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Test and analysis of hydrogen fuel cell system durability

Mingrui Wang[1,*], Yunlong Fang[1], Liyao Xu[2], Qiulai Wang[2] and Bin Zuo[3]

1 DeepWay Technology, Beijing, 100102, China
2 Dongfeng Motor Corporation Technology Center, Wuhan, 430058, China
3 College of Mechanical and Vehicle Engineering, Hunan University, Changsha, 410082, China

* Correspondence author; E-mail: wangmingrui@deepway.ai.

Abstract: A hydrogen fuel cell is a conversion device that converts hydrogen energy into electrical energy. The main factors restricting the large-scale application of hydrogen fuel cells in automobiles are the lifetime and durability of fuel cells. At present, there are few studies on fuel cell durability tests, and the existing test methods have shortcomings, such as narrow coverage of working conditions and short duration. Based on national and industry standards, this paper designs a test method and conducts durability tests for a fuel cell system, and the test results show that after 1200 hours of testing, the average cell voltage degradation of the fuel cell system under the reference current is 4.86%. At low power condition, this degradation is around 4%. As the system output power increases, the degradation gradually increases. At high power condition, the degradation is around 10%. This paper accumulates experience for the durability test of fuel cell system and provides support for the establishment of durability evaluation system.

Keywords: Hydrogen fuel cell system; durability; test; analysis

1. Introduction

With the progress of society and economic development, the population of vehicles burning fossil energy has been rising. This phenomenon brings two serious social problems: oil dependence gradually comes to the fore, and air pollution and greenhouse gas emissions become increasingly serious. The "Domestic and Foreign Oil and Gas Industry Development Report 2021" shows that in 2021, although China's oil dependence has fallen, it still reached 72.2%, far exceeding the safety line of 50%. And the growth of domestic oil consumption is expected to turn to positive from negative in 2022, and the external dependence will resume growth again [1]. This, with the continued increase in vehicle ownership, the transportation sector, including automobiles, accounts for more than 50% of oil consumption. The huge fuel consumption of vehicles has become the main driver of China's escalating external dependence on oil. In next 10 years, the structure of China's automotive products will still be dominated by fuel vehicles. Therefore, it is urgent to promote the development of new energy for traditional energy vehicles, which is an important measure to ensure the strategic security of national energy.

Automobile exhaust emissions have become one of the important sources of many pollutants. The "Second National Pollution Source Census Bulletin" shows that nitrogen oxide emissions from motor vehicles account for 33.3% of total national emissions [2]. According to "Global Energy & CO2 Status Report 2018" published by the International Energy Agency, road traffic emissions currently account for 18% of total global carbon emissions and are an important component of greenhouse gas emissions [3].

Therefore, whether from the perspective of reducing oil dependence to enhance energy security, or from the perspective of reducing air pollution and greenhouse gas emissions, the "decarbonization" of the automotive industry is imperative. In September 2020, China announced at the 75th United Nations General Assembly that it was striving to peak CO2 emissions by 2030 and working towards carbon neutrality by 2060[4].

Hydrogen is a green, efficient and widely available energy storage medium, which is storable and renewable. With the maturity of hydrogen production, storage and transportation technologies, hydrogen strategy is becoming an important part of Chin's energy and environmental strategy under the carbon peaking and carbon neutrality goals.

Hydrogen fuel cell is a device that converts chemical energy into electrical energy, and as the main source of electricity for automobiles, it has some advantages as follows: (1) the product is pure water, no pollutant emission; (2) not limited by Carnot cycle, high energy conversion efficiency; (3) energy is converted into electrical energy through electrochemical reaction, not kinetic energy, it is a static energy conversion device with low noise; (4) high power density, compact structure, space occupying a small percentage [5].

However, the lifetime and durability of hydrogen fuel cells have been one of the major reasons limiting their large-scale application in the automotive industry. The nature of the degradation process of hydrogen fuel cell durability is due to the dynamic evolution of the imbalance in the stack state caused by environmental and operating condition changes, which further causes material performance damage [6].

