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Hydrogen and fuel cell technology in automotive applications

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Summary

Fuel cell is considered to be one of the most promising next-generation energy sources for clean vehicles. This paper introduces the key components of fuel cell electric vehicles, including proton exchange membrane fuel cell stack, auxiliary energy storage system, hydrogen supply system, hydrothermal management system and control system, and explains the operation principle. In addition, this paper analyses the overall development status of hydrogen energy vehicles, discusses the key breakthrough direction and development perspectives.

Keywords: hydrogen electric vehicle, proton exchange membrane fuel cell, energy storage system, hydrogen supply system, hydrothermal management system

1 Introduction

Proton exchange membrane fuel cell (PEMFC) has seen a wide application prospect in transportation sector. In addition to the general advantages of fuel cells, such as higher energy conversion rate than internal combustion engine and environmental friendliness, PEMFCs have also the advantages of cold start, low electrolyte loss, easy separation and elimination of reactants, long service life and high specific power. Therefore, PEMFCs are not only used in power generation facilities, but also favoured by electric vehicles. It is recognized as one of the most impressive development directions of the next-generation electric vehicles [1].

This paper introduces the key components of fuel cell electric vehicles, including proton exchange membrane fuel cell stack, auxiliary energy storage system, hydrogen supply system, hydrothermal management system and control system, and explains the operation principle. In addition, this paper analyses the overall development status of hydrogen energy vehicles, the key breakthrough direction and development perspectives.

2 PEMFC stack

At present, the mainstream PEMFC stack is assembled using the fastening mode of press limit bolt, which has the form of an internal common channel. The so-called PEMFC stack is a stacked combination of single cells composed of membrane electrode assembly (MEA), gas diffusion layer, bipolar plate and sealing gaskets. The cell structure of the fuel cell stack is shown in Figure 1.

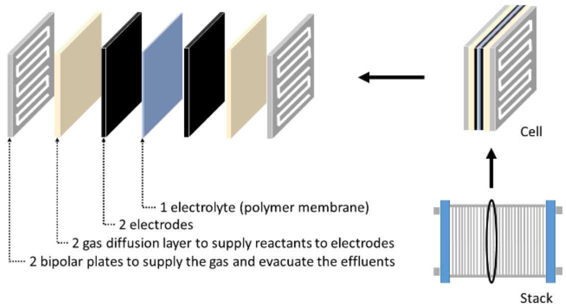


Figure 1 The cell structure of PEMFC

In the internal reaction of a single cell, hydrogen passes through the diffusion layer of the anode in a gaseous state, which loses electrons in the catalytic layer and becomes hydrogen ions. The proton exchange membrane provides a channel for the migration and transportation of hydrogen ions, so that hydrogen ions can pass through the membrane from the anode to the cathode, where they combine with H_2O molecules through hydrogen bonds to form H_3O^+ and pass through the proton exchange membrane in the form of electro migration. Electrons are transported through the external circuit and provide current to the outside [2]; The transportation of electrons depends on the current density and the proton hydration number. In addition, the endplate contains inlet and outlet channels for reaction gas and coolant.

In terms of battery power, the power density of the current fuel cell engine has increased significantly compared with the early stage, basically reaching the level of the traditional internal combustion engine. At present, the output power of foreign fuel cell passenger car engine is 80 ~ 100kW, that of Honda clarity fuel cell engine is 130kW, and that of domestic typical fuel cell car is 35 ~ 50KW. According to the statistical data of fuel cell industry review 2017, the global hydrogen fuel cell shipment power in 2017 was 670 MW, an increase of 30% year-on-year. In terms of battery life, fuel cell life has been able to meet commercial requirements, such as thousands of hours for cars and tens of thousands of hours for buses. In terms of service environment, vehicle fuel cells can adapt to the climate conditions of - 30 ˚C and reach the level of traditional vehicles [3]. Looking at the international market, traditional automobile powers such as Japan and Germany have made full attempts and launched a number of mature products.

The parameter comparison of the above four vehicles is shown in Table 1.

