

Research on Thermal Management System of Advanced Proton Exchange Membrane Fuel Cells in Fuel Cells

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Abstract:

This paper takes proton exchange membrane fuel cell system as the research object. The working mechanism of each component in the system is also studied. A mathematical model of dynamic thermal management of reactor based on the theory of functional conservation is proposed. This project proposes an optimal quadratic programming algorithm based on Lyapunov function, and solves it with iterative algorithm. By using MATLAB/Simulink simulation analysis method, the calculation model of reactor voltage, cathode, proton exchange membrane, anode temperature and other parameters is established. Simulink/Simscape modeling software was used to simulate it. These two models are integrated to form a comprehensive battery simulation model. The operating characteristics of the fuel cell were studied under various failure modes. The simulation results of PEMFC are in agreement with the experimental results. The results show that the method is reasonable. Through the simulation of its failure process, people can understand its failure mechanism more clearly. The research results of this paper have certain guiding significance for the fault diagnosis of the motor.

Keywords: Proton Exchange Membrane Fuel Cell; Thermal Management System; Simulink/Simscape; Modeling; Fault Simulation.

INTRODUCTION

Heat dissipation control of proton exchange membrane fuel cells (PEMFCs) is an important step in ensuring that they operate in an ideal working environment [1]. If the heat dissipation of the battery is not well controlled, the battery's operating efficiency will be reduced, or even the battery will be damaged [2]. PEM refers to a new type of battery in which hydrogen and oxygen are reacted under the synergistic action of a catalyst. Hydrogen dissociates into hydrogen and electrons at the anode. When hydrogen moves to the cathode under the action of the proton exchange membrane, a current is formed through the charge transfer on the electrode surface. In the cathode, hydrogen reacts with oxygen and electrons to form water. Due to its chemical reaction, about 30% of the electricity is converted into heat energy, which causes it to release a lot of waste heat during operation. If it is processed and dissipated, it will cause its temperature to rise, reduce its service life, and even cause damage [3].

The ADVISOR2002 simulation software was programmed using Matlab and Simulink. The method includes two modes. One is a simplified fuel cell system simulation with pure output as the variable. This method assumes that a certain amount of fuel can produce a specified net work independent of the system complexity. The second modeling method is similar to the first simulation calculation method, but its calculation results are based on polarization curves, the number of monomer units and the fuel required for the monomer unit. Ancillary equipment such as compressors, fuel pumps, cooling fans and battery packs are independent. The disadvantage of the ADVISOR model is that it does not include control of heat and moisture, and cannot show the heat exchange with other vehicle components. GC Tool is an open source tool available for use, programmed in C. The product consists of a variety of fuel cells and components, such as reformers, condensers, pumps, nozzles, etc. The software has its own thermodynamic characteristics database, which can customize the system configuration of various components as needed to achieve steady-state and dynamic simulation. Easy5 is similar to GCTool and has its own component library, including battery stacks, reformers, gas cleaning equipment, power supply equipment, and system flow and thermal models. This method has the advantages of being able to optimize and minimize each component, but it does not have its own thermodynamic characteristic database. In the FEMLAB software, a fuel cell modeling software based on Matlab is included. This mode is a steady-state 2D mode, and also includes a 3D mode of a single unit, which can provide a detailed model for the heat transfer and material transport behavior of the system.

It needs to be modeled to realize the numerical simulation of its characteristics. In addition, it can also provide a basis for the formulation of the control scheme of the system when the dynamic characteristics are predicted [4]. The steady-state mathematical model of PEMFC can describe its working condition well, and the dynamic behavior of PEMFC is particularly critical in the actual situation [5]. Through the dynamic modeling of the unit start-stop, the function of each parameter during the unit operation period is studied, and the reaction speed under load fluctuation is shortened. This model has been improved by relevant literature [6] and experimental data. The performance, dynamic thermal response and water consumption control of

the battery were studied in literature [7]. Literature [8] analyzes the interaction between the gas supply and the stack, and gives some important influencing factors that can help improve the working efficiency of the battery to the greatest extent. Reference [9] developed a computer simulation software GC for fuel cell system design and analysis. At present, the dynamic modeling of fuel cells is relatively rare, and literature [10] mainly focuses on the temperature dynamic characteristics of its surface. Literature [11] added the dynamic characteristics of the positive and negative flow fields, and established a dynamic model at the system level. In literature [12], a dynamic modeling method including three dynamic behaviors (including temperature change of fuel cell itself, change of flow field of runner and double-layer charging effect) was established, and Simulink was used for simulation. Literature [13] decomposed fuel cells into three controlled subjects and integrated them with related theories and experiments to build a complete dynamic model. However, the existing mathematical modeling methods are relatively simple, and do not fully consider the influence of dynamics, and need to be further studied. Compressor is the most energy-consuming auxiliary power unit, and its matching with air system and operation optimization have become the focus of scholars at home and abroad. Literature [14] compared the advantages and disadvantages of high voltage and low voltage. At the same power, the parasitic power of low voltage is small, the efficiency is high, and the volume is large, the light specific power is small. The opposite is true for high voltages. At low voltage, its dynamic characteristics are slightly better than that at high voltage, and its hydrodynamic characteristics are better than the latter. Under normal circumstances, the operating pressure has a great impact on its operating characteristics, so when selecting the excess air coefficient, fuel economy and power characteristics should be considered at the same time. The dynamic characteristics of air compressor is one of the key indicators that determine the overall performance of air compressor. BIRD of the University of California, United States, analyzed the time constant of the air system and compared the dynamic characteristics of the air system in high- and low-pressure systems. In literature [15], a set of mathematical models of the stack-air-battery coupling system applicable to the device was constructed to study the variation law of the mass and water of the anode and cathode poles of the battery under different working conditions, and its dynamic behavior was simulated to finally form a relatively complete mathematical model of the stack-air system. This method is relatively simple and easy to implement except that temperature is not included in the calculation.