The industry has just started and a relatively complete testing and evaluation system has not yet been established. The only current national standard on fuel cell durability testing methods is GB/T 38914-2020 "Evaluation method for lifetime of proton exchange membrane fuel cell stack in vehicle application". The standard provides varied conditions such as idle, rated and variable load conditions, but the conditions focus on the output current of the fuel cell and the fuel cell would only be loaded to two specific operating conditions: idle and rated current conditions. The shortcoming is that the test coverage is narrow and does not focus on the output power of the fuel cell. In an in-vehicle environment, the power output characteristics of the fuel cell system are following the power load requested by vehicle, which is of more concern than the output current.

This paper conducts durability tests on a fuel cell system with a rated power of 80 kW, designs durability test conditions based on national and industry standards, accumulates experience for durability tests of fuel cell systems, and provides support for the establishment of a durability evaluation system.

2. Apparatus and method

2.1. Apparatus

The durability test was carried out based on a fuel cell system which could output rate power of 80 kW, which can be seen from Figure 1 and the brief specifications are listed in Table 1, however the detail specifications are currently classified.

Table 1. Brief specifications of fuel cell system.

Item	Parameter
Rated power/kw	80
Rated output voltage/V	540
Output voltage range/V	400–750
Voltage resolution/V	±2
Current resolution/A	±3
Number of cells	334
Flow rate range of air/SPLM	0–5200
Flow rate range of hydrogen/SPLM	0–1820

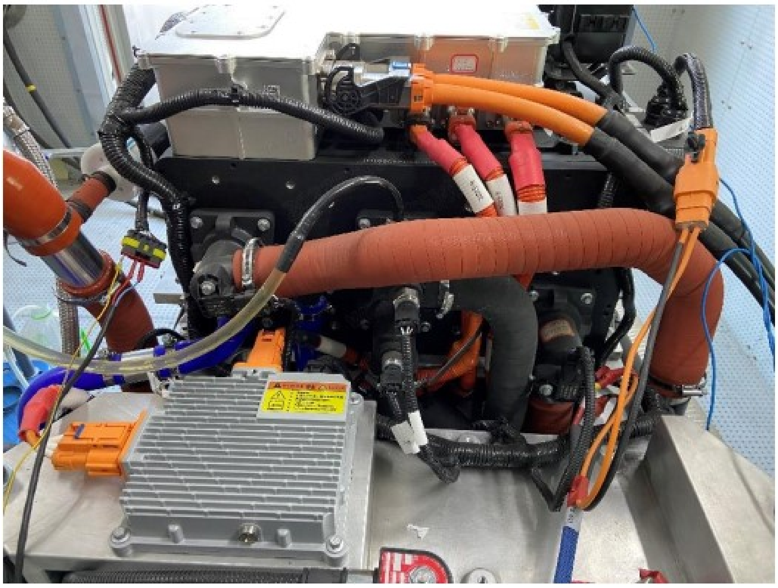

Figure 1. Fuel cell system.

The test bench used in this study is shown in Figure 2 and the brief specification are listed in Table 2.

Figure 2. Test bench.

Table 2. Specifications of test bench.

Item	Parameter
Power range/kw	0–100
Voltage range/V	24–800
Rated current/A	600
Power resolution	0.1% FS
Voltage resolution	0.1% FS
Current resolution	0.1% FS
Flow rate range of air/SPLM	40–8000
Flow rate range of hydrogen/SPLM	10–2000

2.2. Test method

The durability testing methods of fuel cells are mainly divided into steady-state method and dynamic method. The steady-state method involves running the fuel cell at a constant current density or voltage and recording the changes in voltage or current as well as other performance indicators. The test results of fuel cell durability obtained using this method are better than that of dynamic method, however, they are not enough to characterize its durability under on-board conditions. In the automotive operating environment, fuel cells are subjected to various operating conditions such as start-up, shutdown, loading, load shedding, rated and idle power operation. Each of these operating conditions affects the durability of the fuel cell to a different degree.