Table 1 The comparison of four typical commercial FCVs

Name	Mercedes Benz GLC F-CELL	Honda Clarity	Toyota Mirai	Hyundai NEXO
Body size	4915*1875*1480	4915*1875*1480	4890*1815*1535	4670*1860*1630
Vehicle appearance				
Fuel cell power/kW	100	103	114/90	113/95
Fuel cell power density/kW·L^{-1}	/	3.12	3.10	3.10
Hydrogen tank capacity/L	/	141.0	122.4	156
Hydrogen storage quality/kg	4.4	5.46	5.0	6.33

Maximum power of drive motor/kW	100	130	113/114	120
Top speed/km·h^{-1}	170	165	175	179
0-100 km acceleration time/s	11.3	11.0/9.7	9.6/9.5	9.5/10.0/9.2
Range(EPA working condition)/km	/	579	502	569.7-611.6
Range(NEDC working condition)/km	500	750	650	804.7
Battery durability/h	≥5000	5000	≥5000	5000
Low temperature performance of fuel cell/ ℃	-25	-30	-30	-30
Fuel cell platinum consumption/g·kw^{-1}	0.200	0.120	0.175	/
Maximum torque/N·m	350	300	335	300
100km Hydrogen consumption/kg	0.91	0.97	0.76	0.84
Battery pack capacity/kw·h	9.0	/	1.6	1.56

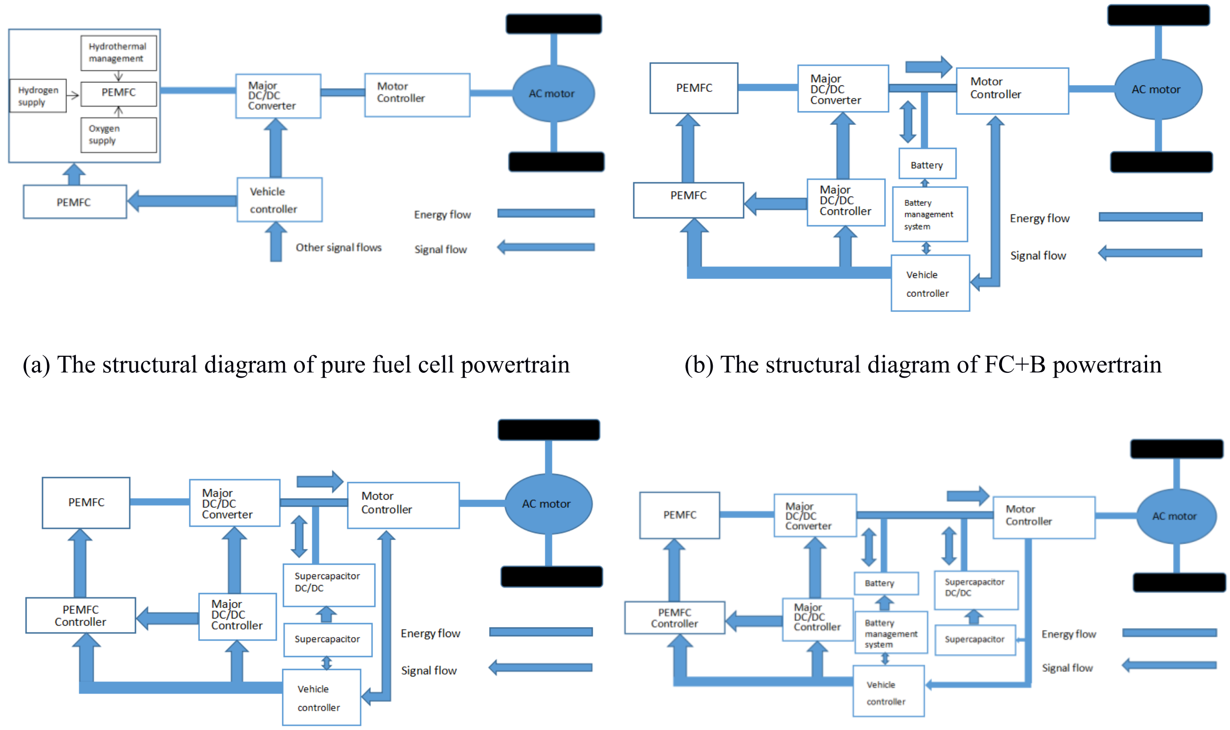
The reasons for the high price of fuel cell vehicles are the complex structure and the use of expensive raw materials. Bipolar plate, catalyst, proton exchange membrane and carbon support in the stack are the main costs of the fuel cell [4]. In addition, equipment such as hydrogen storage cylinder and three-dimensional flow field inside the fuel cell to improve the performance of the whole vehicle also need high costs. In the cost of hydrogen fuel cell system, the stack cost accounts for about 60% of the total system cost, the proton exchange membrane and catalyst cost accounts for about 50% of the stack cost, and the bipolar plate cost accounts for about 40% of the stack cost. The maintenance and fuel supply issues that consumers should consider after buying a car are also a key factor limiting fuel cell vehicles.

