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Fuel Cell Vehicle Thermal Management Research

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Abstract. The vehicle's thermal management system is critical to the safety, durability, performance and passenger comfort of fuel cell vehicles, and is also one of the core technologies of fuel cell vehicles. The thermal management system needs to meet the thermal balance of the vehicle under the operating limit conditions and balance the working temperature of different components. This paper analyzes the structure and control strategy of the thermal management system of different vehicle models through the research summary of the current thermal management technology of fuel cell vehicles, summarizes the impact of different parameters on thermal efficiency, and deeply analyzes the technical research field and development in this direction. The direction gives some methods to improve the performance of the thermal management system during the selection of the R&D technology route and the development process of the enterprise.

Keywords. Fuel cell vehicle, thermal management system, thermal efficiency

1. Introduction

As one of the important development directions of new energy vehicles in the future, fuel cell vehicles are widely regarded as an important research direction for future development. An efficient thermal management system is of great help in improving the life and efficiency of fuel cell vehicles, and which can effectively reduce hydrogen consumption. The main driving force of fuel cell vehicles is the fuel cell, which has the low working temperature (60°C-80°C) and large heat dissipation, so the fuel cell vehicles need a large thermal management system, how to achieve high integration, low cost, high efficiency of the thermal management system is also the current technical bottleneck of its technology development.

The thermal management system of fuel cell vehicles is extremely complex, which has dissipating heat by 90% compared to traditional internal combustion engines. In the face of complex vehicle usage conditions, it is necessary to meet the needs of use under different working conditions in order to achieve industrialization. According to the technical requirements of China's 14th Five-Year Plan, the power of fuel cell stacks continues to increase, and the ability to provide a more efficient thermal management system is required compared to the high-temperature environment used. At this stage,

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the main heat dissipation methods are mainly phase change cooling, heat pipe cooling, air cooling and liquid water cooling, for high-power fuel cell stacks, generally the way of liquid water cooling has more efficient.

At present, the technical improvement of the thermal management system of fuel cell vehicles is still a hot topic, more and more researchers have paid attention to the thermal management system of fuel cell vehicles, including the study of the thermal balance and key heat dissipation of the whole vehicle. Through the analysis of fuel cell vehicles, the main heat sources are divided into four parts, namely fuel cell stacks, air compressors, high-voltage accessories (drive motors and DC/DC, etc.), power batteries, etc. The working principle of fuel cell stacks is to convert chemical energy into electrical energy and heat, so it requires a large heat dissipation capacity. Power batteries generally can use air cooling to meet its use needs due to their low heat dissipation. By analyzing different temperature requirements and heat dissipation capacity, the thermal management of vehicle is divided into three major cooling circuits [1]. They are fuel cell system cooling system, high pressure accessory cold removal system, and air conditioning refrigeration system. In the cooling circuit of the fuel cell system, the fuel cell stack and the intercooler are used as the main heat dissipation components to reduce the intake air temperature; the control circuit of the high-voltage electrical appliance mainly includes the heat dissipation of the motor, air compressor, DC/DC, air conditioning heating and other components; the cooling circuit of the third air conditioner is the key to affecting the comfort of the driver, mainly including the condenser, expansion valve, evaporator, compressor, etc. Due to the limitation of the layout and space of the whole vehicle, the three heat dissipation circuits are coupled to each other in actual use, which puts forward higher requirements for the thermal management system of the whole vehicle. It is necessary to meet the control needs of each circuit under different working conditions in the control strategy, distinguish the priority level, control the speed of the fan, and meet the high heat dissipation requirements of the heating element.

Based on the research methods of the thermal management system of fuel cell vehicles, this paper summarizes the different reasons affecting the performance of the thermal management system of fuel cell vehicles through the analysis of different control strategies, the research status of key technologies and the technical routes of current vehicle enterprises, and which also proposes to improve the technical route analysis and development of the main engine plant thermal management system.