The dynamic method means that the fuel cell output power follows the load changes of the vehicle during actual operation. In this process, the fuel cell system will experience changes in various operating conditions, and its durability performance is better tested, and the test results are more reflective of the real durability performance of the fuel cell.

The Chinese Society of Automotive Engineers have developed an industry standard, T/CSAE 236-2021 “Proton exchange membrane fuel cell engine—Test methods for bench reliability”, for durability testing of fuel cells [7]. This standard is the first domestic group standard that provides a test method for testing the durability of fuel cells, which is of great guidance. The standard stipulates that fuel cells are to be operated continuously for a period at rated power and several representative powers. The duration of one cycle is 180 minutes, and 100 cycles are required to be run, with a total operating time of 18,000 minutes, or 300 hours.

However, the standard has several drawbacks: (1) there are no specific requirements for the power levels selected in the working conditions and the duration, and only a few power levels are selected, which cannot comprehensively verify the durability of fuel cells under different powers; (2) the duration of individual cycles is long, and the whole working conditions approximate a process of steady-state operation; (3) the total duration of the whole test is short. According to the target set by “Technology Roadmap for Energy Saving and New Energy Vehicles 2.0” published by the Chinese Society of Automotive Engineers (CSAE), the fuel cell lifetime for vehicles is required to exceed 15000 hours in 2025 [8]. Therefore, even if the test is passed, it does not fully prove that the fuel cell has reached the lifetime target for automotive use.

The reason for these points of deficiency is that the fuel cell industry is in the early stage of development, and the power levels and performance of fuel cell products vary from company to company, so it is difficult to set a fixed test power point. Secondly, the industry is still exploring the durability of fuel cells, and the severity of operating conditions is still not sufficiently grasped. Furthermore, the cost of fuel cell durability testing is relatively high. Therefore, the industry standard should not set too long a test time to avoid unnecessary burden for enterprises.

Based on the national and industry standards and the application scenarios of this fuel cell system, the test condition was developed, which includes steady-state operation, loading, stopping and purging. An individual cycle takes 1800 seconds, which is shown in Table 3. The whole test condition takes 2400 cycles, and the total running time is 1200 hours. The specific steps of the test are as follows.

1. Start and warm up the fuel cell system, stop the warm-up when the coolant outlet temperature of the fuel cell system reaches 45 °C.

2. Maintain the fuel cell at idle power for 10 seconds, load gradually to rated power with 10% of rated power as a step, and run continuously and steadily for 3 minutes at each step; use the data as the reference data and draw the polarization curve. According to the national standard, the reference current of the fuel cell system is determined as the current under the average cell voltage of 0.7 V [9], and the reference current of this fuel cell system is 266 A.

3. Operate cycle test condition, during the operating test. The polarization curve is retested once every 100 hours and the test data are recorded. Each retest needs to be purged with nitrogen gas for the fuel cell.

Table 3. Test condition of durability test.

NO.	System Power/kW	Duration/s	Cumulative time/s
1	10	180	180
2	20	600	780
3	40	600	1380
4	60	300	1680
5	70	120	1800

3. Test results and analysis

3.1. The degradation of average cell voltage

The initial polarization curve was compared with the final polarization curve according to GB/T 38914-2020 to obtain the decay rate of the average cell voltage of the fuel cell at the reference current. Figure 3 shows the comparison of the initial polarization curve of the fuel cell system with the polarization curve retested after 1200 hours. After test finishing, the average cell voltage at the reference current is 0.666 V, which is 4.86% decayed compared to 0.7 V. Figure 4 shows the histogram of it and the curve of the decay rate after retesting every 100 h. During the first 400 hours, the average cell voltage of the fuel cell system decayed at a fast rate to 0.677 V, with a decay rate of 3.34%. After that, the average cell voltage continued to decay, but the decay trend tended to be flatter than before.

