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Analysis and Solution of the Water Leakage Issue in the Air Exhaust Valve of a Hydrogen Fuel Cell Bus

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Abstract

This paper analyzes the leakage issue of the air exhaust valve in the 80KW system of a hydrogen fuel cell bus and identifies the causes of the problem: an excessive water-air pressure difference leads to stack damage; during commissioning, the sealing ring on the cover of the water tank is not removed and operation under small circulation leads to high water system pressure and an increase in temperature difference; when the system operates in a small cycle, it is forced to manually pull to 40kW, causing the system heat to increase, and the water temperature difference continues to increase to trigger the fault repair procedure and the cooling system pressure failure. Based on the above problems, solutions are proposed to effectively protect the stack, solve the problem of air exhaust valve leakage, and provide some new failure modes and solutions for personnel engaged in hydrogen fuel cell development.

Keywords

PEMFC, water leakage, temperature difference, pressure difference.

1. Introduction

Proton Exchange Membrane Fuel Cells (PEMFCs) are pollution-free during operation, directly using hydrogen and oxygen as fuels, which are converted into electrical energy through electrochemical reactions [1], aligning with the concept of renewable, clean, safe, and efficient energy, and contributing to achieving "dual carbon" goals. The water migration within the proton exchange membrane significantly affects the performance of PEMFCs. An excessive accumulation of water molecules in the proton exchange membrane can hinder proton transport, leading to increased resistance and reduced output power of the fuel cell.

To achieve effective water management, researchers have proposed various strategies. The uneven temperature distribution within PEMFCs greatly affects the uniformity of water content and current density in the proton exchange membrane [2]. PEMFCs use coolant circulation cooling within a very narrow temperature range to ensure efficient operation of the fuel cell [3]. The porosity gradient of the gas diffusion layer can impact the PEMFC system [4-5]. Based on the structure of PEMFCs, the effects of different membrane structures, gas diffusion layers, and flow channel designs on water management are explored [6]. In addition, the porosity of the heterogeneous diffusion layer has a significant impact on the performance of proton exchange membrane fuel cells [7]. Gas diffusion layer intrusion into the flow channel affects fuel cell water management [8]. Designing a reasonable water circulation system is one of the important water management strategies.

Researchers have also proposed various fault diagnosis methods for water management. Data-driven methods use machine learning algorithms to diagnose operation data under fault conditions, which require a large amount of experimental data [9]. Signal processing methods in experimental test-based approaches extract monitoring data for fault detection but can only reflect partial information in PEMFCs [10]. There are also studies on model-based methods and methods based on electrochemical impedance spectroscopy. Good PEMFC water management

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is the main guarantee for the efficient, stable, and safe operation of hydrogen fuel cell vehicles, providing more reliable and efficient solutions for the application of membrane fuel cells.

2. PEMFC Water Management System

The working condition of the PEMFC system is related to internal moisture content, and PEMFC water management has always been a hot topic in hydrogen fuel cell engineering research. During the operation of PEMFCs, fuel entering the air channel carries water, and the cathode catalyst layer contains gaseous water, liquid water, and dissolved phase phase changes. Dissolved phase water generated by the cathode electrochemical reaction can partially transform into liquid or gaseous states and can also be transported between the anode and cathode through the proton exchange membrane. Water in the air channel is discharged in both liquid and gaseous forms, and some moisture entering with hydrogen fuel is discharged through the hydrogen channel. The internal moisture migration process of the PEMFC system is shown in Figure 1.

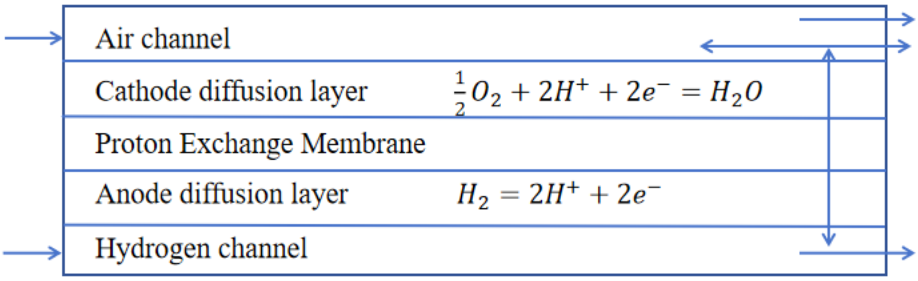

Figure 1. Schematic diagram of internal moisture migration in the PEMFC system.