The temperature field in the reactor is the key factor to ensure the smooth electrochemical reaction of PEMFC and the long period operation of PEMFC. At present, the power generation methods of PEMFC mainly include: fuel/oxidation gas preheating, thermal energy generated by electrochemical reaction and electric energy loss generated by internal resistance. Heat is produced continuously during PEMFC operation, and its temperature rises higher and higher as time goes by, which requires effective heat dissipation. The time constant and hysteresis phenomena of the step characteristics are also different for the reactors under different load states. From the perspective of practical application, literature [16] establishes a dynamic mathematical model that does not need to accurately describe the intrinsic and structural characteristics of the system. A simple heat transfer model of PEMFC stack was proposed in literature [17] to study the influence of operating conditions on the operating characteristics of the battery. The temperature of the stack has a great influence on its output characteristics. If the temperature rise of the stack is too high, it will cause water loss of each layer of film, and it will increase the internal resistance of the stack, resulting in a decrease in the power of the stack. Serious will cause the battery electrode deformation, cracking, adhesion, resulting in permanent damage to the battery. If the temperature is too high, it will have an adverse effect on the electrochemical reaction rate in the pile, and cannot obtain the ideal discharge performance. For this reason, it is necessary to carry out reasonable heat dissipation control of the reactor to make it work in a certain temperature range and make it work under the specified constant temperature conditions. It usually has good power output characteristics near 80 ° C. According to the mathematical model of heat transport of the reactor, the temperature control of the reactor is realized through a reasonable control strategy. The current research is mainly based on the steady-state heat transfer model based on the working mechanism of a single battery, but the existing theories and methods are difficult to apply to the real-time temperature control of the stack, and the control accuracy is not high. Therefore, it is necessary to construct a relatively simple mathematical model of heat transfer and a reasonable control algorithm to achieve more accurate temperature control effect. The model has simple structure and high calculation precision. Simscape modeling adopts the entity structure based on the real system, which does not need to follow the mathematical operation mode of Simulink, and uses the digital-physical information transformation function to realize the organic combination with the general Simulink simulation. In this paper, a fuel cell temperature model was built using Simulink software, and a thermal management system model was established based on Simscape physical modeling platform. The mathematical model of the whole reactor temperature is constructed. A self-tuning method based on linear quadratic programming is used to design the proposed controller.

PEMFC SYSTEM

Fuel cell systems include: fuel cell stack, hydrogen supply system, air supply system, humidity regulation system, thermal management system and control system (Figure 1 cited in Neural Computing and Applications, 2020, 32:10229-10243.). In engineering practice, multiple monolithic units are usually connected in series according to load requirements. The device uses a hydrogen tank to fuel it and injects it into the battery through a pressure reducing valve, allowing it to undergo an electrochemical reaction, while the remaining hydrogen is re-injected into the stack by a hydrogen circulating pump. The gas supply system includes an air filter and a compressor, which transfer oxygen to the fuel cell. The humidification system realizes the control of the moisture inside the battery, and its main device is the humidifier. In order to make the reactor work within an ideal range, its main function is composed of a radiator, a coolant pump, and a coolant box. A lot of heat energy will be released during the operation of the fuel cell, and it must be quickly dissipated by the coolant, otherwise it will cause excessive heat inside the battery, resulting in drying of the diaphragm. The coolant must also be heated at low temperatures to avoid freezing of the chemical reaction products. By controlling the control scheme of various valves, pumps, radiator fans, etc., the supply of gas, water and heat is regulated to ensure the power generation characteristics of the fuel cell.