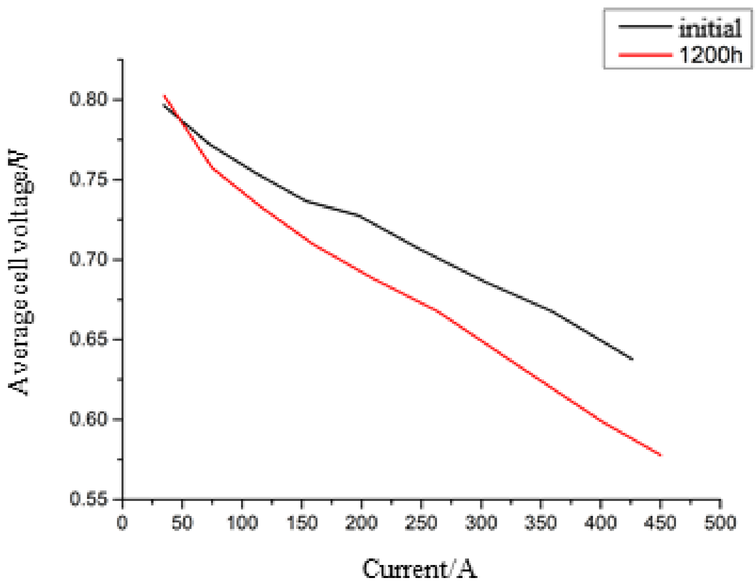

Figure 3. Polarization curve at initial and 1200 h.

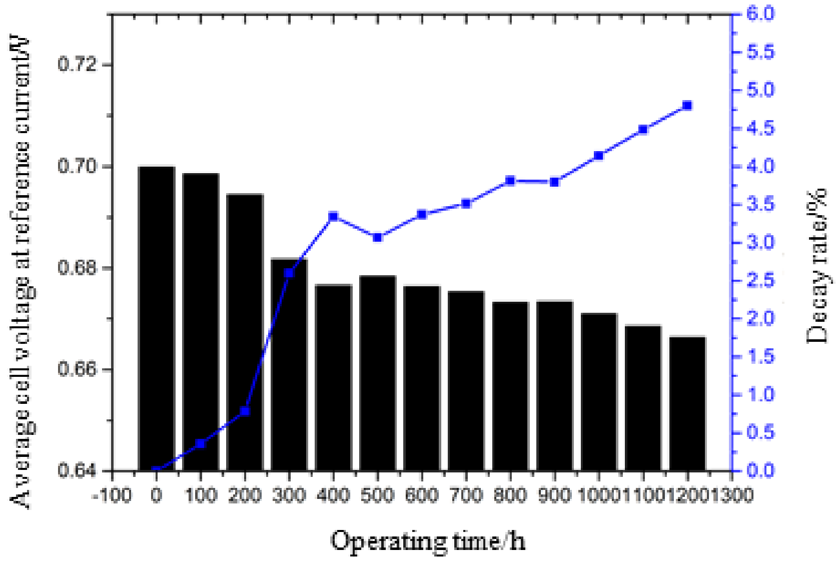

Figure 4. Average cell voltage and its degradation.

3.2. Average cell voltages at different power

In the automotive scenario, the decay of the fuel cell system at different powers is also a concern. As can be seen in Figure 5, the decay trend of the average cell voltage at different system output powers is similar, except that the overall level of the average cell voltage shows a gradual decrease as the system output power increases, and the decay trend of the average cell voltage is gradually intensified as the system output power increases, with a small rebound in the average cell voltage after 600 hours, and then a flat decay. This rebound is most obvious when the system output power is 40 kW and 60 kW.

The reason for this phenomenon is that the products of the fuel cell are mainly water and the water content increase with the increase of the system output power. As a result, the catalyst of the fuel cell membrane electrode oxidizes in the presence of the generated water as well as air to produce platinum oxides, they cause a decrease in the activity of the catalyst and these oxides adhere to the catalyst surface, thus reducing the activation area.

However, the nitrogen purged prior to each retest removes the water and air generated in the flow channel, causing a reversible reaction of these nitrogen oxides to re-form platinum metal, resulting in an increase in catalyst activity. As a result, the average cell voltage rises again when the retest is performed. As the test continues and the platinum oxides gradually accumulate, the catalyst activity still decays slowly [10].

