of the fuel cell stack should be 180 kW.

The fuel cell stack consists of 418 single cells, and the air supply system consists of an air filter, an air flow meter, a temperature-humidity-pressure integrated sensor, an air compressor, an intercooler, etc. The hydrogen supply system consists of a medium pressure solenoid valve, a proportional valve, a hydrogen circulating pump, a hydrogen concentration sensor, a temperature sensor, a water heater, etc. The cooling system consists of a circulating water pump, an expansion tank, an electronic thermostat, etc. The system uses 50% glycol solution as coolant.

2.2 Experiment procedure

The 130 kW fuel cell system cold start-up experiment will be performed as follows.

- Set the temperature of the environmental chamber to a specific temperature and place the fuel cell system in it for more than 12 hours.
- After the thermal insulation work is completed, open the high-voltage and low-voltage loads (600 V/24 V) and open the hydrogen inlet valve, and check for any H₂ leakage at the valve.
- After all preparations are completed, open the PC interface of the fuel cell system, as shown in Figure 5, and then send a cold start command to the fuel cell system. Then the control unit performs a self-check on the fuel cell system, checking the state and communication of system components such as the air compressor, hydrogen circulating pump, and water pump for normal operation. Then the cold start program will be executed. The water pump, drainage valve, hydrogen supply module, and air compressor work in sequence. Then loading is conducted. During the preheating process, as the coolant temperature increases, the system power gradually increases to the set power.

- After the system runs stably at the set power for a period of time, execute the shutdown procedure. Afterwards, the load of the fuel cell stack decreases to the idle load, and the purging procedure begins. Dry air/H₂ is used to purge the air/hydrogen pipelines separately, removing any remained water and preparing for the next cold start. During the shutdown-purging process, the coolant temperature maintains a relatively high level, and the minimum shutdown-purging time is set to 30 s, the maximum shutdown-purging time is set to 500 s, and the real part threshold of the shutdown-purging impedance is 750 m Ω .
- After the purging is completed, close the hydrogen inlet valve and the high-voltage and low-voltage loads. Keep the fuel cell system at a set temperature for another 12 hours until the next cold start experiment begins.

2.3 Experiment results and discussion

2.3.1 Performance calibration at room temperature

Before starting the cold start experiment, we need to calibrate the performance of the 130 kW system at room temperature (25°C). At debug mode, the loading process is conducted by constant current mode with loading current of 0A, 66 A, 99 A, 132 A, and 165 A. The system will run at each operating point for 3 minutes, and we take stable values as the calibration values, as shown in Table1. The total voltage of the fuel cell stack, the average cell voltage of the fuel cell stack, and the range of cell voltage at each operating point are shown in Figures 6(a), 6(b), and 6(c).

Figure 5 The PC interface (see online version for colours)

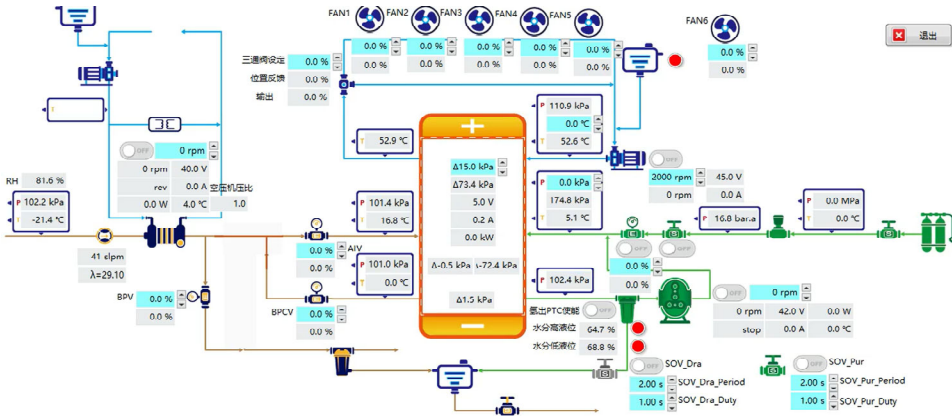
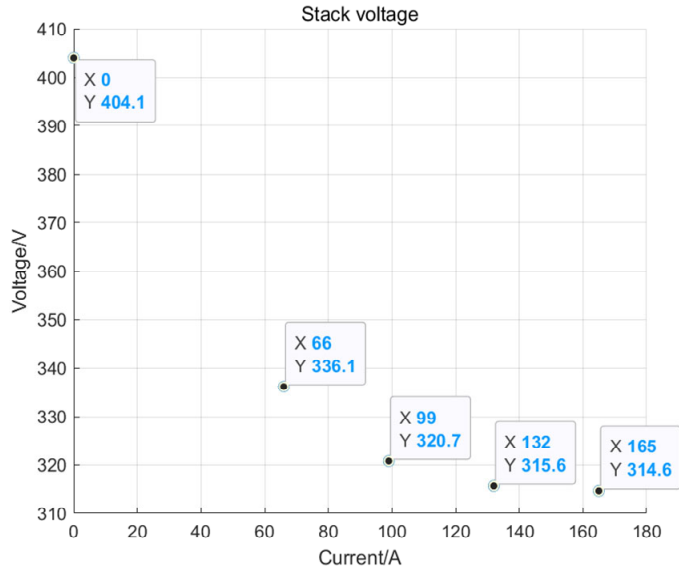