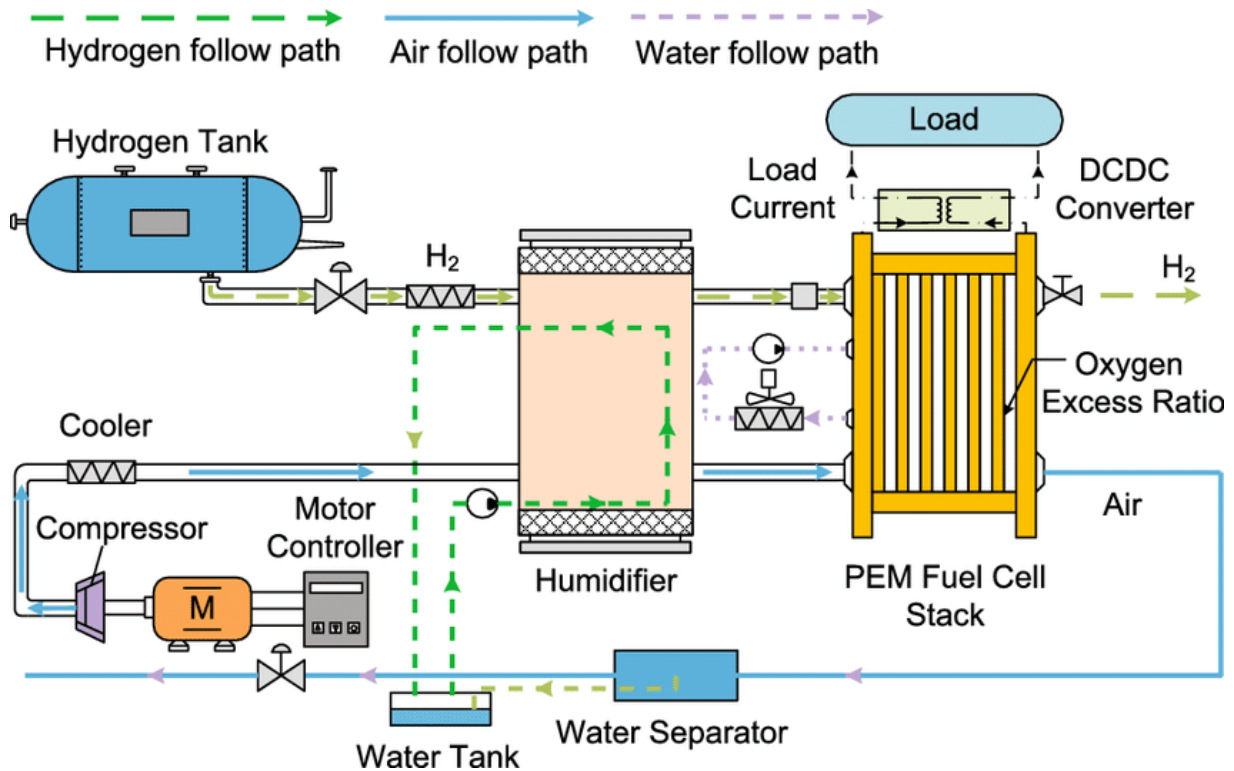


Fig.1 Schematic diagram of fuel cell system composition

$$\begin{cases} S_1 = -\lambda_1 S_1 - \lambda_2 S_1^4 + \eta_1 S_2 + \lambda_3 + \mu_1 \beta_1 + (\mu_2 - S_1) \beta_2 + (\lambda_4 S_1 + \lambda_5 S_1 \ln S_1 + \lambda_6) e \\ S_2 = -\eta_1 S_2 + (\eta_2 - \eta_3 S_2) \rho_w + (S_1 - \mu_2) \beta_2 \\ f = S_1 \end{cases} \quad (1)$$

The cooling water quantity ρ_w is the adjustment of the water intake. f is S_1 the output of the system. The output current e of the stack is measurable because of the load. The internal resistance coefficient β_1 and the heat exchange coefficient β_2 between the reactor and the cooling water are unknown parameters respectively. Where $\lambda_1 \sim \lambda_{16}, \eta_1 \sim \eta_3, \mu_1, \mu_2$ is a constant, in this pattern. Under exceptional conditions, when there is no heat transfer pile.

$$\begin{cases} S_1 = -\lambda_1 S_1 - \lambda_2 S_1^4 + \eta_1 S_2 + \lambda_3 + \mu_1 \beta_1 + (\lambda_4 S_1 + \lambda_5 S_1 \ln S_1 + \lambda_6) e \\ f = S_1 \end{cases} \quad (2)$$

The established thermodynamic system is a nonlinear system with single input and single output with uncertainties and disturbances. A self-regulating controller with stability is proposed for (1). In order to make formula (1) clear, this paper proposes formula (3).

$$\begin{cases} S_1 = \eta_1 S_2 + g_1 + \beta^S \delta_1 + \phi e \\ S_2 = g_2 + \varepsilon \rho_\omega + \beta^S \delta_2 \\ f = S_1 \end{cases} \quad (3)$$

e is the current density per unit. ρ is for material flow. S stands for the temperature of the reactor. t is for time. ε stands for the molar ratio of nitrogen to oxygen in the atmosphere. Where δ is the black factor of the surface layer. ω means liquid.

$$g_1 = -\lambda_1 S_1 - \lambda_2 S_1^4 + \lambda_3 \quad (4)$$

$$\delta_1 = \begin{bmatrix} \mu_1 \\ \mu_2 \end{bmatrix}, \beta^S = [\beta_1 \quad \beta_2], g_2 = -\eta_2 S_2 \quad (5)$$

$$\phi = \lambda_4 S_1 + \lambda_5 S_1 \ln S_1 + \lambda_6, \varepsilon = \eta_2 - \eta_3 S_2 \quad (6)$$

$$\delta_2 = \begin{bmatrix} 0 \\ S_1 - \mu_2 \end{bmatrix} \quad (7)$$

THERMAL MANAGEMENT SYSTEM MODEL AND PARAMETER SETTING

It was modeled using MATLAB/Simulink/Simscape software (FIG. 2 cited in Int.J.Mol.Sci.2022, 23(16), 9157). The main components such as the radiator, cooling water pump and cooling water tank were designed (Figure 3 is quoted in Energies 2022, 15(10), 3656).