3 Auxiliary energy storage system

According to the use of auxiliary energy storage system use in the powertrain, fuel cell vehicles can be divided into pure fuel cell vehicles and hybrid fuel cell vehicles. At present, pure fuel cell powertrains are rarely used in automotive applications, most of which are hybrid powertrains with different auxiliary power sources. The addition of auxiliary power sources can reduce the cost of the whole vehicle. When the vehicle has peak power demand such as starting, climbing and acceleration, the auxiliary power sources can quickly respond to the peak power. In this way, the requirements for the dynamic response of the fuel cell are low, and the fuel cell can work under its high-efficiency working conditions. In addition, the auxiliary energy storage system can also recover braking energy and improve the energy efficiency of the whole vehicle.

3.1 Pure fuel cell driven vehicle power system

Figure 2(a) shows the structure of a pure fuel cell, with only one power source. All the power load on the car is borne by the fuel cell. Its disadvantages are very obvious. One is the high maintenance cost brought by pure fuel cells; Second, the vehicle operation needs high dynamic performance and reliability; Third, the braking energy cannot be recovered. Therefore, this configuration has not been put into actual production.



(a) The structural diagram of pure fuel cell powertrain

(b) The structural diagram of FC+B powertrain

(c) The structural diagram of FC+C powertrain

(d) The structural diagram of FC +B+ C powertrain

Figure 2 The structural diagram of different powertrains

3.2 Fuel cell + Battery (FC+B) Powertrain

Figure 2(b) shows the structure of fuel cell power system with "Fuel Cell + Battery (FC + B)" hybrid drive, which is also the well-known series hybrid fuel cell vehicle. In the driving mode, the fuel cell and battery together provide energy for the driving motor, and the motor converts electrical energy into mechanical energy and outputs it; When braking, the motor can also generate electricity, and the excess energy is recovered by the battery. The excess energy output can be borne by the battery pack under the change of driving mode. Because this configuration has been widely used in actual production, its low-temperature start-up performance has been fully tested and the effect is good. However, affected by the number of battery packs, the dead weight of the whole vehicle has been greatly improved, which has become an urgent problem to be solved.

3.3 Fuel cell + Super Capacitor (FC + C) Powertrain

Figure 2(c) shows the structure of the fuel cell power system with "fuel cell + super capacitor (FC+C)" hybrid drive. The innovation of this configuration is the use of emerging capacitor technology. Due to the long service life and high efficiency of the capacitor, the transient characteristics of the whole vehicle with this configuration are greatly improved, and the impact of the motor on the fuel cell is alleviated to a certain extent. However, the capacity of super pole capacitor is one order of magnitude less than that of battery, so this configuration can only carry out short-distance charge and discharge driving, so it has not been popularized on a large scale. It also means that its commercial promotion takes a long time.