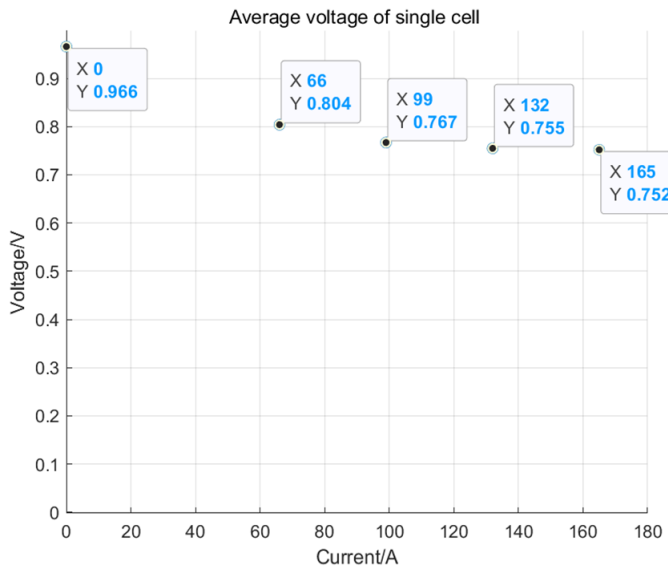
Table 1 Reference value of operating parameters at manual mode

Current density /(mA/cm ²)	Loading current /(A)	Stack voltage /(V)	System power /(kW)
200	66	332	20.02
300	99	319	29.25
400	132	315	38.4
500	165	315	47.8

Figure 6 (a) The total voltage of the fuel cell stack, (b) The average cell voltage of the stack, and (c) The range of cell voltage at each operating point (see online version for colours)

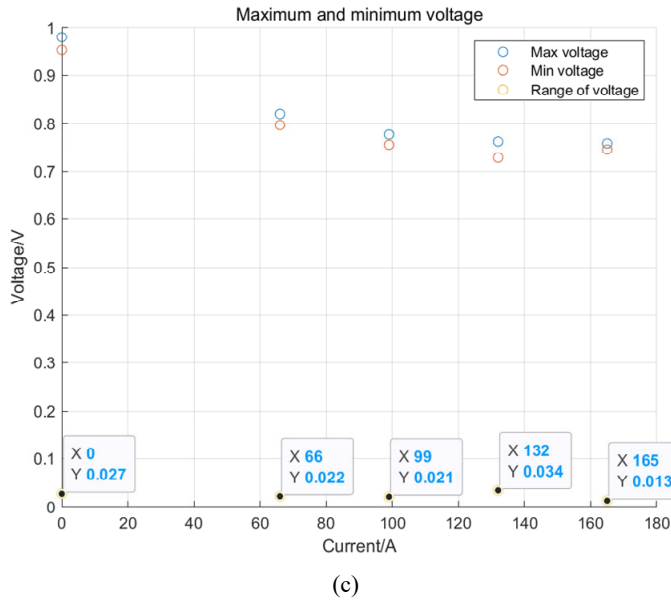


(a)



(b)

Figure 6 (a) The total voltage of the fuel cell stack, (b) The average cell voltage of the stack, and (c) The range of cell voltage at each operating point (continued) (see online version for colours)



2.3.2 Ambient temperature at -5°C

Before the experiment began, the system has been placed in the environmental chamber for more than 12 hours, and the PC displayed the coolant inlet and outlet temperature of -6°C , the relative humidity is 49.20%. When starting for the first time, set the target power of 40 kW and follow the start process mentioned in 2.2. After one min, the CVM of the fuel cell stack displays that the voltage of 180–190 cells is lower than the others', and the FCU appears an error state. The low voltage of the cells causes the shutdown and the cold start failure.

The system is left idle until the coolant temperature drops back to -6°C . The target power is set to 17.5 kW, and a start command is sent again. The coolant temperature gradually rises to 0°C within about 60 seconds. Due to instantaneous loading, there is a small voltage dip, and then the voltage gradually stabilises. The system runs stably at the target power for about three minutes, which proves that the cold start is successful. Then, the shutdown program is executed. The voltage and current curves, and the temperature at the coolant inlet and outlet during the startup process, are shown in Figure 7.

