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Research on Thermal Balance Test and Evaluation Technology of Fuel Cell Vehicle

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Abstract:
In the development and use of fuel cells, thermal management systems are of great significance for the efficiency and durability of fuel cell vehicles, and the testing and evaluation of thermal balance are crucial. Therefore, relevant research has been conducted on the thermal balance testing and evaluation of fuel cells. Through theoretical and technical analysis, a testing and evaluation method for thermal management systems applicable to various extreme working conditions has been proposed, forming testing and evaluation conditions and indicators for each system of fuel cell vehicles. This article analyzes the thermal balance test results of fuel cell vehicles. The research results indicate that the thermal equilibrium of fuel cell vehicles under extreme conditions will reduce power and increase temperature differences for heat dissipation.

Keywords: Fuel cell vehicle; Heat balance; Test evaluation

INTRODUCTION

In the commercial operation of fuel cell vehicles, thermal management is a significant technical challenge that affects the development of fuel cell vehicles [1-3] and has a decisive impact on the safety and service life of the entire vehicle. Currently, the power source of fuel cell vehicles is mainly divided into two parts: the battery and the fuel cell. Due to the particularity of fuel cells, their power generation efficiency is 40% - 60%, and the rest of the power is dissipated as heat. In the entire vehicle design process, 95% of the generated heat needs to be forcibly dissipated through the radiator. When the external temperature of the fuel cell is relatively high, the temperature gradient between the internal and external working temperatures is small, causing heat dissipation problems. On the other hand, due to different heat sources in the vehicle, the cooling requirements also vary. Generally, the vehicle needs three to five channels for heat dissipation and cooling. This leads to the complexity of the overall vehicle structure, especially for passenger cars, where the complex structure is challenging to arrange.

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Currently, many researchers have conducted technical studies on the thermal management of fuel cell vehicle systems. Wang [4] analyzed typical thermal management systems and introduced the thermal management system of Mirai in detail. Wang [5] established a thermal management model for fuel cell vehicles, studying the impact of different fan selections and operating conditions on the thermal management of fuel cell vehicles. Şefkat [6] developed a fuzzy logic control algorithm to improve the overall energy efficiency of fuel cell hybrid vehicles. Pu [7] analyzed the impact of flow, pressure, and heat on the thermal management system and proposed optimization suggestions for system structure design. SAE [8] also published related introductions and analyses of the thermal management system of fuel cell vehicles.

Considering the structural differences between fuel cell vehicles, pure electric vehicles, and traditional vehicles, fuel cell vehicles have multiple heat sources and high-temperature control requirements. It is necessary to comprehensively evaluate the thermal management system of fuel vehicles according to the control of multiple heat sources and different temperatures. Existing standards include "GB/T 12542-2020 Road Test Method for Automobile Thermal Balance Capability" [9], "T/CSAE 114-2019 Wind Tunnel Test Method for Automotive Powertrain Cooling Environment" [10], etc. This work analyzes the thermal balance testing and evaluation of fuel cell vehicles, explaining the working principles of thermal management systems, and conducts balance testing and evaluation of thermal management systems under actual working conditions.

FUEL CELL THERMAL WORKING PRINCIPLE

The generation and release of heat in fuel cells run through the entire electrochemical reaction process. The reasons for heat generation in fuel cells are mainly divided into three types: chemical reaction heat generated by electrochemical reactions, Joule heat generated by ohmic polarization, and radiation heat. Among them, radiation heat accounts for less than 1% of the total heat and can be ignored in the specific design process. The calculation formula for fuel cell heat generation [11] is as follows:

$$Qgen=(1.482-Vcell)\times Incell \quad (1)$$

Where Qgen is the generated waste heat power, Incell is the transient output current of the stack, and Vcell is the transient output voltage of the stack.

When the fuel cell is running, all the heat generated must be dissipated, which means that the chemical reaction heat and Joule heat generated by ohmic polarization need to be carried away by circulating cooling water. The heat carried away by circulating cooling water is as follows:

$$\Delta Q=C\times N1\times Aw\times V\times \rho\times(Tout-Tin) \quad (2)$$

Where C is the specific heat capacity of water, N1 is the number of channels, Aw is the cross-sectional area of the channels; V is the flow velocity; ρ is the density of water, and T is the outlet temperature. Therefore, according to the formula, the heat carried away by circulating cooling water is the main way of heat dissipation for fuel cells.