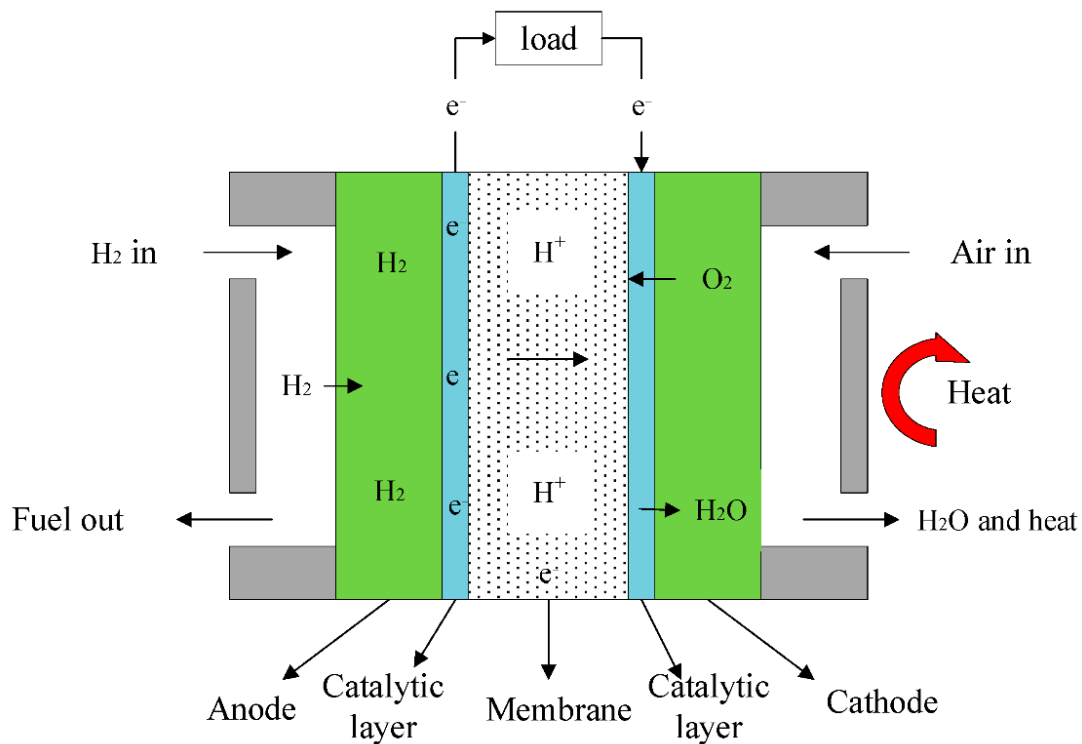


Fig.2 Thermal management system model

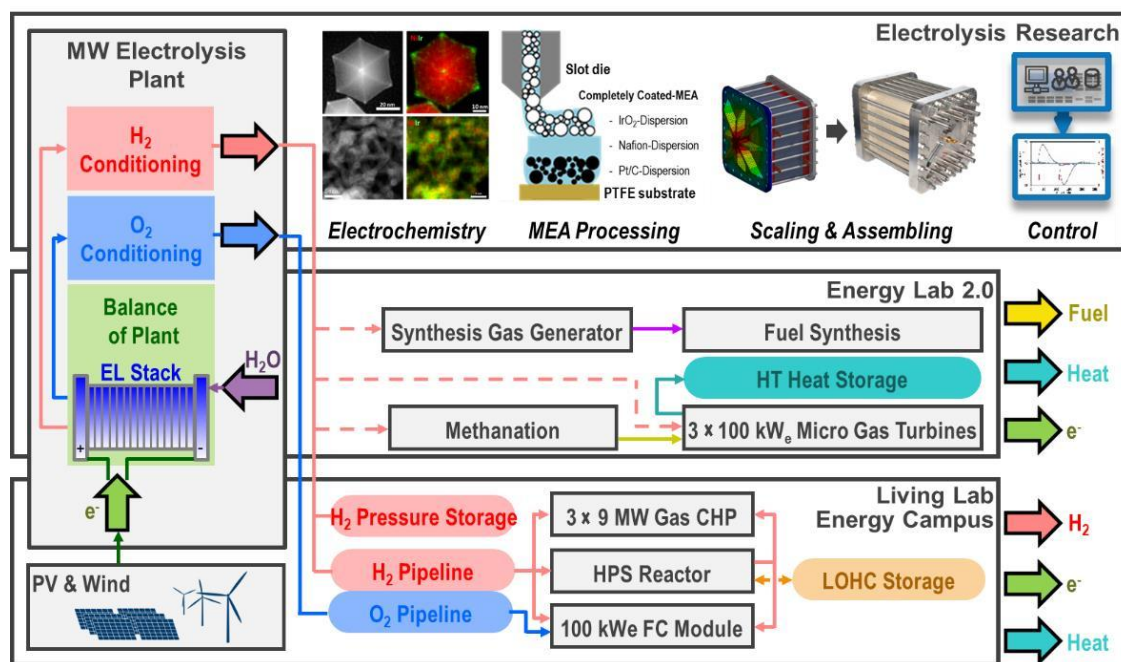


Fig.3 Pipeline module, control mass flow source module and transfer mechanical converter module

The thermal management system of water tank pipeline is simulated by pipe assembly. In this model, the flow of liquid from hole A to hole B is positive, so an ideal mechanical energy can be simulated in this model. M is the control signal that controls the quality flow rate of the coolant flowing through. This component is not in the case of inlet and outlet pressure difference, it is assumed that it does not exchange heat with the liquid. This module is used to simulate the refrigeration pump. The translation mechanism converter is a simulated fluid and mechanical transmission interface, it can be used as part of a linear drive, in its interior to accommodate different liquids, and change with its specific heat, when it is in the open state, its internal pressure also changes. Using the mathematical model established, the numerical simulation of the cold storage pool is carried out.