3.4 Fuel cell + Battery + Super Capacitor (FC +B+ C) Powertrain

Figure 2(d) shows the structure of hybrid drive fuel cell power system with "fuel cell + Battery + super capacitor (FC + B + C)". The biggest highlight of the system is that a group of super capacitors are connected in parallel on the series hybrid fuel cell system, which realizes the effective combination of high energy density of fuel cell and high power density of super capacitor. When the automobile needs high power output, the super capacitor can give full play to its own advantages. However, the control of this system is very difficult and the research and development cost is very high, so it is almost invisible in the market.

3.5 Other types of powertrains

In fact, the hybrid fuel cell power system structure of "ultra-high speed flywheel + fuel cell + battery (FC + B + FW)" also exists. As a mechanical energy storage element, the ultra-high speed flywheel in traditional vehicles can still play an important role in the field of electric vehicles. Moreover, as an important component for storing the energy and inertia outside the power stroke of the engine, the flywheel technology has been relatively mature after a long time of testing. In view of its long service life, high efficiency and environmental friendliness, if the follow-up research can overcome the material problem of the flywheel, there is no doubt that it can greatly improve the efficiency of the battery system. However, subject to the high cost of technological breakthrough, the technology has not made much progress.

4 Hydrogen Supply System

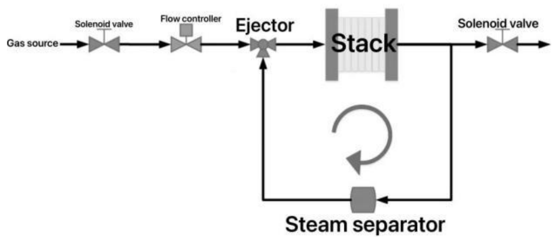
In PEMFC, higher reaction gas pressure can significantly improve the performance of the stack, but exceeding the mechanical strength of the proton exchange membrane will cause its perforation and fracture. Therefore, when the hydrogen pressure of the anode increases, the cathode air must also be pressurized by the air compressor to ensure an appropriate pressure difference. In engineering, in order to ensure the normal operation of PEMFC and improve the utilization rate of reactants, the tail gas circulation method is usually adopted, i.e., the gaseous water inside the reactor is carried out with the remaining reaction gas, while the gaseous water and liquefied water are separated by the centrifugal device, and then transported back to the anode by the circulating pump for reuse. At the same time, dew point humidification is used to humidify the newly input hydrogen. The self-humidifying fuel cell stack developed by Toyota represents an advanced international level, and the self-humidification technology still has broad development space in the future. As an important part of vehicle fuel cell system, hydrogen supply system (HSS) works together with air supply system, water management system and electronic power system to ensure the stable supply of hydrogen flow and pressure and realize hydrogen recycling [5]. For the problems of internal drainage and gas penetration of the battery, the previous solution was to discharge hydrogen and discharge the excess water inside the battery at the same time. However, too high hydrogen discharge frequency will reduce the utilization efficiency of hydrogen and even cause explosion danger; Too low hydrogen removal frequency will lead to battery flooding and impurity gas accumulation. At present, hydrogen circulation is mainly used in industry. In the working process of fuel cell system, pure hydrogen is introduced into the anode. After electrode reaction, there will be residual hydrogen without complete reaction. If it is directly discharged into the atmosphere, it will cause environmental pollution, waste of energy and great safety hazards. In order to solve this problem, different circulation methods can be used to recover the unreacted hydrogen.

Two different hydrogen supply systems are introduced in the following of this section.

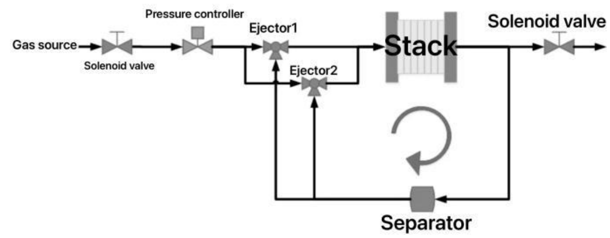
4.1 Single ejector mode

In the working process of the fuel cell, the anode is generally supplied with high-pressure hydrogen storage tank. At present, the pressure of high-pressure hydrogen storage tank is about 20 ~ 45 MPa, up to 70 MPa. For economic considerations, air can be used to replace pure oxygen. The structural diagram of single ejector is shown in the figure. After the hydrogen is discharged from the hydrogen storage tank with high pressure, it is depressurized through the pressure regulating valve and pressure regulator in turn, and then enters the humidifier.