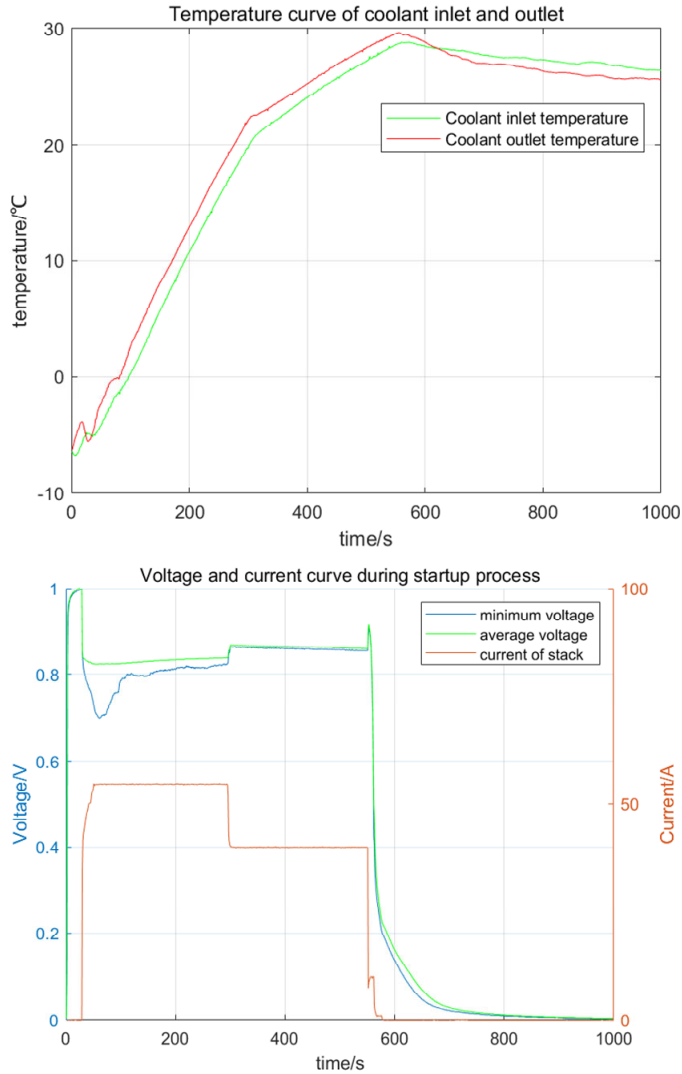
The result shows that during cold start, it is not possible to load a high power directly, which can easily lead to a locally low voltage in the fuel cell stack and poor system performance, resulting in cold start failure. Therefore, the starting loading power should be appropriately reduced.

2.3.3 Ambient temperature at -15°C

At the beginning of the experiment, PC displays an ambient temperature of -15.1°C and a relative humidity of 64.8%. As shown in Figure 8(a), the loading method is step

loading, gradually loading to 132 A within 200 s, then the system runs stably for about 130 s, and then continues step loading. The loading stops at 169 A, and the system runs stably for about 110 s. As shown in Figure 8(b), during the loading process, the inlet and outlet temperature of the coolant rises from -14°C to 0°C within 43 s (10 s to 53 s), and to 61°C within 210 s, with a temperature rising rate of about 0.33°C/s . Then the system tends to stabilise, fluctuating within a small range.

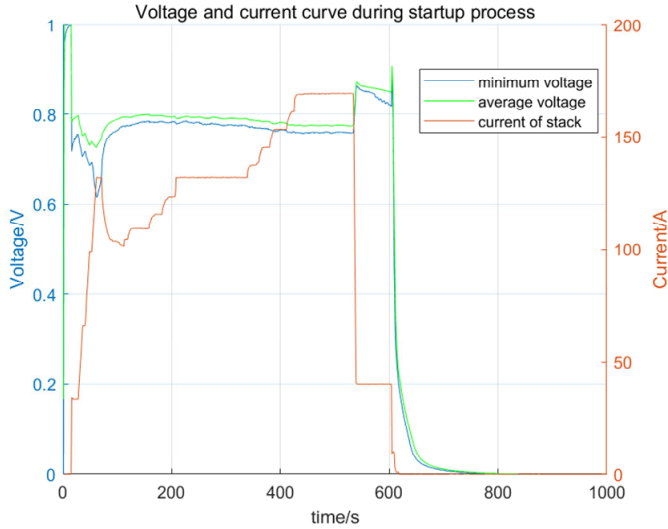
Figure 7 The voltage and current curves, the temperature at the coolant inlet and outlet when start at -5°C (see online version for colours)



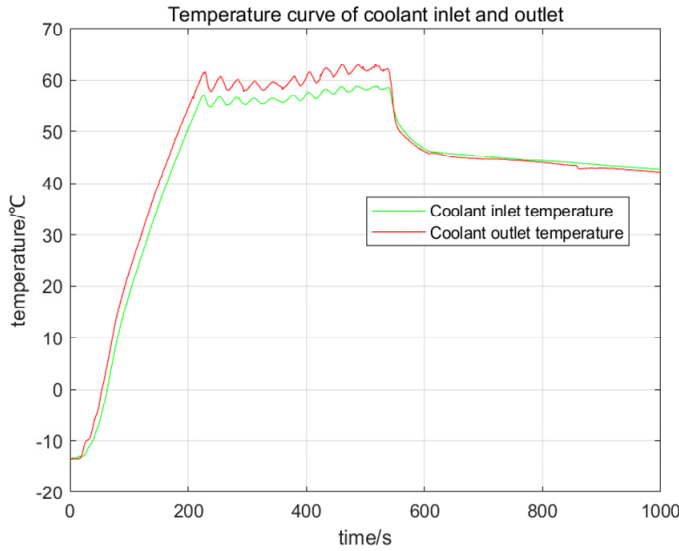
Similar to the voltage change at -5°C , there is also a small voltage dip during instantaneous loading, but the voltage at -15°C will quickly recover to a stable level. At 533 s, the shutdown procedure, i.e., the load reduction process is executed. And the non-auxiliary cold start at -15°C is also successful. The high-frequency impedance curve