Thermal regulation

Thermal management of fuel cells can ensure that they work at a suitable operating temperature and improve their power generation efficiency. In the actual production, the algorithm is simple, robust and reliable, so it has been well applied in the actual production. Aiming at the heat dissipation problem of PEMFC, a new design scheme of PEMFC thermal management system based on temperature difference is proposed. A temperature sensor module with temperature detection function is added to a temperature sensor module that can test the temperature of the battery. The PID control block diagram is shown in Figure 4 (the picture is quoted in Appl.Sci.2023, 13(1), 520).

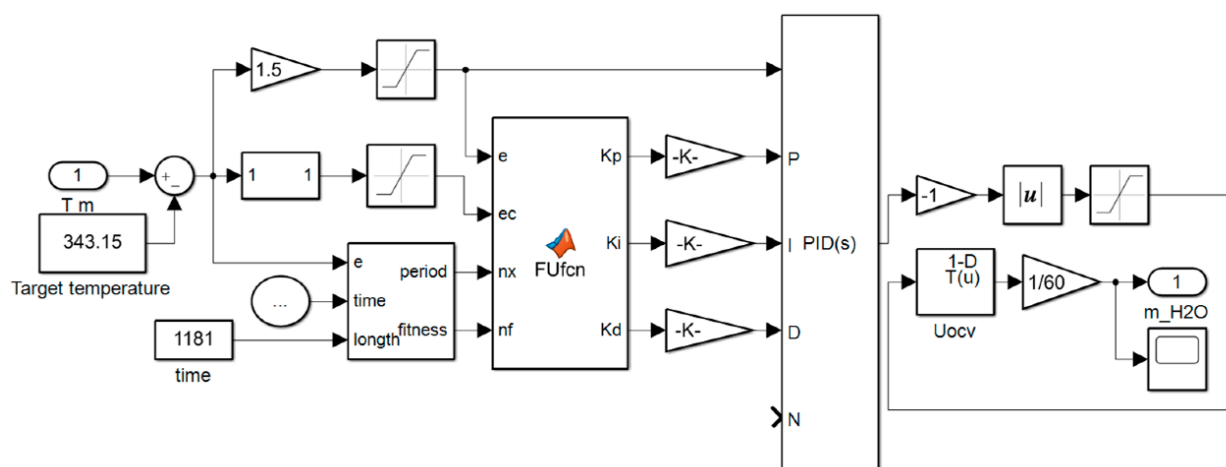


Fig.4 PID control block diagram of fuel cell thermal management system

Simulink was used to simulate it, and the influence rule of the designed PID controller on the temperature of the fuel cell stack was obtained (Figure 5).

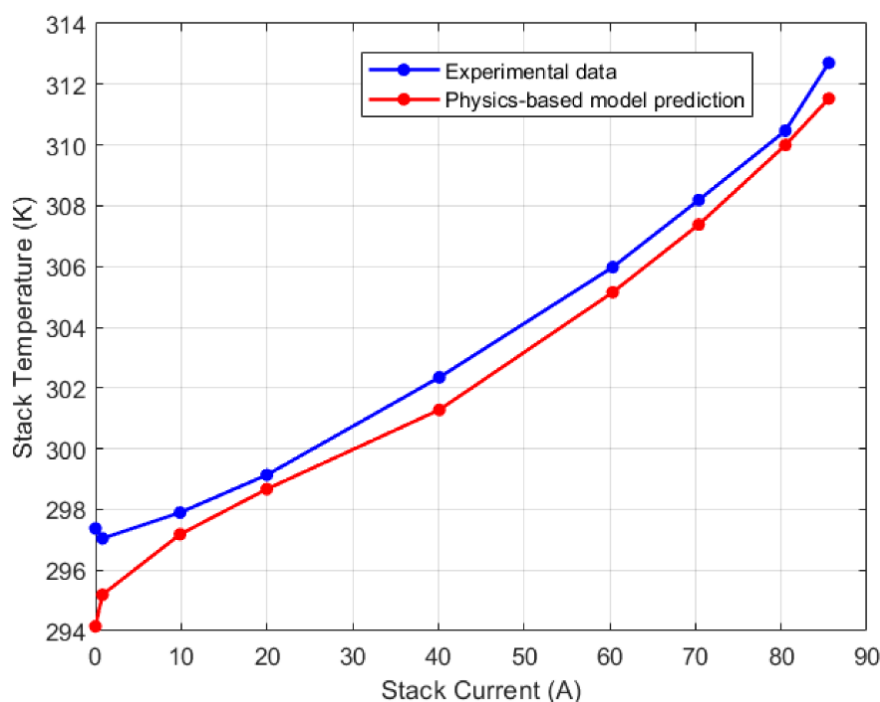


Fig.5 Reactor temperature control results

At A load current of 50 A, the reactor can reach the predetermined 80°C in 0.9 seconds, then rise to 82°C, and tend to 80°C after 100 seconds, after reaching a steady state, the vibration basically disappears. The experimental results show that the temperature rise of the stack increases sharply under PID regulation under the condition of load current from 50~ 80A and 80~ 100A, and then recovers to the original value soon, which proves that PID control is effective. When the load current is reduced from 100 A to 60 A, the temperature rise of the reactor decreases sharply, and then rises steadily to the predetermined target value. Therefore, the PID controller proposed in this paper can respond to the change of load quickly and realize the rapid heating of the pile while keeping its working state at the target level.