Since the H+ generated at the anode migrates to the cathode in the form of hydrated hydrogen ion H3O+, the wet hydrogen after humidification can increase the migration speed of hydrogen ions. The higher the hydration degree of proton exchange membrane, the stronger the ion migration ability, and the better the performance of fuel cell. However, excessive water will increase the resistance of hydrogen entering the electrode and even cause water flooding. If the water content is too low, it will increase the resistance in the process of proton transmission. The remaining hydrogen after the reaction will be used as the secondary flow and enter the reactor again for reaction after passing through the ejector. Its structural diagram is shown in Figure 3(a).



(a) A kind of single ejector mode for FCV [6]



(b) A kind of dual ejector mode for FCV [6]

Figure 3 Different hydrogen supply system

4.2 Dual ejector mode

DTI company of the United States proposes a design scheme of parallel hydrogen return with double ejectors [7]. The hydrogen return system is mainly composed of hydrogen shunt valve and two ejectors with different flow rates. According to the different power of the electric reactor, the hydrogen is circulated through the high and low flow ejectors respectively. When the electric reactor works in the high power range, the high flow ejectors are used for hydrogen circulation. When the electric reactor works in the high power range, Hydrogen circulation through low flow ejector. Compared with the hydrogen return mode of single ejector, the parallel hydrogen return mode of double ejector has a large working range, which can meet the use requirements of the stack under different power [6]. Its structural diagram is shown in Figure 3(b).

Subsequently, other hydrogen supply modes have been developed through different scientific research institutions and laboratories. However, most of them remain in the experimental verification stage and cannot be put into commercial production. Table 2 gives several representative hydrogen supply systems and their comparisons.

Table 2 Several representative hydrogen supply systems [6]

Hydrogen supply mode	Technical scheme	Technical features	Programme representative
Direct flow mode	The unreacted hydrogen in the reactor is directly discharged into the environment	The structure is simple, but it will cause hydrogen waste and potential safety hazards	Theoretical research stage
Dead end mode	The hydrogen supply system forms a closed system	The structure is simple, but it has high requirements for hydrogen purity and is prone to flooding	Theoretical research stage
Pressure change hydrogen return mode	Hydrogen circulation is realized by using the change of inlet and outlet	The structure is simple, the cost is low, but the response is slow, and the	Japan Aerospace Research Institute

	pressure of electric reactor	performance consistency of the stack is poor	
Hydrogen return mode of single hydrogen circulating pump	The unreacted hydrogen and permeated water are circulated to the inlet of the fuel cell by the hydrogen circulation pump for recycling	Wide working range, active adjustment and rapid response; However, the volume and weight are large, additional power consumption, noise and vibration are large	Toyota Motor Corporation; Weichai Power; Yihuatong
Single ejector hydrogen return mode	The ejector is used to transport the unreacted hydrogen to the inlet for recycling	Simple structure, low cost and no parasitic power, but the working range is narrow and the reliability of low power range is poor, so it can not be adjusted actively	Hyundai Motor Company; Honda Motor Company; Guangzhou Automobile Group Co., Ltd

For several vehicles that have been put into the market, they have developed different hydrogen storage systems and hydrogen supply systems according to their own characteristics and user needs. These cars have made major breakthroughs in both the market-oriented process and key parameters, such as battery efficiency, maximum power and battery durability [8]. Let's make a comprehensive comparison of Mercedes-Benzes GLC F-CELL, Honda Clarity, Toyota Mirai and Hyundai NEXO.