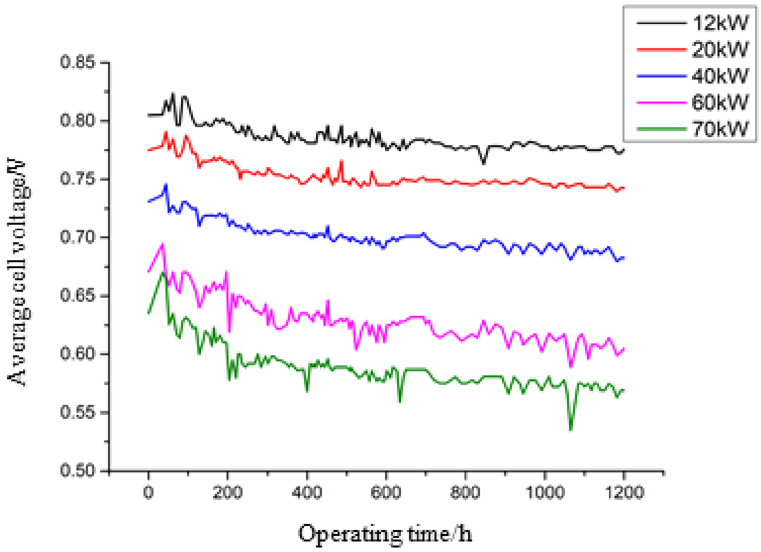

Figure 5. Average cell voltage at different power.

The above experimental data can be used to calculate the decay rate of the average cell voltage relative to the initial voltage at different power levels. Referring to Table 4, the decay rate is around 4% when the system output power is maintained at 10 or 20 kW, and reaches and basically stabilizes at 10% when the system's output power reaches 60 kW and above. Therefore, to improve the durability of the fuel cell system for in-vehicle applications, it should work in the low and medium power conditions as much as possible and avoid working in the high-power condition.

Table 4. Degradation at different power.

System power/kW	Initial voltage/V	End voltage/V	Decay rate/(V/h)	Decay rate/%
10	0.805	0.775	25.0	3.72
20	0.775	0.742	27.5	4.26
40	0.731	0.683	40.0	6.57
60	0.671	0.604	55.8	9.99
70	0.635	0.569	55.0	10.39

4. Conclusion

At the reference current, the average single cell voltage decay rate of the fuel cell gradually increased with the test, and the decay rate dropped back slightly after 500 hours, and then increased gently, and the decay rate was 4.86% after 1200 hours.

The change pattern of the average cell voltage at different system output power levels is similar, with the overall level showing a gradual decrease, all leveling off after 500 hours. And after 600 hours, the average cell voltage has a small rebound, and then a gentle decay. This small rebound is most obvious when the system output power is 40 kW and 60 kW.

As the system output power increases, the average voltage decay rate gradually rises, but also shows a pattern of differentiation. At the low power level, the decay rate is basically maintained at about 4%, and at high power level, the decay rate is basically maintained at about 10%. Therefore, to improve the durability of the fuel cell system in vehicle applications, it should work in the low and medium power conditions as much as possible.

5. Prospect

This paper conducts durability tests for a fuel cell system with a rated power of 80 kW, and the test duration is extended to 1200 hours, which accumulates experience for durability tests of fuel cell systems and provides support for the establishment of a fuel cell durability evaluation system. However, there are still some follow-up works to be carried out.

1. Due to the performance of the fuel cell system itself and the test cost, the test length is still far from the 15000 hours' target specified in "Technology Roadmap for Energy Saving and New Energy Vehicles 2.0". Therefore, the use of data-driven, degradation mechanism models and other methods should be considered to predict the lifetime of the fuel cell system based on this test data. And the prediction results should be verified when the conditions allow.

2. To study how to make the fuel cell system work at the right power as much as possible to get better durability with good response to the whole vehicle load in conjunction with the actual situation of vehicle application.

Acknowledgments

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Conflicts of interests

The authors declare no conflicts of interests.

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