Model Verification

The rationality and accuracy of the mathematical model are verified by comparing with the experimental results. The ambient temperature is 25 degrees Celsius. The reactor operating temperature is 72 °C. The air pressure for hydrogen supply is 3.044×10⁵Pa. The air pressure for gas supply is 3.044×10⁵Pa. The peroxide ratio is 2. The polarization curve of the fuel cell pack model was obtained by comparing with the test data in reference [18], and the results are shown in Figure 6.

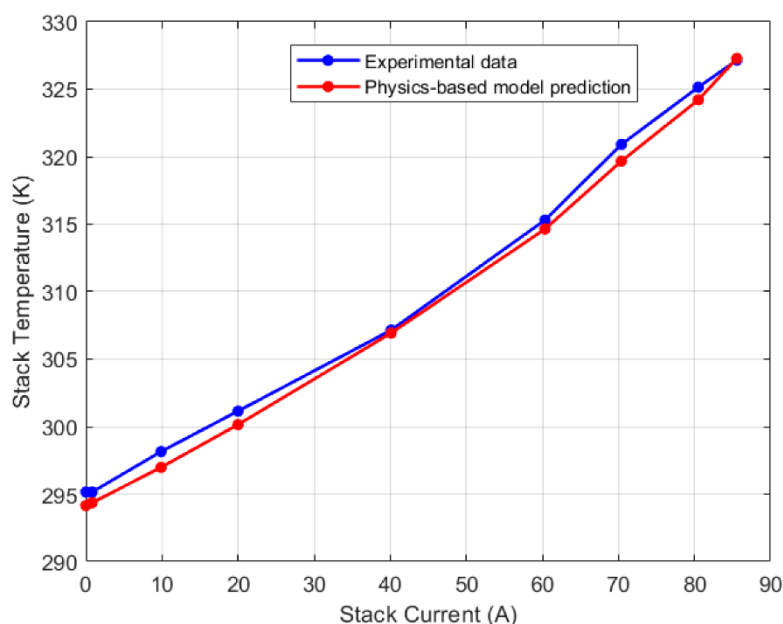


Fig.6 Comparison of polarization curves between model and experiment

The polarization curve obtained by the mathematical model established in the paper is very close to the test result. In the range of 0-0.05A /cm², the output of the model is slightly smaller than the test result, with the maximum deviation of about 0.025V and the relative deviation of about 2.02%. The results show that there is a certain gap between the simulated results and the measured results in the range of 0.05-0.8A /cm², the maximum deviation is about 0.044V, and the relative error is about 4.51%. The results show that the simulation results decrease slightly in the range of 0.8-1.0A /cm², the maximum deviation is about 0.017V, and the relative error is about 2.25%. The theoretical analysis shows that the deviation between the simulated calculated value and the measured value is less than 5%, the mathematical model established in this paper is reasonable.

In order to test the mathematical model of the thermal management system, the project intends to adopt the same method as the literature [19], set the flow rate of the coolant in the mathematical model to A constant value, and gradually increase the load current from 80 A to 200 A. The calculation is made with A step size of 40 A and compared with the temperature difference of the test (Figure 7) [20-21]. The experimental results show that under the load of 80 A, the maximum deviation of the measured results is about 0.214°C, and the difference between the measured results and the actual measured results is not more than 3.19%. Under the load of 120 A, the maximum deviation of the measured results is about 0.512°C, and the difference between the measured results and the actual measured results is 8.62%. Under the loading condition of 160 A, the maximum deviation of the measured results is about 0.2214°C. Under the load of 200 A, the maximum measurement deviation of the measured result is about 0.621°C, and the difference between the measured result and the actual measurement result is not more than 2.225%, which indicates that the method can reflect the temperature change inside the battery well and simulate the heat generation state of the reactor well.