TEST PLAN AND VEHICLE TEST

Vehicle Information

This paper takes the Toyota fuel cell electric vehicle Mirai as the research object. The basic parameters of the vehicle are shown in Table 1:

Table 1. Fuel Cell Vehicle Parameters

Product Name	Car	Product Number	Toyota Mirai
Maximum Permissible Total Mass (kg)	2160	Curb Weight (Kg)	1850
VIN	JTDBVRBDXGA000378	Transmission Ratio	8.779
Battery Volume / Energy Density	3.1kW/L, 2.0KW/Kg	Drive Motor	MG2
Wheelbase (mm)	2780	Number of Seats	5

Toyota Mirai Thermal Management System

The layout of the Toyota Mirai thermal management system is shown in Figure 1. Its cooling system is liquid-cooled, with an electric water pump sending coolant to the stack, including the main radiator, auxiliary radiator, water control valve, air conditioning, intercooler, stack, electric water pump, temperature sensor, and deionizer. The cooling method of this thermal management system is liquid cooling. The electric water pump sends the coolant to the stack, and the cooled liquid flows through the radiator via the water control valve, forming a closed cooling circuit. During the operation of the thermal management system, the electric water pump, temperature sensor, and water control valve work together to achieve precise control of the stack temperature by changing the flow rate of the coolant. The design of dual radiators (main and auxiliary radiators) can better meet the heat dissipation needs under high heat load, ensuring the normal performance of the vehicle.

Test Conditions

During the test preparation process, the vehicle must meet the relevant safety technical requirements of "GB/T 24549-2020 Safety Requirements for Fuel Cell Electric Vehicles" [12].

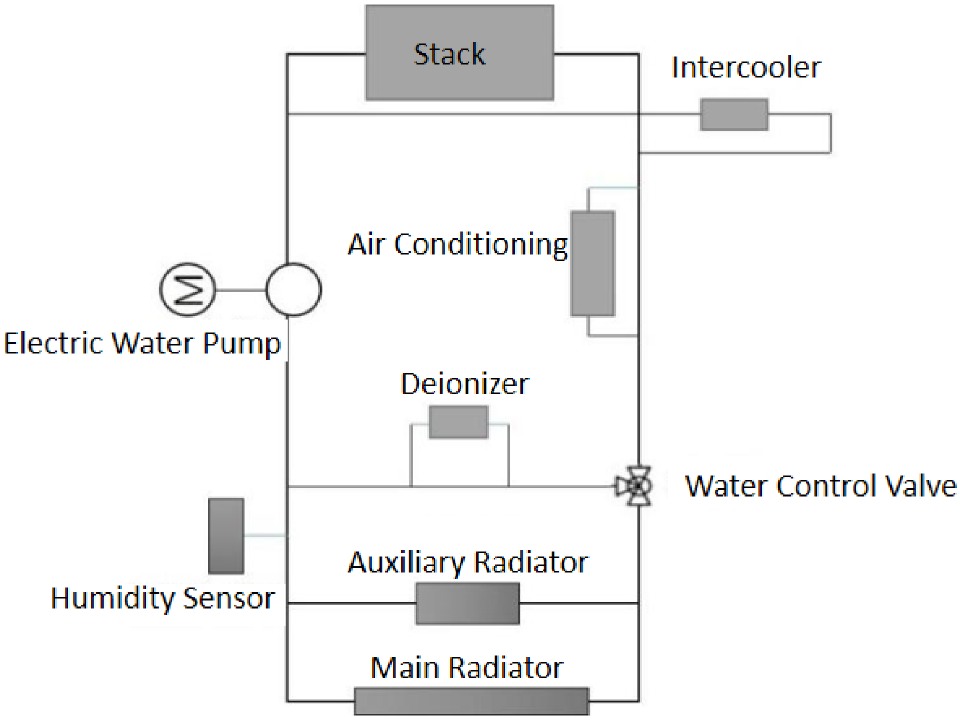

Figure 1. Toyota Mirai Thermal Management System Layout

Table 2. Test Equipment Parameters

Equipment Name	Equipment Model	Manufacturer	Test Parameters	Measurement Range	Measurement Accuracy
Chassis Dynamometer	48"MIM 4WD	AVL	Speed	(0~250) km/h	-
Environmental Chamber	763'/40-60/RoSo	WEISS	Temperature Humidity	(-40~60) ℃ (10~90) %RH	±0.5°C
Data Collector	MW100	YOKOGAWA	-	-	±5%RH
Temperature Sensor	Type K Thermocouple	Eurasian	Temperature	(-200~+1400)°C	Class I