Generally, the higher the internal humidity of the stack, the better the power generation performance of the battery. However, excessive internal humidity can cause water accumulation, blocking the reaction channels. At the same time, water temperature control is closely related to system work efficiency, and both humidity and temperature are within the scope of water management analysis and control [11-12]. The generation and transport equation of dissolved phase liquid water can be represented by the following formula:

$$\frac{\partial}{\partial t}\left(\varepsilon_i M_{w,H_2O}\frac{\rho_i}{EW}\lambda\right)+\nabla\cdot\left(\overrightarrow{I_m}\frac{n_d}{F}\right)M_w=\nabla\cdot\left(M_w D_w^j\nabla\lambda\right)+S_\lambda+S_{gd}+S_{ld} \quad (1)$$

In the formula: ε_i is the porosity of the porous medium; ρ_i is the density of the proton exchange membrane; EW is the equivalent of the proton exchange membrane; λ is the content of dissolved phase water; n_d is the permeability resistance coefficient; D_w^j is the moisture diffusion coefficient; S_λ is the rate of water generated by the reaction in the cathode catalyst layer; S_{gd} is the phase change rate between the gas phase and the dissolved phase; S_{ld} is the phase change rate between the liquid phase and the dissolved phase.

3. Control Equations

There are electronic, proton, and water transport migration processes in the internal reaction of proton exchange membrane fuel cells, which comply with the laws of fluid mechanics, including conservation of energy, mass conservation, momentum conservation, and component conservation [13].

Mass conservation equation:

$$\frac{\partial(\varepsilon\rho)}{\partial t} + \nabla \cdot (\varepsilon\rho\vec{u}) = 0 \tag{2}$$

In the formula: ε is the porosity; $\vec{u}$ is the velocity vector; ρ is the density of each phase, t is time.
Momentum conservation equation:

$$\frac{\partial(\varepsilon\rho\vec{u})}{\partial t} + \nabla \cdot (\varepsilon\rho\vec{u}\vec{u}) = -\varepsilon\nabla p + \nabla \cdot (\varepsilon\mu\nabla\vec{u}) + S_u \tag{3}$$

In the formula: p is the stress; μ is the viscosity of the fluid; S_u is the momentum source term.
Energy conservation equation:

$$\frac{\partial(\varepsilon\rho c_p T)}{\partial t} + \nabla \cdot (\varepsilon\rho c_p\vec{u}T) = \nabla \cdot (k^{eff}\nabla T) + S_Q \tag{4}$$

In the formula: c_p is the specific heat capacity; T is the temperature; k^{eff} is the thermal conductivity; S_Q is the energy source term.
Component conservation equation:

$$\frac{\partial(\varepsilon c_k)}{\partial t} + \nabla \cdot (\varepsilon\vec{u}c_k) = \nabla \cdot (D_k^{eff}\nabla c_k) + S_k \tag{5}$$

In the formula: c_k is the concentration of each component; D_k^{eff} is the diffusion coefficient of each component; S_k is the source term.

4. Vehicle Leakage Detection and Cause Analysis of Leakage Problems

4.1. Vehicle Leakage Detection.

After a road test of a proton exchange membrane fuel cell (PEMFC) bus, the coolant in the main water expansion tank of the fuel cell system was found to be empty. During the process of refilling the coolant, liquid discharge was observed at the air outlet, as shown in Figure 2.

Figure 2. Liquid discharge at the air outlet

Based on the above problems, the following debugging process was carried out:

The program automatically runs at 40kW, and after 170s of operation, an excessive air-water pressure difference causes a fault shutdown. As shown in Figure 3.