of the whole process is shown in Figure 8(c). In the initial stage, the impedance decreases due to the gradual hydration of the proton exchange membrane as the internal reaction of the cell progresses. During the shutdown-purging process, the impedance increases because residual water inside the cell is removed, causing the membrane to gradually dry and the impedance to rise, reaching approximately 142 m Ω .

Figure 8 (a) The voltage and current curve, (b) The temperature curve and (c) The impedance curve when start at -15°C (see online version for colours)

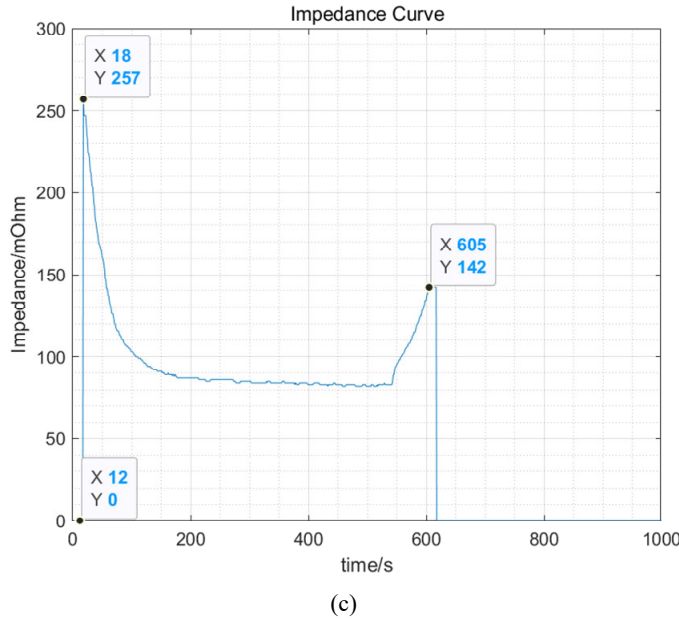


(a)



(b)

Figure 8 (a) The voltage and current curve, (b) The temperature curve and (c) The impedance curve when start at -15°C (continued) (see online version for colours)



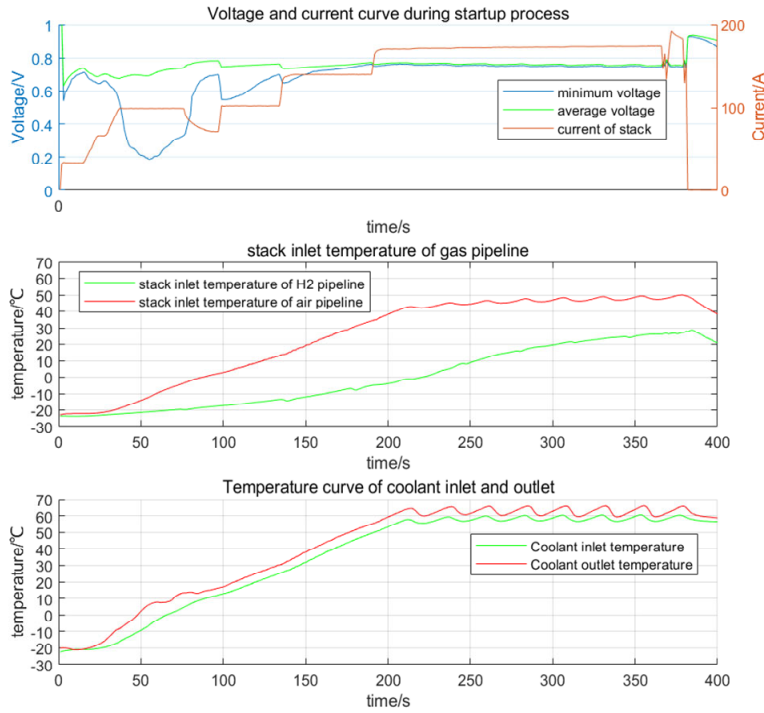
2.3.4 Ambient temperature at -25°C

The system has been placed in the environmental chamber at -25°C for 12 hours, the relative humidity is 71.2%, and the coolant outlet/inlet temperature is $-25.2/-25.3^{\circ}\text{C}$. To achieve self-start without auxiliary heat source at -25°C , various operating conditions need to be adjusted to find the optimal combination of parameter. First, set the current loading slope 5 A/s, cooling water pump speed 2,000 rpm, minimum/maximum shutdown-purging time 30 s/500 s, real part threshold of impedance during shutdown-purging 750 m Ω , startup power 40 kw in the cold start program variables, and then send a start command. OCV is 452 V. Then conduct the preheating loading program.