The measurement location can be selected based on actual conditions, meeting the temperature requirements of the test field or the wind tunnel laboratory that meets relevant safety requirements. This experiment was conducted in the wind tunnel laboratory of China Automotive Technology and Research Center Co., Ltd., which can control and record the temperature and energy sensor data in real time. The recommended measurement temperature is generally 40°C, but it can be determined according to the manufacturer's requirements. The test vehicle usually needs to be placed in the test temperature environment for more than 12 hours so that the components on the vehicle reach the test environment temperature. See Table 2 for detailed equipment information.

Test Methods

Installation of Test Sensors

Based on the structure and principles of fuel cell vehicles, sensors are installed at measurement points that can reflect their thermal balance. The sensors are mainly divided into four types: temperature sensors, flow sensors, pressure sensors, and current voltage sensors. It is necessary to continuously record the state of the entire vehicle, especially the working state of the power system and the hydrogen supply system. Temperature sensors are the most important and complex to install in thermal balance testing. The recommended sensor installation positions are shown in Table 3.

Table 3. Temperature Sensor Installation Parameters

Serial Number	Measurement Parameter	Sensor Installation Position
1	Ambient Temperature	Installed at a height of 1.5m with the vehicle, away from heat sources; ventilated and avoiding direct sunlight
2	Stack Surface Temperature	On the surface of the stack
3	Chimney Inlet Water Temperature	At the center of the intake pipe
4	Chimney Outlet Water Temperature	At the center of the outlet pipe
5	Radiator Inlet Water Temperature	At the center of the radiator inlet pipe
6	Radiator Outlet Water Temperature	At the center of the radiator outlet pipe
7	Power Battery Surface Temperature	On the surface of the power battery
8	Power Battery Inlet Air Temperature	At the center of the intake pipe
9	Power Battery Outlet Air Temperature	At the center of the outlet
10	Water Pump Inlet Temperature	At the center of the inlet pipe
11	Water Pump Outlet Temperature	At the center of the outlet pipe
12	Motor Inlet Water Temperature	At the center of the inlet pipe
13	Motor Outlet Water Temperature	At the center of the outlet pipe
14	Humidifier Inlet Air Temperature	At the center of the intake pipe
15	Humidifier Outlet Air Temperature	At the center of the outlet
16	Intermediate Cooler Inlet Air Temperature	At the center of the intake pipe
17	Intermediate Cooler Outlet Air Temperature	At the center of the outlet
18	Condenser Temperature	At least 9 points evenly distributed in front of the cooler, facing the intake
19	Fan Temperature	Air temperature at different locations
20	Heater Inlet Water Temperature	At the center of the intake pipe
21	Heater Outlet Water Temperature	At the center of the outlet pipe
22	Deionizer Temperature	Installed on the surface of the pipe wall, close to the heat source
23	Air Compressor Temperature	Installed on the surface of the pipe wall, close to the heat source
24	Front Cabin Temperature	Front, back, middle of the left side, top, bottom, and the highest position of the engine compartment (generally at the exhaust manifold position)
25	Ambient Relative Humidity	Corresponding to the location of the ambient temperature measurement sensor
26	Sunlight Intensity	Placed on the roof, away from heat sources

Flow and pressure are crucial factors in studying thermal management strategies for fuel cell mass and heat transfer. Generally, it is necessary to monitor the pressure and flow signals of the main cooling components, as shown in Table 4.

Table 4. Pressure and Flow Measurement Parameters

Serial Number	Measurement Parameter
1	Hydrogen Tank Pressure
2	Hydrogen Inlet Pressure
3	Intake Pressure
4	Cooling Water Inlet Pressure
5	Cooling Water Flow Rate
6	Hydrogen Inlet Flow Rate
7	Intake Flow Rate

Current and voltage measurements can comprehensively test heat loss and energy distribution. It is generally necessary to record the current and voltage electrical signals of the stack, key components, battery, etc. Detailed information is shown in Table 5.