2. Working Principles of the Heat Management System

2.1. Design Requirements of Thermal Management System for Fuel Cell Vehicles

The key core components of fuel cell vehicles: fuel cell systems, motors, controllers and power batteries and other work conditions are closely related to temperature, in order to meet the temperature requirements of different components, the development of high-performance, high-efficiency thermal management system is the technical difficulties of fuel cell vehicles. The heat source of the entire vehicle is mainly divided into four parts [1, 2], which are fuel cell stacks, motors, air compressors, DC/DC and other high-voltage electrical, evaporators and compressors for air conditioning, and power battery systems. Due to the different working temperatures of each circuit, as shown in Table 1, three cooling circuits are generally used for separate cooling, of which most of the cooling of the power battery is dissipated in the form of air cooling, so there is no need for a separate cooling circuit.

Table 1. Thermal dissipation parameters for key components of the thermal management system.

	Cartridge element	Thermal power production	Operating temperature	Heat dissipation element
Fuel cell stack cooling system	Stacks, intercoolers	60-150kW	60°C-85°C	Radiator
High voltage electrical cooling circuit	Air compressors, motors, DC/DC	20kW	Air compressor (100°C), motor (65°C), DC/DC (60°C)	Radiator
Air conditioning cooling system	Evaporators, compressors	20kW	18-28°C	Condenser

Among them, the heat dissipation power of the fuel cell stack exceeds half of the heat dissipation power of the whole vehicle, mainly because the working principle of the fuel cell stack, the hydrogen that occurs in the electrochemical reaction is emitted in an electrical and thermal manner, such as the 100 kW fuel cell stack running, the ability to design the radiator needs to reach 100 kW. Another reason is that the heat dissipation of fuel cell stacks is mainly based on the cooling system [3], and the heat dissipation of the tail row system and radiation is not more than 5%, which needs to be designed to consider the large operating environment and function.

2.2. Thermal Management Structure of Fuel Cell Vehicles

Through the study of the heat dissipation devices and working temperatures of fuel cell vehicles, it is found that the thermal management system of fuel cells is mainly cooled by water cooling. Due to the different structures of the whole vehicle, the layout and scheme of its cooling system are also different. For fuel cell passenger cars, the integration and design of thermal management systems is far more difficult than commercial vehicles, and the current leading fuel cell models are Toyota's Mirai (Figure 1), Honda's Clarity (Figure 2) and Hyundai's NEXO (Figure 3). The structural analysis of the thermal management systems of the three models is as follows:

The maximum power of the fuel cell stack of the Mirai model reaches 114 kW, and its full power operation is larger, and two circuits are used in the structural design for heat dissipation, and when the stack heat production is small, the small cycle is used to dissipate heat, and the reverse use of the control thermostat and large cycle to achieve the cooling effect. In order to avoid the high load operation of the thermal management system, this design has several highlights, first of all, in the control strategy, it will avoid the continuous operation of this working condition as much as possible with full use of the air flow rate to relieve the pressure of heat; secondly, make full use of the parallel design of the main and auxiliary radiators and the size of the thermostat to circulate the color traces for effective temperature adjustment. Under typical low temperature start conditions, make full use of the heat production capacity of the stack itself, and effectively increase the ability to warm the machine by adjusting the polarization curve.

Clarity's thermal management system is different from Mirai's, which is shown in Figure 2, and its thermal management system mainly consists of a heater, water pump, radiator and thermostat. The deionizer is connected in parallel with the stack to give an effective outgoing coolant, and the thermostat can quickly adjust the size of the radiator. The whole structure is simple and the utilization rate is high.

NEXO as a representative of medium-sized vehicles, its new thermal management system mainly includes radiators, four valves, PTC heaters, pumps, COD heaters and two-way valves, etc., using a variety of types of valve structures to improve the corresponding control of temperature. The thermistor installed in the car can effectively utilize the waste heat in the car by adjusting its own power. At the same time, the design of the four-way valve is also an innovation of the thermal management system, which effectively improves the starting capacity under low temperature conditions.