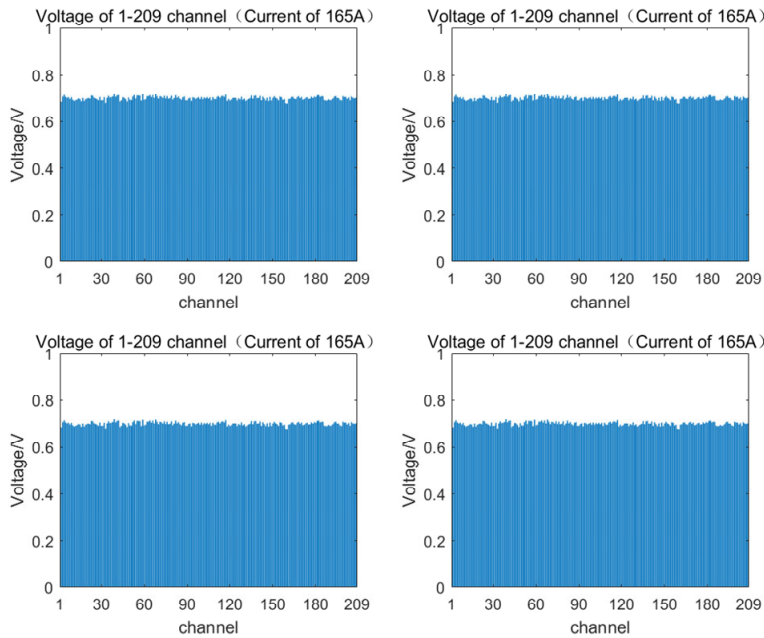
As mentioned earlier, the system has 418 single cells. In order to simplify the data calculation, every two single cells are taken as a channel. When the loading current is 99 A, the voltage of channel 209 and channel 1 is too low. Especially, the voltage of channel 1 is below 0.15 V and continues to drop below 0.1 V, causing the system to shut down and cold start to fail. At this time, the outlet and inlet temperature of the fuel cell coolant are $-15.7^{\circ}\text{C}/-6.2^{\circ}\text{C}$.

Then try starting again at -25°C , keeping all other conditions unchanged, increase the water pump speed to 3,000 rpm, reduce the startup power to 30 kW, and send the start command. OCV has not been established yet, and PC shows HRB fault. The analysis suggests that the cause may be the freezing of the hydrogen circulating pump. Instead of power loading, we attempted to use current loading method with current of 33 A and 99 A. However, we found that there was still a phenomenon of emergency shutdown due to low voltage of single cell. We analysed that the residual water was not completely removed during shutdown-purging, so we added a manual purging process during the next startup.

Figure 9 (a) The voltage, current and temperature curves, and (b) The voltage of all channels when start at -25°C (successful startup) (see online version for colours)



(a)



(b)

Before starting, set the automatic program variables: current loading slope 3 A/s, cooling water pump speed 3,000 rpm, minimum/maximum shutdown-purging time 50 s/500 s, maximum shutdown blowing time of 500 s, and real part threshold of impedance during shutdown-purging 750 m Ω . It can be seen that we have reduced the slope of current loading, increased the minimum purging time. And PC displays the relative humidity as 58.4%. Then switch the FCU working mode to debug mode on the PC control interface, set the water pump speed to 3,000 rpm, the air/H₂ pressure difference to 15 kPa, and the air compressor speed to 40,000 rpm. Open the bypass valve and back pressure valve, then open the proportional valve, and start manual purging. After purging for seven minutes, restart the system and OCV is 410 V. First, loading from 30 kW to 40 kW, then reduce the load to 20 kW, and then load to 30, 40, and 50 kW in sequence. The system starts successfully. The current voltage curve of the successful start-up process is shown in Figure 9, and the consistency of single cell voltage during successful start-up is shown in Figure 9. It can be seen that the consistency of the fuel cell stack is relatively good, and there is no obvious phenomenon of low cell voltage.

As can be seen from the above, the relative humidity at which the fuel cell can successfully start at -25°C (58.4%), is lower than that at which the start fails (71.2%). The higher the relative humidity, the more moisture inside the fuel cell, and the greater risk of freezing. When the relative humidity approaches saturation, water is more likely to form ice crystals in the cathode catalyst layer and flow channels, covering the active surfaces and reducing the diffusion pathways for the reactant gases. Under low-temperature conditions, if the relative humidity is high, the water inside the fuel cell is more likely to freeze, leading to a failed cold start.