Table 5. Current and Voltage Measurement Parameters

Serial Number	Test Parameter
1	Stack Current
2	Stack Voltage
3	Battery Current
4	Battery Voltage
5	Air Compressor Current
6	Air Compressor Mechanical Pressure
7	Heater Current
8	Heater Voltage

Comparing traditional methods for testing the thermal balance capability of automobiles with the analysis of dynamic driving road conditions, it can be seen that the conditions have evolved from a single vehicle speed steady-state limit condition to high-speed conditions, high-speed climbing conditions, low-speed climbing conditions, and other dynamic driving conditions. With the development of automotive thermal management testing capabilities and the actual road conditions in China, the "China Automotive Driving Conditions" (GB/T38146-2019) are used as one of the evaluation conditions for thermal balance capability. Detailed test results are shown in Table 6.

Table 6. Operating Parameters for Testing Fuel Cell Vehicles

Operating Condition	Temperature Pre-treatment	Speed	Slope Post-treatment	Driving Time
High-Speed Condition	40°C, 40% humidity, no light, gas-liquid temperature reaches 40±1°C	140 km/h	0% Cool down by turning off until temperature drops to the test point, then start the test	Drive to thermal balance
High-Speed Climbing Condition		120 km/h	3% Cool down by turning off until temperature drops to the test point, then start the test	Drive to thermal balance
Low-Speed Climbing Condition		40 km/h	10% Cool down by turning off until temperature drops to the test point, then start the test	Drive to thermal balance
Urban Operating Condition		China conditions	0% Cool down by turning off until temperature drops to the test point, then start the test	Drive to thermal balance

Note: "China conditions" refers to "China Automotive Driving Conditions" (GB/T38146-2019).

DATA ANALYSIS AND VERIFICATION

According to the established test plan, the Toyota Mirai fuel cell vehicle was selected for thermal balance testing. The rated power of the fuel cell stack is approximately 68kW. Sensors were arranged in the engine compartment, passenger compartment, cargo compartment, hydrogen system compartment, and chassis. The fuel cell vehicle was moved to the wind tunnel laboratory for thermal balance testing at 40°C. First, the fuel cell vehicle was immersed in the test temperature for more than 12 hours. At this time, the vehicle's status and the battery's SOC status were recorded. After completing the preparations, data acquisition instruments and exhaust emission concentration testers were started. The test process is mainly divided into three steps. First, start the vehicle according to the manufacturer's specified test method; second, execute the test conditions. According to the selected test conditions, achieve the specified test conditions at the speed the vehicle can reach, and then conduct the test. Finally, monitor important sensors and signals. When the monitoring point is stable for 4 minutes and the temperature change does not exceed ±2°C, the vehicle is considered to have reached a thermal balance state.

The test mainly focuses on thermal balance testing under three conditions: China conditions, 0% slope + maximum speed, and 3% slope + maximum speed. The equilibrium temperatures of the fuel cell stack under the three working conditions are shown in Table 7.

Table 7. Inlet and Outlet Water Temperatures of the Fuel Cell Reactor under Various Test Conditions

Test Condition	Reactor Inlet Water Temperature (°C)	Equilibrium Temperature	Reactor Outlet Water Temperature (°C)	Equilibrium Temperature	Reactor Outlet Water Temperature (°C)	Maximum Immersion Temperature
China Conditions	73.6	78.1	——		——	——
Maximum Speed + 3% Slope	81.5	86.7	86		——	——
Maximum Speed + 0% Slope	87.5	91.2	92.0		——	——

This experiment uses "China conditions" to evaluate the thermal balance, which can fully reflect the thermal balance capability of the vehicle under China conditions. The focus of the experiment is to analyze the changes in the cooling temperature of the fully immersed vehicle at 40°C. As shown in Figure 1, under the "China conditions," the temperatures of the cooling components are relatively moderate, and there are no significant temperature differences. The average temperature of the condenser is around 40°C, and the average temperature of the fuel cell stack radiator is about 50°C. The temperature of the cooling system in each part is relatively stable. The temperature difference between the inlet and outlet temperatures of the reactor is within ±5°C. It can be seen that under the operating conditions of China conditions, the thermal vehicle management system can accurately control the reactor temperature, radiator temperature, and other related components through good matching and calibration, keeping the temperatures within a relatively comfortable range.