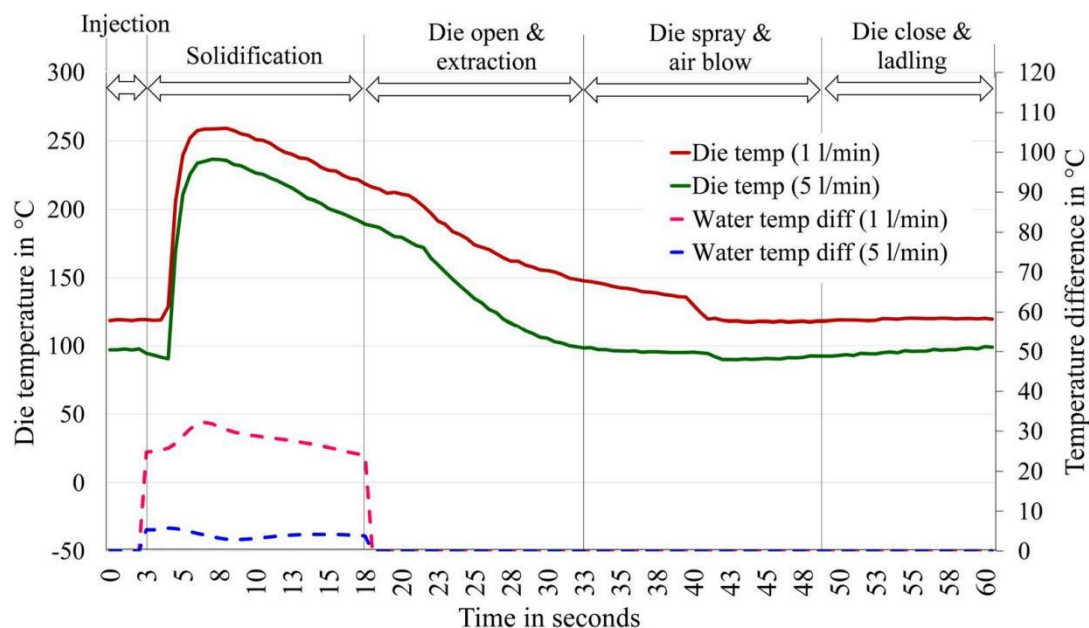
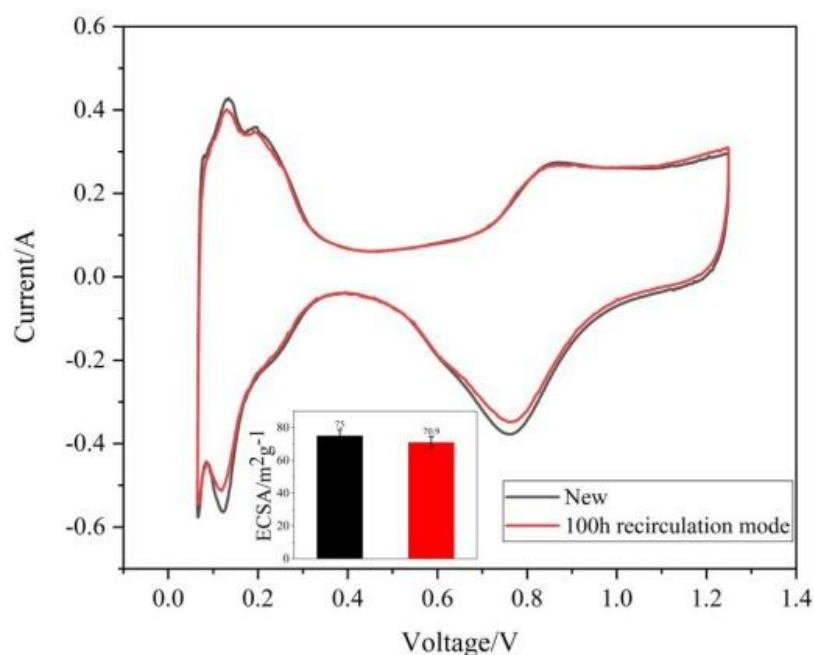


Fig.7 Comparison of temperature difference between model and experimental cooling water inlet and outlet reactors

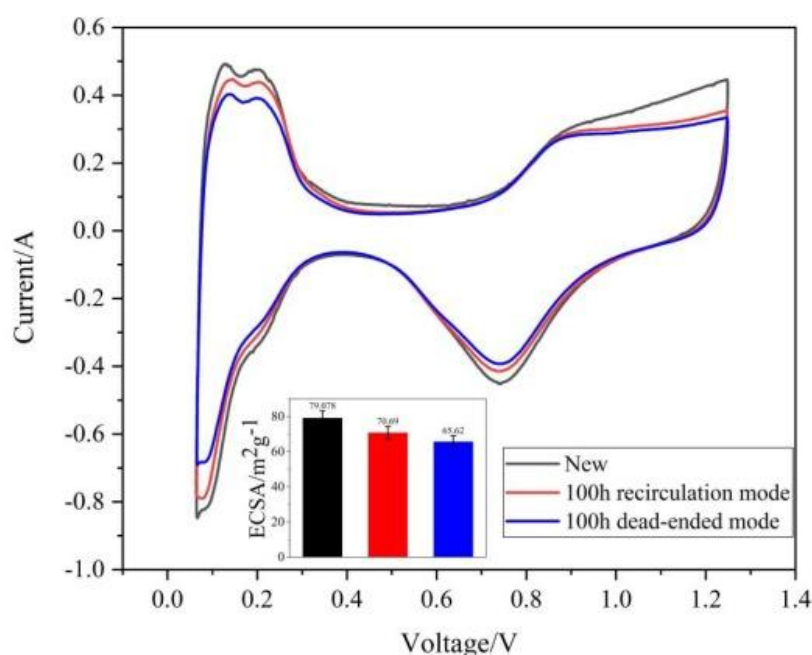
THERMAL MANAGEMENT SYSTEM FAULT SIMULATION

The heat dissipation fan fails

Figure 8 shows the characteristic curve of the fuel cell [22]. The cooling of the heat sink fan is realized by cooling the heat sink. At 80% power, the fan works under normal conditions [23]. After its efficiency drops to 30%, the cooling fan has aged, resulting in a decline in its efficiency. In the case of 0 power, the fan is completely damaged due to damage [24]. When the efficiency of the heat sink fan is 80%, the heat sink discharge temperature reaches a constant value of 346 K. At a 30% reduction, the coolant exit temperature gradually approaches a constant value of 353 K. If the fan fails, it will reduce the moisture content of the film and reduce its heat dissipation efficiency. After the failure of the fan, the moisture content in the film rapidly decreases from 14% to 7% from about 15 s, and from the initial wet state to the dry state.