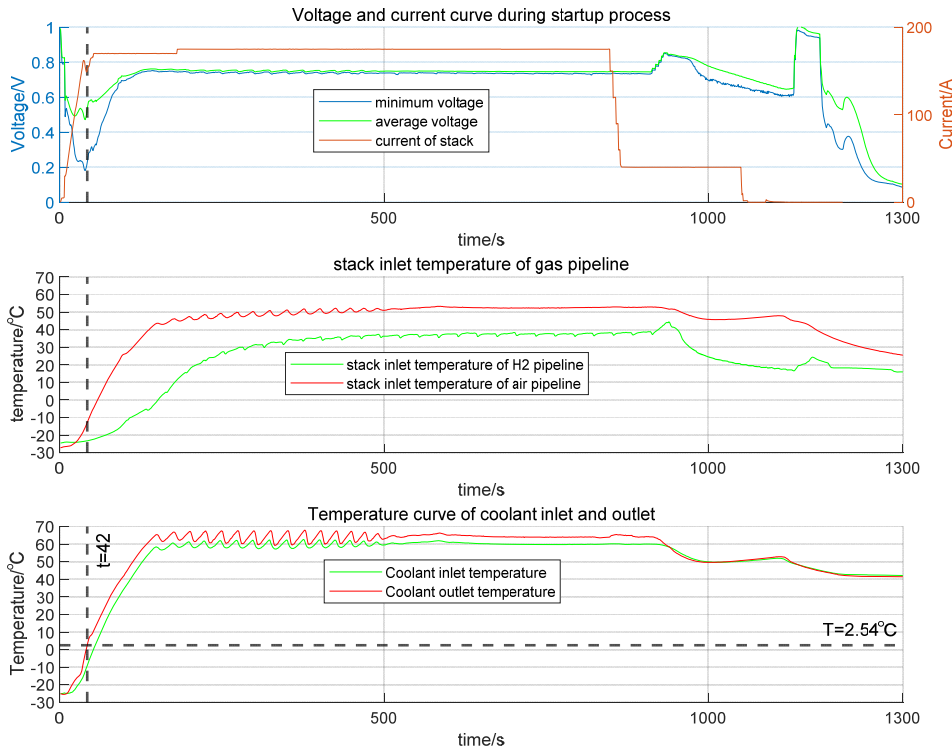
2.3.5 Ambient temperature at -30°C

Before the experiment began, the coolant outlet/inlet temperature was $-28.3/-29.0^{\circ}\text{C}$, and the system stayed at -30°C for more than 12 hours. The -30°C experiment uses the manual loading start strategy. Adjust the system to Debug mode, set the hydrogen/air pressure difference to 15 kPa, open the medium pressure valve and proportional valve, set the HRB to 5,000 rpm, set the drainage valve opening cycle to 1 s/30 s, set the nitrogen discharge valve opening cycle to 0.5 s/40 s, set the water inlet temperature to 60°C , set the water pump to 3,000 rpm, set the air compressor to 40,000 rpm, set the bypass valve to 100%, turn on the air compressor and HRB.

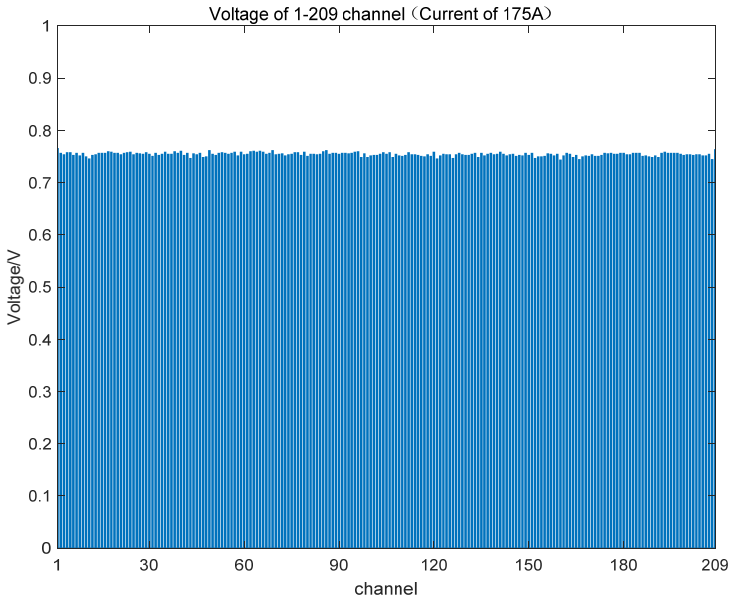
After one minute, set the DCF input current limit to 175A, open the air inlet valve and back pressure valve to 100%, close the bypass valve to 0%, open the water/N₂ drainage valve, turn on the DCF input contactor and DCF enable, and prepare to start. After one minute, adjust the DCF target values of 5 A and 30 A in sequence, then manually increase the loading current. During the rapid loading period, the voltage of end-plate cell is relatively low, which is 0.188 V. The lowest voltage occurs when the current is around 160 A. Then reduce the current appropriately, and the voltage of end-plate cell rises, finally reaching 170 A. The cold start at -30°C is successful.