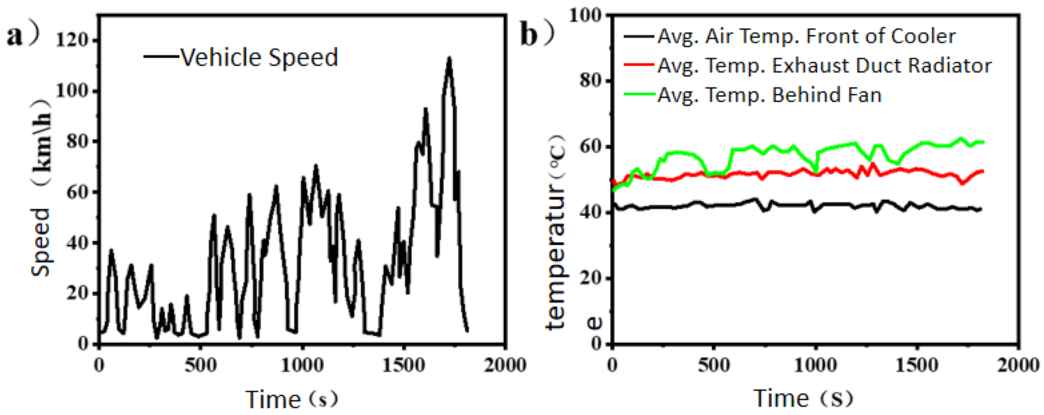

Figure 2 a. Vehicle speed under China conditions b. Average temperature in front of the cooler, exhaust duct radiator, and behind the fan under China conditions

At a test temperature of 40°C, the vehicle ran at its maximum speed continuously for 20 minutes. As shown in Figure 3a, although the vehicle's maximum speed was set to 175 km/h, the actual maximum speed reached 156 km/h and remained stable at 150 km/h thereafter. This is mainly because the power of the fuel cell stack continuously increased at the maximum speed. When the power reached about 70 kW, the fuel cell stack could balance the heat generated by the motor. The vehicle adjusted the operating power to achieve the target, and the rated power of the fuel cell stack eventually stabilized at about 60 kW. As shown in Figure 3d, during this process, the SOC of the power battery briefly increased and then continued to decrease, stabilizing at around 38%. This indicates that the driving power of the vehicle is jointly provided by the power battery and the fuel cell.

As shown in Figure 3b, during the process from starting the vehicle to reaching the maximum speed, the maximum power of the fuel cell stack can reach about 80 kW. At this time, its temperature is 68.6°C (Figure 3c), which means that when the temperature of the fuel cell stack reaches this level, its power will be limited.

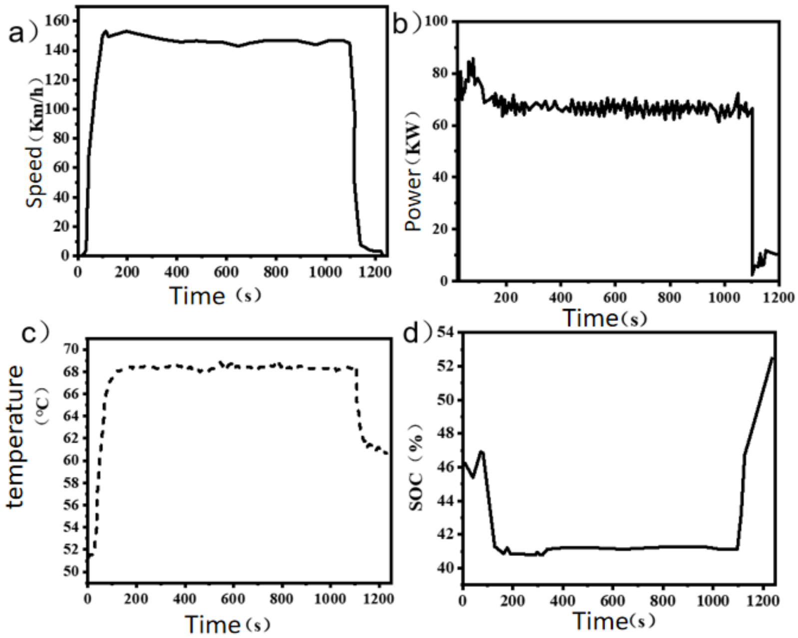

Figure 3 a. Vehicle Speed b. Stack Power c. Reactor Temperature d. Power Battery SOC Variation Curve