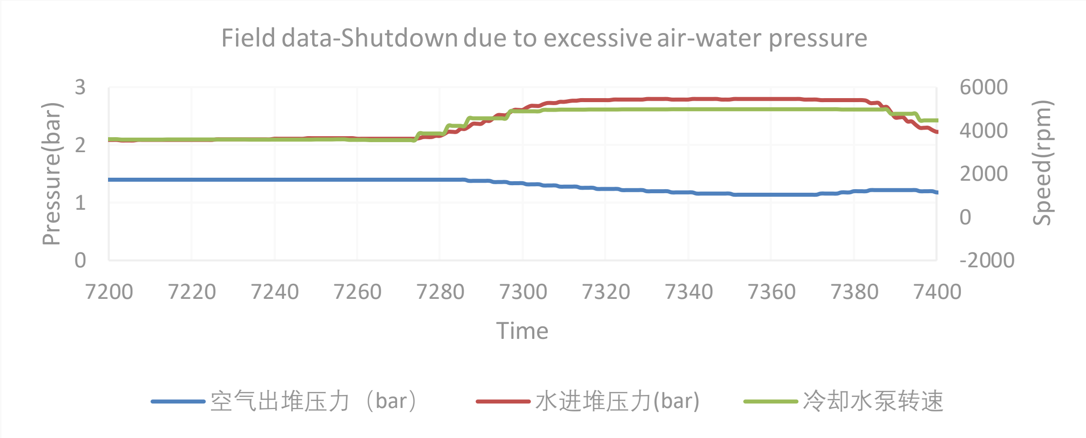

Figure 3. Air-water pressure change diagram

After restarting at 10kW, the lowest single cell is found to be low, and manual blowing is performed, with a large amount of water discharged from the air tail. The water level in the water tank was observed not to decrease.

After returning from a road test of the entire vehicle, it was found that the coolant in the water tank had leaked out.

After refilling the coolant, liquid discharge is observed at the air tail.

4.2. Analysis of Vehicle Water Leakage Issues.

After the system confirmed the emergence of the issue and deemed it highly unlikely to be resolved, the system was coordinated with the plate heat exchanger for maintenance. Upon disassembling the fuel cell stack, a significant amount of coolant was found in the cavity. Leak detection on the stack revealed that the leakage rates of water-hydrogen, hydrogen-air, and external leaks were all within the normal range, but there was a severe cross-leakage between water and air. It was determined that the membrane electrode was not damaged, but the bipolar plates might have certain leakage points. The stack was disassembled and each bipolar plate was inspected for leaks, revealing that two plates exhibited leakage. These plates were destructively disassembled, and it was found that the adhesive bond in the middle section of the plates had partially separated, indicating that the excessive water pressure differential had ruptured the bonding adhesive. This confirmed that the hydrogen-air pressure differential was too high.

Based on the fault phenomenon, it is believed that after a large temperature difference occurred, the fault repair strategy led to an increase in the pump speed. The excessive water pressure is the direct cause of the fault, but the reason for the large temperature difference and why a high pump speed leads to excessive water pressure needs to be determined. After replacing the damaged bipolar plates and reassembling the stack for testing, the system was assembled and tests were initiated on the test bench to analyze the previous faults. To avoid secondary damage to the stack, only the impact of each parameter was verified, without strictly reproducing the fault.

When the fault occurred, it was in a small circulation loop, and a plate heat exchanger was added. It is necessary to investigate whether these two factors affect the water pressure operation: the fuel cell system was reassembled, and the plate heat exchanger was connected to the water circuit of the fuel cell system. Water was added and air was evacuated. After the evacuation, the water pressure was 1.1bar without the pump operating. The water pressure at different three-way valve openings when the pump was operating at 2300RPM was tested. As shown in Table 1.

Table 1 Water inlet pressure at different three-way valve openings

Three-way valve opening	20	30	40	50	80	90	100
Water inlet pressure (bar)	1.3	1.3	1.3	1.3	1.35	1.37	1.38

The table shows that under the same pump speed, when the three-way valve switches from a large circulation loop to a small circulation loop, there is a noticeable increase in water pressure, indicating that small circulation operation affects water pressure. The data in the table, compared to the water pressure data without the plate heat exchanger, shows no significant difference, which rules out the impact of the plate heat exchanger on water pressure.

The sealing ring on the expansion water tank cover was not removed during debugging, which may have also led to excessive water pressure. When the system was operated at 20kW, the water temperature rose to about 66℃. The system was operated with the expansion water tank cover tightened and loosened, and the recorded data is shown in Table 2.

Table 2 Data of tightening and loosening the expansion water tank cover

Pump speed (rpm)	2300	2780	2780	2400	0	0	2300
Water inlet pressure(bar)	1.54	1.45	1.4	1.37	1.14	1.06	1.54
Expansion tank cover status	Tight	Loose	Loose	Tight	Tight	Loose	Tight
Three-way valve angle	83	80	20	20	20	20	83

Analysis of the data in the table shows that after the water temperature increased, the sealing of the expansion water tank cover had a significant impact on water pressure. Under similar water circuit three-way valve openings, when the cover was tightened, the high water pressure limited the further increase of the pump speed, resulting in reduced water flow, which led to a larger temperature difference. When the expansion water tank cover was loosened, the water pressure significantly decreased, allowing the pump speed to increase further to 2780 RPM, increasing water flow and reducing the water temperature difference to a normal level, as shown in Figure 4.