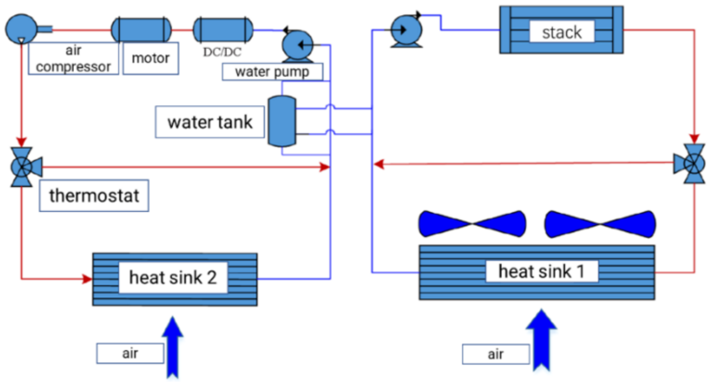

Figure 1. Layout scheme of Toyota Mirai fuel cell thermal management system.

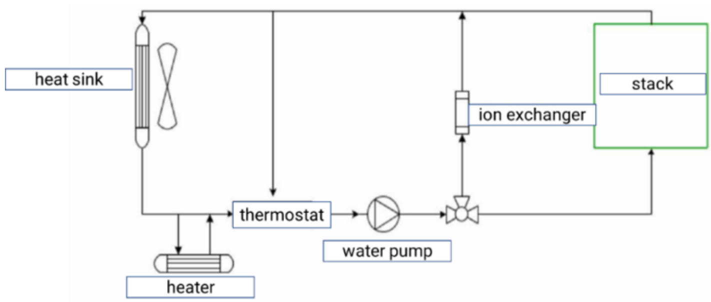

Figure 2. Layout scheme of Honda's clarity fuel cell thermal management system.

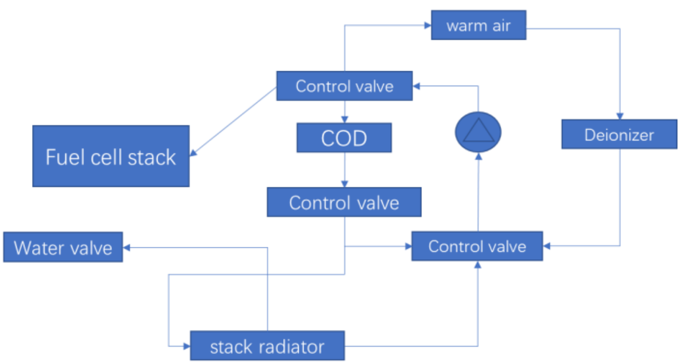

Figure 3. Layout scheme of modern NEXO fuel cell thermal management system.

2.3. Thermal Management Analysis of Fuel Cell Vehicles

(1) Fuel cell stack heat generation analysis

Fuel cell stack is the core component of the fuel cell vehicle power system, in the process of chemical energy into electrical energy, the fuel cell stack will lose a part of the heat energy, the source of heat mainly includes chemical reaction heat, Ohm polarization heat, environmental thermal radiation, etc., and ultimately which cause the temperature of the entire fuel cell stack to rise. The efficiency of the fuel cell stack is 40%-60%, so the remaining 40%-60% is all dissipated in the form of heat.

(2) Heat generation analysis of electrical units

Motors, motor controllers, DC/DC, air compressors and other heat dissipation power are more than 1 kW, through different vehicle drive types, the vehicle control unit can determine the maximum heat generation of these heat dissipation devices, and then design the corresponding to meet the working temperature conditions of the heat dissipation parts of the working parameters, and which can provide better heat dissipation needs.

(3) Heat analysis of air conditioners

The comfort of the occupant compartment is an important evaluation index of the vehicle, and the heat dissipation performance of the air conditioner is one of the core contents of the indicator. For fuel cell vehicles, the air conditioning settings are not different from the models of traditional internal combustion engines, and the electrical components for heat dissipation mainly include compressors, condensers, evaporators, and two-way valves. In the design of the entire thermal management system, it is necessary to consider the series and parallel analysis with other thermal circuits to improve its integration. Generally due to the problem of heat recovery, the refrigeration system and heating system are generally divided into two ways, and the waste heat generated by the stack is used to provide heating effect for the air conditioner, which effectively improves the efficiency of the thermal management system.