As shown in Figure 3b, when the fuel cell stack remains stable at a power output of 65 kW, its temperature can reach 68°C. This is the criterion for determining the thermal balance state, and the temperature is essentially the operational temperature limit of the fuel cell. It can be seen that during the thermal balance control process, the vehicle mainly utilizes the thermal capacity of the fuel cell stack and its temperature regulation capabilities to adjust control strategies.

As shown in Figure 3c, during the rapid heating process of the fuel cell stack, the initial temperature is 51.4°C, and the equilibrium temperature is 68.92°C, which takes a total of 59.1 seconds. During this process, the battery pack heats up rapidly at a rate of 0.53°C/s. At this time, the operating temperature of the fuel cell stack has reached a certain height, indicating that it is in a high-temperature operating stage, and it cannot continue to heat up rapidly after a short period.

When the vehicle is driving at a speed of 140 km/h under immersion conditions of 40°C, the temperatures of the main cooling components are shown in Figure 4b. It can be seen that the average temperatures before the low-temperature radiator and the FCS radiator are relatively low, with temperature variations controlled around 17°C. The temperature changes before and after the sub-FCS radiator are larger, showing a higher rate of temperature increase.

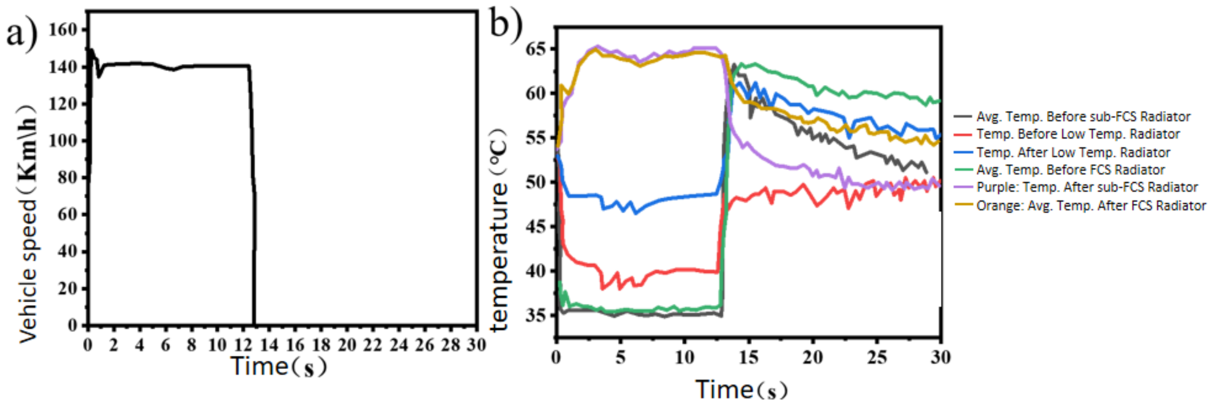

Figure 4 Average temperature changes before and after the cooling module under the conditions of 140 km/h and 40°C, with respect to vehicle speed and time. a. Speed-Time Variation Curve b. Temperature Variation Curve

CONCLUSION

Based on the analysis of the thermal management principles of fuel cell vehicles, this paper developed a method for evaluating the thermal balance of fuel cell vehicles, test schemes, and signal acquisition plans. Test conditions and operating conditions were formulated based on the fuel cell. Through this method, the thermal balance of advanced fuel cell vehicles was tested and analyzed. The thermal balance of fuel cell vehicles under extreme conditions is achieved by reducing and increasing power to dissipate temperature differences. This work provided key temperature measurement points and specific measurement locations during the testing process, which can directly guide the thermal balance test operations for the entire vehicle.

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