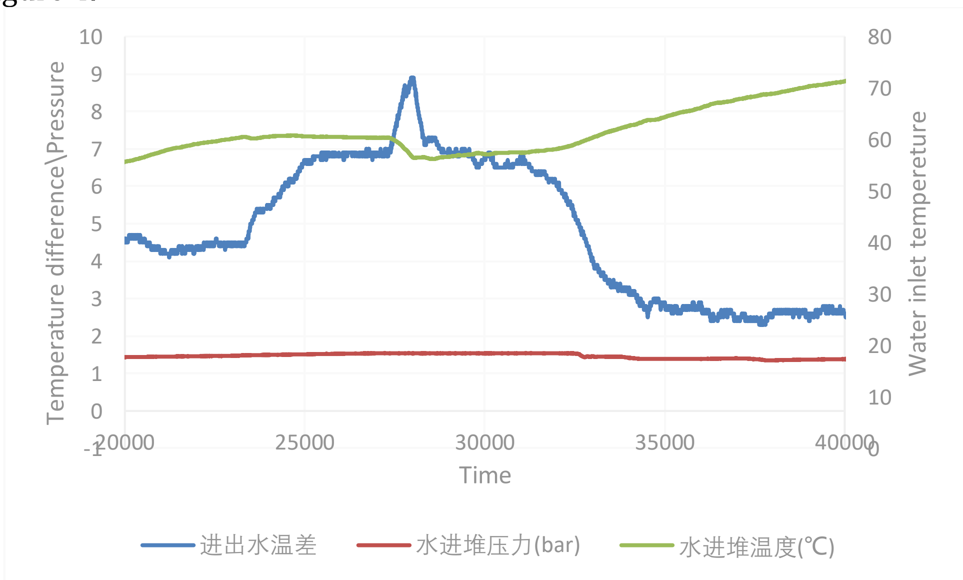

Figure 4. The impact of water flow on water temperature difference.

As shown in Figure 4, near the time point of 32500, corresponding to a pump speed of 2300, the expansion water tank cover was loosened, and the pump speed increased to 2780 RPM, causing a rapid decrease in temperature difference. It can be seen that the phenomenon of a large temperature difference on-site was influenced by the pressure inside the water tank, and removing the sealing ring of the expansion water tank led to an improvement.

5. Rectification Measures and Verification Results for Vehicle Water Leakage Issues

5.1. Rectification Measures.

To prevent the risk of stack damage due to excessive pressure differentials, the following modifications were made to the program:

The control of the pressure differential between the gas and water circuits was limited in the program, with the control target being that the water inlet pressure is not greater than the air inlet pressure by more than 0.25bar, and the hydrogen inlet pressure is not greater than the water inlet pressure by more than 0.25bar.

The water inlet pressure protection value was changed from 2.9 bar to 2.5bar.

When the temperature difference exceeds 7°C, the power will no longer increase to prevent a temperature difference fault in the small cycle.

5.2. Verification Results.

As shown in the figure below, through the modification of the program, the pressure differential between air and water was controlled within 0.25bar under different power levels and during rapid changes in power. This can effectively protect the stack and prevent similar issues from occurring.