3. Optimization of Thermal Management Systems

3.1. Optimization of Control Strategies

Fuel cell vehicles need to consider the temperature adjustment of the three major cooling circuits under the actual use conditions, so that the power system and air conditioning and electrical of the fuel cell vehicle are in a suitable temperature state, and the control strategy is coordinated [4]. The logic of the entire control needs to be considered: (a) the priority control logic of the cooling circuit; (b) the energy control of the heat dissipation device, reducing the energy control of the long time; (c the way of waste heat recovery to improve thermal efficiency.

Based on the above analysis, relevant research work has been carried out continuously. Jiang [5] designed a thermal management control strategy to enable it to start quickly in a low-temperature environment and meet the requirements of use, the thermal management has adopted four working modes to adjust the temperature and vehicle state. Firstly, the temperature of the fuel cell stack reaches the starting temperature through the heater, and then the temperature of the crew cabin is adjusted through the size circulation and the heat exchanger. Using this way, the electricity consumed by the heater reduces hydrogen consumption by about 10%. Experiments [6-8] prove that the electric heater can effectively reduce the consumption of hydrogen. The source of temperature control is to reduce the generation of heat. Through the energy control method, for the electric-electric hybrid fuel cell vehicle, the generation of heat can be limited by limiting the high power output. The thermal management system not only needs to consider the heat dissipation in high temperature conditions, but also needs to consider the heat supply in low temperature environment. It is not only necessary to meet the rapid warming of the passenger cabin and fuel cell stack at low temperatures, but also to reduce the energy consumption in the process. The recycling and utilization of waste heat has become a research hotspot. The heat stored in fuel cell stacks (60-80°C) at low temperature can be fully utilized to effectively recover the waste heat generated by fuel cell stacks and provide the energy required by vehicles [5]. The difficulty of recycling waste heat lies in controlling the temperature of fuel cell stacks and passenger cabins. Temperature control strategy is required to meet the requirements under different operating conditions and environmental conditions. There are many studies on the control strategy of cooling system, but the influence of hydrogen supply from hydrogen supply system on fuel cell stack cannot be ignored [9-12]. Zhu [13] and others give full consideration to the metal hydrogen storage vessel thermal control integration for hydrogen and fuel cell system of energy of the coupling relationship between each other, who put forward a kind of thermal management strategy based on PID controller to control the supply of hydrogen flow rate. By this way, the thermal management can reduce the heat load of fuel cell system in order to reduce the deterioration of the battery, which can prolong the service life of the fuel cell.

3.2. Optimization of Key Components

In the process of integrated design of the actual vehicle, different heat sources need to be considered to select and match different heat dissipation components, especially radiators, water pumps, fans, etc. In recent years, after the planning and development of the 13th Five-Year Plan, full-power fuel cell vehicles have become the main research directions of major automobile manufacturers. Improving thermal efficiency under the same working conditions is the key to selecting components. Heat dissipation area, intake air velocity, position arrangement, etc. are the key to affecting efficiency of radiators [14, 15]. Li [2] designed extreme working conditions of vehicle speed of 20 km/h, temperature 45°C, heat production up to 105kW, which can simulate the outlet temperature of the stack and the temperature changes of each component, using the simulation study of full-power fuel cell vehicles, put forward the requirements for the heat dissipation efficiency of key components. Due to the different temperature requirements of each part, the efficiency requirements of its heat dissipation components are also different, such as the working temperature of the stack, air compressor, DC/DC is about 75°C, 100°C and 60°C, so the corresponding work efficiency is 49%, 60% and 92% respectively. The ultimate solution to the thermal management system of fuel cell vehicles is to effectively improve heat dissipation. Zeng [16] showed that the use of deionized water and increasing the flow of coolant can effectively improve the thermal efficiency of the thermal management system. As an indispensable part of the thermal management system of fuel cell vehicles, the thermostat plays a significant role, and after several generations of updates, the thermostat has been greatly improved in terms of response rate, temperature control and life [17].