Then adjust the back pressure valve to 22%, set the opening cycle of the drainage valve to 3 s/30 s, set the HRB to 4,000 rpm, and set the air compressor to 48,000 rpm. The water pump is set to 3,600 rpm. Change the current limit of DCF to 180 A, continue manually increasing the load to 175 A. The system maintains stable operation for about 10 minutes. The cold start at -30°C is successful.

Figure 10 (a) The voltage, current and temperature curves, and (b) The voltage of all channels when start at -30°C (successful startup) (see online version for colours)



(a)



(b)

Adjust the DCF target value and start reducing the load from 175 A to 40 A in step of 30 A, then the purging process is started. The inlet water temperature is set to 50°C, the water pump is set to 3,000 rpm, the HRB is set to 3,000 rpm, the opening cycle of drainage valve is set to 1 s/2 s, the back pressure valve is adjusted to 100%, and the air compressor is set to 50,000 rpm.

After three minutes, the impedance reaches a maximum of 1,082 m Ω , and adjust the DCF target value to 10 A and 0 A in sequence. The bypass valve of the air circuit is opened, and the hydrogen circuit was closed. The stack was discharged through an electric relay, the voltage gradually decreases, and the system is shut down.

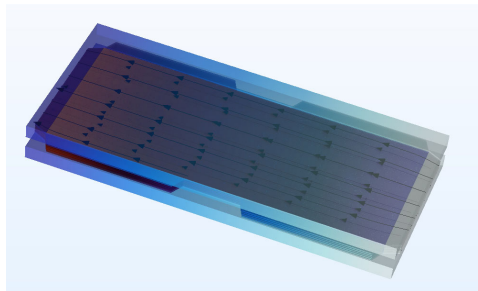
The system starts successfully. The current voltage curve of the successful start-up process is shown in Figure 10, and the consistency of single cell voltage during successful start-up is shown in Figure 10. It can be seen from Figure 10(a) that in the cold start experiment at -25°C, the current loading method is a stepwise loading with a relatively slow loading rate. In contrast, in the cold start experiment at -30°C, the current is rapidly loaded from 0 to around 170 A within 40 seconds. During this process, a large amount of heat is generated, which is sufficient to support the electrochemical reactions inside the fuel cell. This increases the rate of temperature rise, ultimately leading to a successful cold start. It can be seen from Figure 10(b) that the consistency of the fuel cell stack is also good, and there is no obvious phenomenon of low cell voltage.

2.3.6 Analysis of the heat transfer process during cold start

This study employs the simulation environment provided by AVL-Cruise M and COMSOL6.3 software to build the model. For convenience, the following assumptions are made for the model:

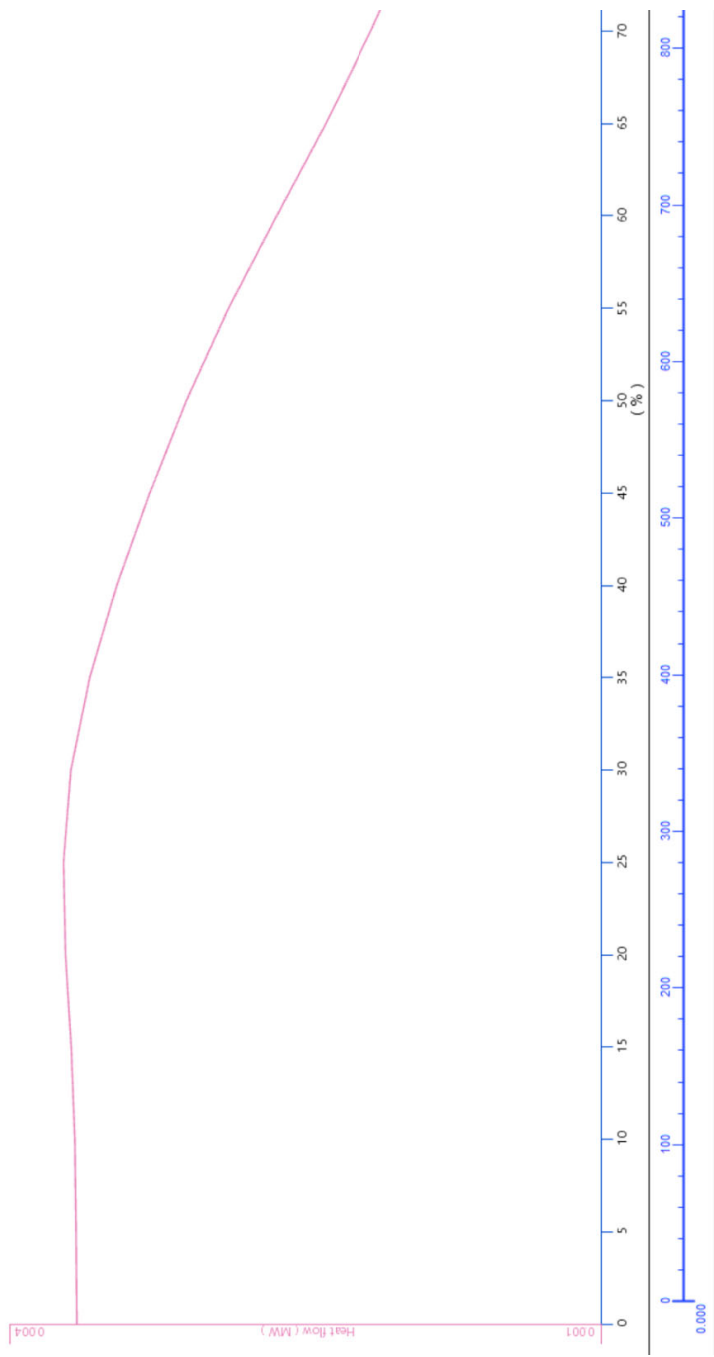
- 1 All gases are considered as ideal gases.
- 2 Only the diffusion of heat and mass in the direction perpendicular to the plane is taken into account.
- 3 The internal pressure variations within the fuel cell are neglected.
- 4 It is assumed that the heat exchange between the fuel cell stack and the external environment is uniform.