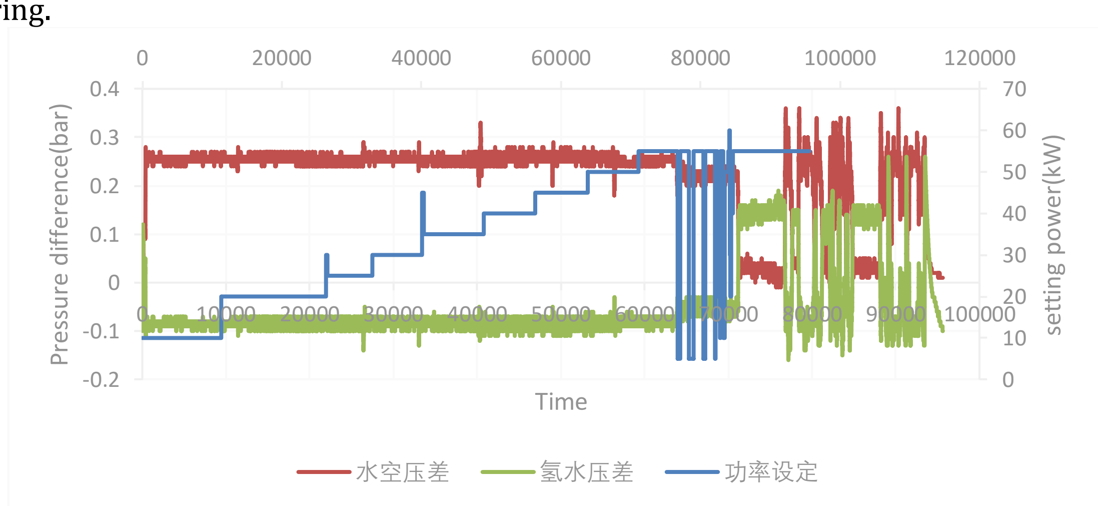

Figure 5. Pressure difference change diagram

6. Conclusion

The stack damage was caused by an excessive water-air pressure differential;

The sealing ring on the water tank cover was not removed during debugging, and operation in a small circulation loop led to high water circuit system pressure and low cooling system flow, which in turn caused an increase in temperature difference;

When the system was operated in a small circulation loop and manually loaded to 40kW, the system's heat generation increased, and the water temperature difference continued to increase until it triggered the fault repair procedure. The pump speed rapidly increased, but the sealing ring and small circulation caused excessive water pressure during the speed increase, triggering a cooling system pressure fault;

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The plate heat exchanger had little impact on the pressure differential and temperature difference.

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References

[1] Y.X. Cai, Sh.Sh. Liu, N. Fu, et al. Research progress on high temperature proton exchange membranes, Materials Reports, vol. 30 (2016), 57-62.

[2] L.P. Mike, P.M. Jeremy, M.D. Robert, et al. Evaporatively-cooled PEM fuel cell stack and system, ECS Trans, vol. 3 (2006) 1207-1214.

[3] S.G. Kandlikar, Z. Lu. Thermal management issues in a PEMFC stack - A brief review of current status, Applied Thermal Engineering, vol. 29 (2009) 1207-1214.

[4] Zh.Y. Chen, R.L. Zhou, J.X. Li, et al. Effect of porosity gradient of gas diffusion layer on water management of PEMFC, Internal Combustion Engine & Powerplant., vol. 39 (2022) 41-47.

[5] Y.S. He, M.L. Bai, L. Hao. Pore Structure and Pore Scale Simulation of Permeability of Micro-Porous Layer in PEM Fuel Cell, Journal of Shanghai Jiao Tong University. vol. 54 (2020) 1053-1064.

[6] J.Zh. Xu, T.C. Ma, L.L. Zou. Research status of water management of proton exchange membrane fuel cells, Journal of Jiamusi University(Natural science edition). vol. 37 (2019) 845-848.

[7] J.R. Yu, H. Chen, H. Guo, et al. Effect of heterogeneous diffusion layer porosity on the performance of proton exchange membrane fuel cells, Energy conservation. vol. 8 (2024) 26-29.

[8] F. Lyu, Zh.M. Bao, B.W. Wang, et al. Investigation on impact of gas diffusion layer intrusion into channel on water management in fuel cell, CIESC Journal. vol. 75 (2024) 2929-2938.

[9] R. Ma, Z.J. Ren, R.Y. Xie, et al. A comprehensive review for proton exchange membrane fuel cell modeling based on model feature analysis, Proc. of the CSEE. vol. 41(2021) 7712-7730.

[10] J.W. Liu, Q. Li,W.R. Chen. A fast fault diagnosis method of the PEMFC system based on extreme learning machine and Dempster-Shafer evidence theory, IEEE Transactions on Transportation Electrification. vol. 5 (2019) 271-284.

[11] H.J. Liu: Study on Hydrothermal Management and Performance Optimization of PEMFC (Shandong University, China 2020).

[12] X.J. Ma, X.F. Chen. Water Management Control of PEMFC Based on Fuzzy Mode, Journal of Academy of Armored Force Engineering. vol. 29 (2015) 76-79.

[13] Ch. Lin: Study on hydrothermal management of water-cooled proton membrane fuel cells (Shanghai Jiao Tong University, China 2020).