3.3. Optimization of Operating Conditions

The limit operating conditions and working temperatures of general passenger cars are similar, and the heat dissipation capacity can be effectively improved by increasing the working temperature of the fuel cell stack and increasing the flow of air [18]. The working temperature of the fuel cell stack is difficult to increase due to its working characteristics, so the method of increasing air flow has become the focus of most main engine plants. Xia et al. [14] improved their heat dissipation capacity by designing to increase the power of the fan, the area of the radiator, and the position layout. In addition to the design of the vehicle itself, the driver's driving habits and traffic conditions also have an impact on the thermal management system, Rodriguez [19] considering all the cooling environment and the load environment of the air conditioner, design and study the intelligent vehicle thermal management model analysis, which can more realistically simulate the actual vehicle usage state. Zeng [16] studied the study of heat dissipation efficiency on the thermal management system, and studied the influence of the heat transfer efficiency of the radiator on the thermal characteristics and working conditions of fuel cell vehicles. The results show that the efficiency of the radiator is greatly affected by the coolant and air flow rate, the efficiency of the radiator increases with increased coolant flow and decreased air velocity.

3.4. Simulation Study of Thermal Management System

In the design and development process, OEMs need to improve the thermal management system of fuel cell vehicles from the following directions: (1) selecting a good heat dissipation material, which can make the internal and external temperature difference of the components low; (2) designing the limit working conditions to meet the maximum heat dissipation needs; (3) the control strategy optimization can effectively remove the heat dissipation under the highest operating conditions of the fuel cell stack. The establishment of a comprehensive model of the thermal management system is a great improvement for improving the state form of fuel cell vehicles under different working conditions, and the current simulation study includes the control of the whole and the simulation of key working conditions and components. Fuel cell vehicle cooling system is very different from conventional fuel vehicles [20], under the same high load cycle, its heat transfer area is increased by 70%, in contrast, the use of simulation can be used to monitor and optimize the state of the thermal management system at all times.

Efficient thermal management system has always been the goal pursued by researchers, through the optimization of control strategies and algorithms, so that the efficiency of fuel cell thermal management systems can be improved. By considering reasonable control strategies and heat analysis, a comprehensive fuel cell vehicle thermal management system model [21] is established, which adopts proportional integral differential method and multi-stage control to adjust the speed of pumps and fans, which can analyze the changes when the whole vehicle is under the influence of different thermal energy, which is of great significance to the thermal management design of the vehicle. Tao et al. [22] investigated the integration of advanced control algorithms into refrigeration systems, including an electromechanical compressor, a cooling pump, and several radiator fans. The results show that it not only minimizes temperature fluctuations in batteries and ice compared to traditional cooling control methods, but also reduces the overall auxiliary power consumption of the cooling system by 45%.

In the selection and structural design of parts, research can also be carried out by means of numerical simulation. Wang et al. [1] designed and optimized the thermal management scheme by establishing a model of fuel cell system and high-pressure cooling system, and realized that the optimization and selection of different working conditions and the adjustment of reasonable control strategies. Niu et al. [23] studied fuel cell temperature characteristics and model structure to clarify the function, objectives and control requirements of the thermal management system of the water cooling system, and built a test platform for the thermal management system based on PLC control. Toli [24] used numerical simulation methods to study the impact on the performance of 1kW fuel cell stacks without external humidification, including bipolar plate material coefficients, flow field pressure, radiator configuration, etc., and analyzed the factors affecting fuel cell stacks in principle. It was found that the temperature of the entire interior of the boundary temperature reactor had a great influence.

4. Summary

The thermal management system of fuel cell vehicles plays a key role in the operation of the whole vehicle. By studying literature research of different control strategies and methods, the way to optimize the thermal management system capabilities are summarized. The study of the influence of different material parameters, flow rates, radiator types on the limit working conditions, and the mainstream control methods and structures are understood by comparing the three typical fuel cell vehicle thermal management system structures, which provides effective suggestions for the subsequent research and development process.

Starting from the mechanism summary and influencing factor analysis, the efficiency of the thermal management system of vehicle fuel cell can be improved by the following methods:

(1) Improving the control strategy of the thermal management system, and match the heat generation algorithm for different test conditions and fuel cells;

(2) Selecting a good bipolar plate material so that it can have good heat dissipation performance;

(3) Increasing the heat dissipation area and air intake can effectively improve the performance of the thermal management system.

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