4.3 Safety of hydrogen supply system

The hydrogen supply system includes high-pressure hydrogen storage tank, pressure reducing valve, pressure regulating valve, circulating device (circulating pump or ejector), pressure stabilizing tank, sensor, various solenoid valves and pipelines [9]. The collision sensor in Mercedes-Benzes GLC F-CELL will monitor whether there is a serious collision, and close the tank valve and main hydrogen gas valve on the hydrogen cylinder within a few milliseconds to quickly reduce the pressure of the hydrogen cylinder from the maximum 70 MPa to 1 ~ 1.2 MPa within the average pressure range. At the inlet of the fuel cell stack, another pressure regulating valve reduces the pressure of the fuel cell stack on the hydrogen side to 0.1 ~ 0.3 MPa. Ensure that the hydrogen pipeline and fuel cell stack will not leak even in case of serious accidents [10]. Its hydrogen storage tank and hydrogen feeding assembly is shown in Figure 4. Honda clarity will redesign and compress the stop valve, regulator, pressure sensor and other components as built-in modules, reducing the number of parts used in the high-pressure hydrogen supply system by 74%, greatly reducing the risk of hydrogen leakage. At the same time, the hydrogen sensors at each position will timely monitor the hydrogen concentration, close the stop valve and cut off the hydrogen source [11]. In order to prevent hydrogen embrittlement in the hydrogen supply pipeline, aluminium alloy is used as the main body of the high-pressure parts in contact with hydrogen in the Mirai hydrogen supply system. Alum treatment of the aluminium body surface ensures stable sliding characteristics and reduces wear. In order to prevent the hydrogen penetration on the diaphragm of the high-pressure sensor from affecting the accuracy of the sensor, Mirai adds the film with special surface treatment to the inner surface of the diaphragm. After detection, the amount of hydrogen solid solution formed in the diaphragm is reduced by 90%, so that it can be used for a long time in the high-pressure hydrogen environment without adverse impact on the accuracy of the sensor [12].

At this stage, there are still some problems in HSS, such as low hydrogen utilization rate, high R &amp, D cost, difficult technical requirements and so on. As an important part of the power system of new energy vehicles, the research and development of HSS will still become a hot direction in the future.

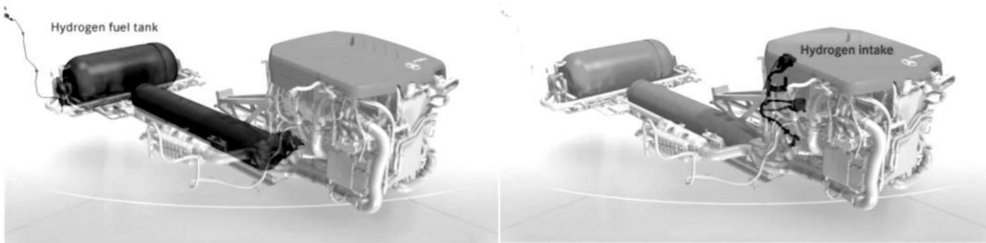


Figure 4 Mercedes-Benzes GLC F-Cell hydrogen storage tank and hydrogen feeding assembly [13]

5 Hydrogen storage system

In the early stage, 304 stainless steel or chrome molybdenum steel is usually used as the material of hydrogen storage tank, but they are too heavy and do not meet the lightweight requirements of FCVs. According to the different materials of hydrogen bottles and external winding and wrapping materials, the academic circles divide hydrogen bottles into four categories, which are successively called type I, type II, type III and type IV bottles. From the perspective of shape, the four kinds of bottles have little difference, and they are all "bottle" shape. There are no packages on the surface of type I bottles, and there are generally some packages on the surface of type II bottles. It is difficult to distinguish between type III and IV bottles in terms of appearance. Their bottle surfaces have parallel and cross packages, as shown in Figure 5.