Figure 11 The thermal conduction and the flow chart during the cold start-up process at -25°C, (a) the thermal conduction during the cold start-up process at -25°C, (b) the flow chart during the cold start-up process at -25°C (see online version for colours)



(a)

Figure 11 The thermal conduction and the flow chart during the cold start-up process at -25°C , (a) the thermal conduction during the cold start-up process at -25°C , (b) the flow chart during the cold start-up process at -25°C (continued) (see online version for colours)



(b)

Based on the structure of the fuel cell stack, the model is established and simulated in the software. The structure of the stack: 418 single cells, the reaction active area of a single cell 330 cm², thickness of membrane 8 μm, thickness of bipolar plate 2 mm. The flow field is designed as a parallel flow field. The simulation results are shown in Figure 11.

During the cold start process, the heat generated by the reactions is first produced in the MEA, and then transferred to the surrounding areas through the GDL and bipolar plates. Since the GDL has a relatively high thermal conductivity, the heat is rapidly transferred from the cathode catalyst layer to the GDL, and then diffused outward through the bipolar plates. As the low-temperature reactant gases (hydrogen and air) flow through the flow channels, they undergo convective heat transfer with the fuel cell stack, carrying away a portion of the heat. The end plates of the fuel cell stack are in contact with the cold external environment, leading to faster heat dissipation, especially for the cells near the end plates, whose temperature rise is significantly slower than that of the cells in the middle of the stack.

2.3.7 System degradation before and after multiple repeated cold start experiments

Multiple cold start experiments have been conducted on this 130 kW fuel cell system, and freezing-melting cycles may have an impact on the cell structure and performance. Therefore, after completing all the cold start experiments, a performance degradation test of this fuel cell stack should be conducted. Restore the temperature of the environmental chamber to 9°C and the humidity to 56% RH. First, turn the water pump for raising the water temperature to the same level as the ambient temperature. Then, set the starting power to 20 kW to warm up the system.

After the system is started up, set the target power to 30 kw to quickly raise the water temperature and run stably for three minutes, ensuring the consistency of internal temperature of the stack. Then the system executes an automatic shutdown program. Manually conduct loading based on calibration parameters and compares the performance degradation of the stack under different current density. Run the system for three minutes at each operating point, taking some stable value as a reference. And the operating values after cold start experiments is shown as Table 2, compared to Table 1, there is nearly no performance degradation, which to some extent indicates that the cold start strategy adopted in this study has almost no impact on operation life of this 130 kW fuel cell stack.

Table 2 Reference value of operating parameters at manual mode after cold start experiments

Current density /(mA/cm ²)	Loading current /(A)	Stack voltage /(V)	System power /(kW)	Stack degradation /(%)
200	66	334	19.84	0.60
300	99	325	29.79	1.88
400	132	315	38.53	0
500	165	314	47.72	-0.32

3 Conclusions

This study investigated the cold start of a high-power fuel cell system without auxiliary heating; including performance, start up strategies, operating parameters at -5°C , -15°C , and -25°C . A group of starting up experiments were conducted. And the conclusion is as follows.

- During cold start at -5°C , the target power should not be too high, otherwise it will cause locally low voltage inside the stack to be too low, resulting in cold start failure. As long as the loading power is proper, there will be no problem with cold start at -5°C .
- Cold start at -15°C of this system is also successful, and the coolant temperature rises above 0°C within 43 seconds, with a temperature rising rate of 0.33°C/s .
- Cold start at -25°C requires adjusting the operating parameters and adding a manual purging process to remove the water inside the pipeline. By adopting a strategy of loading-unloading-reloading, the system can successfully start with good voltage consistency.
- Cold start at -30°C requires manual quick loading, leading to a rapid increase in current and heat generation.
- This study also compares the performance degradation of the fuel cell stack before and after multiple cold start experiments, and the result shows that the impact of multiple cold starts on the performance and life of the fuel cell stack is nearly negligible.

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