(a)



(b)

Fig.8 Fuel cell performance curve in radiator fan failure mode

Cooling water flow rate is too low

FIG. 9 shows the characteristic curve of the fuel cell under the coolant flow mode at low speed. Due to pipeline breakage, pipeline blockage, water tank rupture, water tank shortage, water pump failure, resulting in poor cooling water circulation. Through the analysis of the above problems, the flow rate of the coolant can also directly reflect the severity of the failure, choose 1.5 kg/s of sufficient coolant as a judge whether the device is in good condition [25]. When the flow rate of the cooling medium decreases, the pressure of the cooling medium decreases from 1.33×10^5 Pa to 1.21×10^5 Pa. The coolant flow speed is not enough will also cause the coolant out of the reactor temperature is high, in the case of the coolant flow rate of 0.5 kg/s, the coolant out of the

reactor temperature continues to rise, about 80 seconds to reach a stable state, then the temperature has risen to 370 K, beyond its optimal operating temperature and then have an adverse impact on its output characteristics to reduce the output voltage.

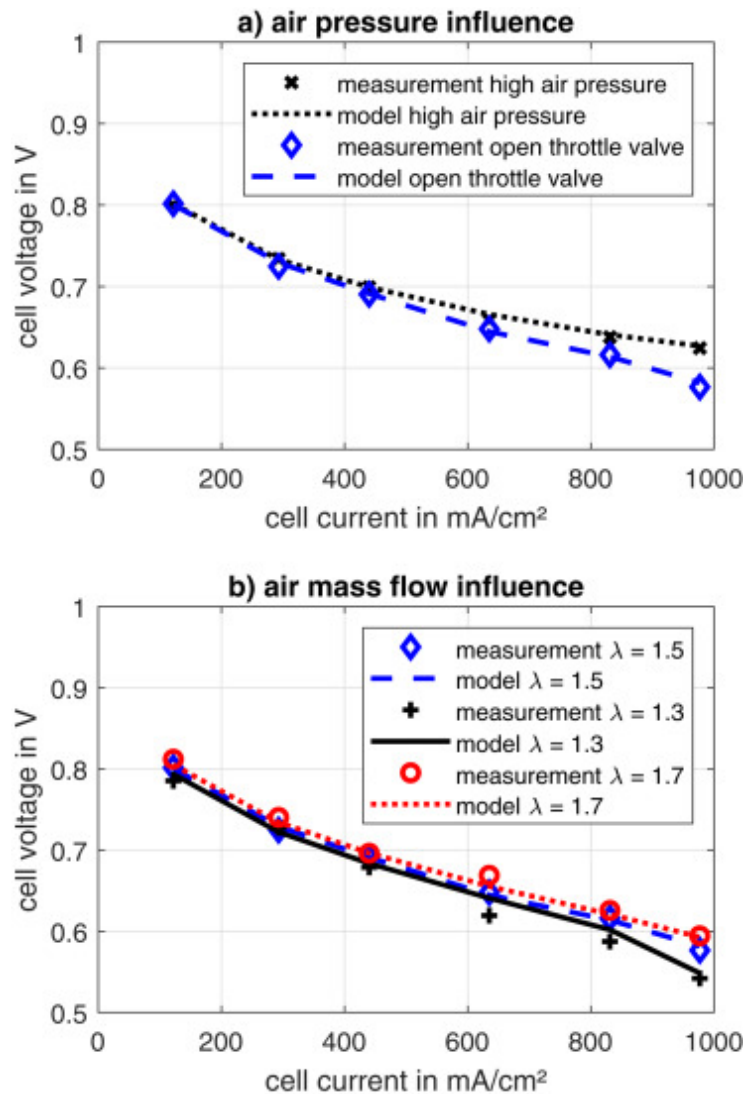


Fig.9 Fuel cell performance curve in coolant flow deficiency mode

CONCLUSION

This project takes PEMFC as the research background, integrates mathematical mechanism and physical modeling, establishes a comprehensive PEMFC numerical simulation method, and carries out the failure simulation of PEMFC thermal management system. The mathematical mechanism model of PEMFC reactor was constructed by using MATLAB/Simulink analysis method, and the physical model of battery was constructed by using Simscape technology. A mathematical model of thermal management system which can simulate various faults is established. In the thermal management system, after the failure of the cooling fan, its reactor temperature will rise with the aggravation of the fault, far exceeding its optimal operating temperature; In this process, due to the rapid reduction of membrane moisture content, film drying is produced, so that its output voltage is greatly reduced. When the coolant flow speed is not enough, the pressure of the coolant is sharply reduced, which will also lead to a high coolant exit temperature when the reactor is discharged, thereby reducing the efficiency of the battery. The simulation results show that by monitoring the coolant pressure, the reactor temperature and the reactor voltage, the operation status can be grasped in real time and the fault detection can be carried out.

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