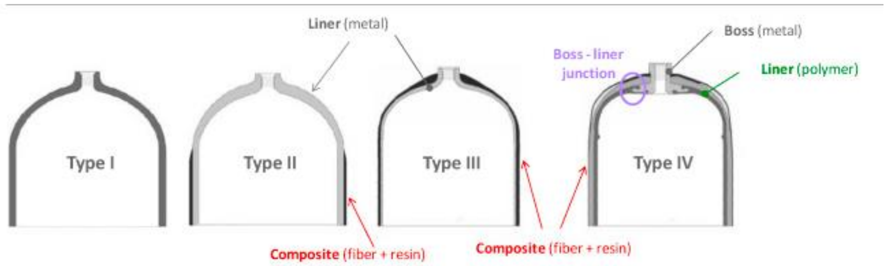


Figure 5 Four kinds of hydrogen bottles [14]

Mercedes Benz GLCF cell adopts Norwegian hexagon type IV hydrogen storage tanks. One large and one small hydrogen storage tanks are arranged in the collision protection area between the vehicle floor and the axle and protected by the surrounding auxiliary frame. The material adopts carbon fibre shell, and the hydrogen storage capacity reaches 4.4kg, the hydrogen storage pressure adopts the global standard 70MPa, and the required hydrogen fuel can be filled in only 3 minutes [15]. Honda clarity adopts a type III hydrogen storage tank with one large and one small aluminium alloy lining, which meets the international technical standard GTRNO.13[10]. Mirai reduced the number of high-pressure hydrogen storage tanks to two and reduced the volume to be placed under the rear seats. As shown in Figure 7, the hydrogen storage tank is composed of a three-layer mixed material structure. The innermost material is a plastic inner tank, which is used to seal the air. The middle layer is carbon fibre reinforced plastic (CFRP) with high compression resistance, the outer layer is glass fibre reinforced plastic (GFRP) with high impact resistance, and an annular protective layer with fall and fire resistance at both ends. By improving the CFRP layer and reducing the material consumption, the weight of hydrogen storage tank is greatly reduced [16]. Hyundai has independently developed hydrogen storage tank technology. NEXO has three hydrogen storage tanks of the same size and uses a new material with excellent impermeability. The material is made of carbon fibre and covered with an insulating coating that can withstand high temperature for a long time [17].

6 Hydrothermal management system

Water management in PEMFC has been a great challenge over time. This is because under high current operation, the reaction heat production makes the proton exchange membrane dry and the exchange rate slows down. In extreme cases, it will cause mechanical damage to the membrane. Small stacks do not require humidification; However, in large stack systems, both air and hydrogen must be humidified at the inlet [18]. The enthalpy humidity diagram can be used to determine the characteristics of gas water vapour mixtures. The humidification process of a commercial humidifier is shown in Figure 6. Point A represents the inlet point with dry bulb temperature T_1 and humidity H_1, and point B represents the required dry bulb temperature T_2 and humidity H_2. The method to reach point B is to enter from A, increase humidification first, and go right along the isotherm; then wait for humidity heating, and the heat humidity ratio in this process, moving vertically in the enthalpy humidity diagram.

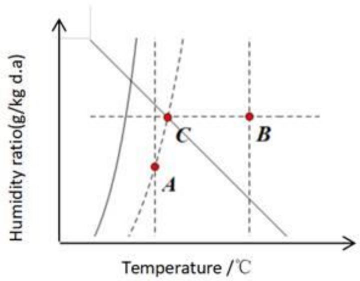


Figure 6 The humidification process of a commercial humidifier

Several technologically advanced and representative vehicles are introduced and their hydrothermal management system are described in the following of this section.

6.1 Toyota Mirai fuel cell system design

Toyota Mirai, which was listed in Japan in 2014, has launched two generations of models after eight years of development. In the fuel cell system, the humidity of electrolytic liquid membrane must be controlled to ensure sufficient proton conductivity and stable power generation. This function is usually realized by an external humidifier. However, the external humidifier will increase the pressure loss of the air system, which will increase the load of the system and require additional parts, which increases the complexity of the system and is not conducive to the integration and miniaturization of the system. The generation Mirai has attracted public attention with its unique self-humidification technology. The main implementation method is to improve the water removal rate by using three-dimensional fine grid flow field on the cathode surface made of new hydrophobic materials. In addition, the precise stamping process is adopted in the anode to manufacture a precise channel that can be compatible with the entry of hydrogen and the flow of coolant at the same time [19]. The 3D flow field design of wet fuel cell stack cathode is shown in Figure 7.

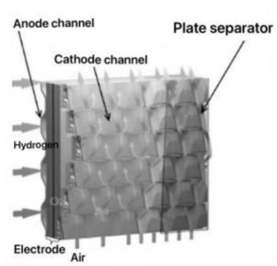


Figure 7 The 3D flow field design of Maria [20]

Because the specific structure puts forward higher power requirements for Mirai's battery, their stack heat dissipation system is also continuously improved, forming its own characteristics. The cooler and the stack cooling circuit are connected in parallel, and a deionizer is also installed in the cooling system to meet the insulation requirements of the coolant and dissipate the heat to the greatest extent.

6.2 Honda clarity fuel cell system design

Unlike Toyota Mirai, which adopts internal self-humidification design, the clarity car developed by Honda adopts an external humidification system that is easier to understand. It adopts the method of reducing the depth of air flow channel to reduce the thickness of the battery, and the flow direction of air and hydrogen inside the battery is set to reverse flow. As shown in the figure, the humidified air provides water to the PEM on the inlet side. After the reaction, the generated water moves to the outlet side and supplies the proton exchange membrane, and then this part of water is back diffused to the anode side. The above operation strengthens the water circulation at the reaction interface and makes the humidity distribution in the membrane uniform.

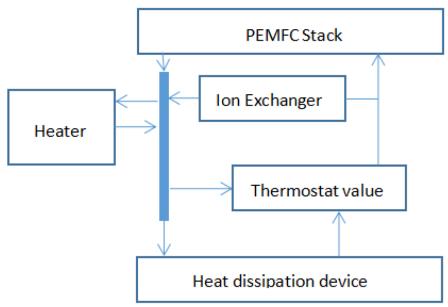


Figure 8 The external humidification of Clarity

6.3 Design of modern NEXO fuel cell system

NEXO fuel cell system is composed of air supply system, hydrogen supply system and thermal management system. The main components of the air supply system include filter, air compressor, humidifier, air stop valve and back pressure valve, etc. The main components of the hydrogen supply system include hydrogen stop valve, hydrogen supply valve, ejector, purge valve, dehydrator and drain valve; The main components of the thermal management system include radiator (fan), four-way valve, PTC heater, water pump, COD heater and two-way valve. The layout and components of air supply system and hydrogen supply system are basically consistent with the international mainstream forms. The difference is that NEXO uses two-way valve and four-way valve, and uses PTC (positive temperature coefficient) thermistor and COD heater for rapid heating, which improves the responsiveness of reactor refrigerant temperature control, so it has good low-temperature cold start ability [19].

7 Control system

The control system is an intelligent electronic control system for the power system. Due to the large number of control objects and complex functions of the hydrogen power system, a large amount of information exchange and logical interaction must be carried out among various objects. At the same time, the controllers have their own corresponding systems. Therefore, at present, the distributed control system is mostly used to control the whole power system, and CAN bus distributed control is often used, i.e., in addition to the central processing system, each object controlled by the central system also has its own control subsystem. With the development of motor and drive systems, the control system tends to be intelligent and digital, which will greatly improve the comprehensive performance of the whole system.

8 Conclusion

This paper introduced the key components of fuel cell electric vehicles, including proton exchange membrane fuel cell stack, auxiliary energy storage system, hydrogen supply system, hydrothermal management system and control system, and explained the operation principle. Several commercial fuel cell vehicles have been studied, while different technologies have been compared. However, we are still in the early stage of hydrogen power system development. The hydrogen power technology shows a relatively long industrial chain, a large technical field span and many technical bottlenecks, while low-cost technology has not yet been fully developed. As many countries have positioned the application of hydrogen-powered vehicles as a medium and long term plan, in the next 10 to 30 years, the rapid development of fuel cell technology, coupled with the support of policies and infrastructure, is expected to usher in the large-scale commercialization of hydrogen-powered vehicles.

Acknowledgments

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