

Application Status and Difficulties of Fuel Cell Technology

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Abstract. With the gradual deterioration of the earth's environment, human is now facing numerous problems, environmental protection has become a hot topic and key problem in the present era. Compared with internal combustion engines, fuel cells have more fuel options. It can use hydrogen as its fuel, which has the advantages of non-pollution, high specific energy and high efficiency. Hydrogen has been proposed as a new alternative energy source for many years, thus the theory is well established, s, the formation of related industries will be relatively easy. This paper summarizes the application status and technical difficulties of fuel cells, analysed the possible promotion direction in the future. In conclusion, fuel cell has a promising development and market prospect, it is now developing rapidly in the field of passenger vehicles, while other industries still have broad prospects. Also, there are many problems such as catalyst attenuation, high cost, storage and transportation.

Keywords: Fuel Cell Technology, hydrogen fuel cells, hydrogen storage, hydrogen transport, the catalyst.

1. Introduction

The aggravation of environmental pollution makes it urgent to develop clean energy in order to achieve global energy saving and emission reduction. According to the “UN's Climate Change 2022: According to Climate Change Mitigation”, the average annual global emissions of greenhouse gases between 2010 and 2019 are at the highest level in human history, with emissions reaching 59 billion tons in 2019. That's a 12% jump from global emissions of 52.5 billion tons in 2010, represent an average annual increase of 1.3% over the past decade. In comparison, global emissions climbed about 2.1% a year in the decade before that, almost twice as fast. Traditional energy is mostly non-renewable energy, release energy through burning. in the process of combustion, they will produce different kinds of gas, dust particles, pollute the air, water, especially the emissions of greenhouse gases, will definitely aggravating global warming, so looking for clean energy has become a top priority. As a kind of electrochemical power generation device, hydrogen fuel cells, which are non-polluting, high efficiency and low noise secondary energy sources, have become a solution for energy emission reduction in various countries [1]. Industrial hydrogen production methods are generally divided into three types, as shown in Figure 1.

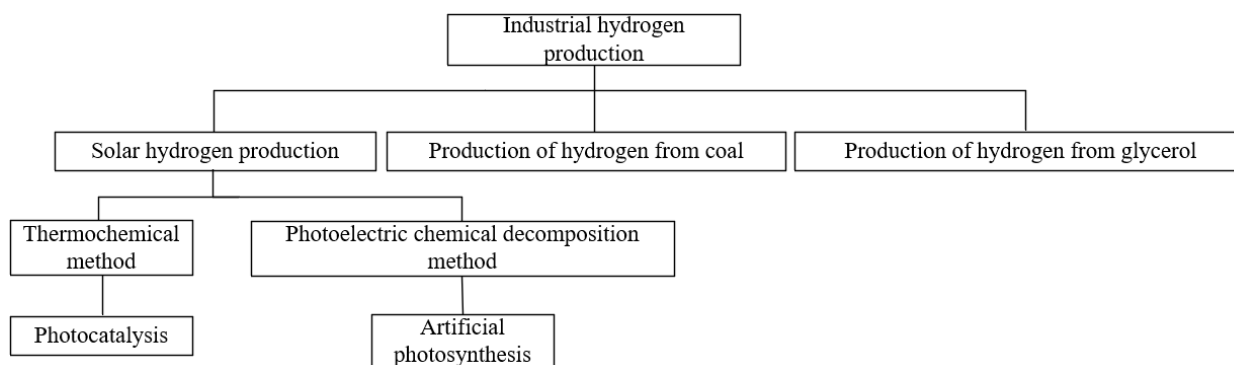


Figure 1. Industrial hydrogen production methods

Electrolysis of water to produce hydrogen generally through photodecomposition of hydrogen, mainly concentrated in thermochemical method, photoelectric chemical decomposition method, photocatalysis method, artificial photosynthesis and biological hydrogen production and other technologies. Hydrogen production from coal is cheap and suitable for large-scale production, but it

will cause environmental pollution. The process of hydrogen production from methanol is relatively simple, but the carbon emission is also high. Many countries in the world have introduced policies related to hydrogen energy in recent years, as shown in part of the table. In December 2021, the Ministry of Industry and Information Technology (MIIT) encouraged the application of hydrogen and other alternative energy sources in the steel, cement, chemical and other industries in the "14th Five-Year Plan" for Green Industrial Development. The U.S. Department of Energy (DOE) has released the Hydrogen Energy Program Development Plan, which defines the country's hydrogen fuel cell industry development framework for the next decade and beyond. As an island country with a severe shortage of fossil energy, Japan also promoted the development of hydrogen energy as a national policy in the "Japan Rejuvenation" strategy issued by the Abe government in 2013. In addition, the Japanese government released a "Basic Strategy for hydrogen energy" at the end of 2017 in order to make hydrogen energy affordable and build a hydrogen economy.

Despite the rapid development of the hydrogen fuel cell industry and a series of policy support, the development of hydrogen fuel cells still faces some difficulties, such as the high cost of hydrogen fuel cells and the lack of a relatively complete supporting transportation and storage facilities. This paper studies the existing types of hydrogen fuel cells and their application status in various industries, and analyses and summarizes the current problems faced by hydrogen fuel cells.

Table 1. Recent hydrogen energy related policies

Country department	Policies	Purpose
the Ministry of Industry and Information Technology (MIIT)	<i>The 14th Five-Year Plan for Green Industrial Development</i>	Encourage the application of hydrogen energy in the secondary industry
United States Department of Energy (DOE)	<i>Hydrogen Energy Programme Development Plan</i>	Identify the development framework for the hydrogen fuel cell industry in the country for the next decade and beyond
The Abe administration of Japan	<i>Japan's Recovery Strategy</i>	Promoting the development of hydrogen energy as a national policy
	<i>Basic Strategy for Hydrogen Energy</i>	Making hydrogen affordable and creating a hydrogen economy

2. Types of fuel cell and principles

2.1. Basic hydrogen and oxygen fuel Cell (AFC)

Alkaline fuel cell is one of the earliest fuel cells. It uses hydrogen as fuel, oxygen as oxidant and platinum as electrode to convert chemical energy into electric energy through the reaction of fuel. The advantages are fast start-up, high efficiency (50%-55%), reliable performance, and easy thermal management of the electrolyte cycle. Its disadvantages include high leakage risk, the presence of the electrolyte poisoned by carbon dioxide, and the need for additional cooling devices to ensure that it can work normally at a lower temperature [2]. The figure is a simple diagram of an alkaline hydroxide fuel cell (Figure 2).

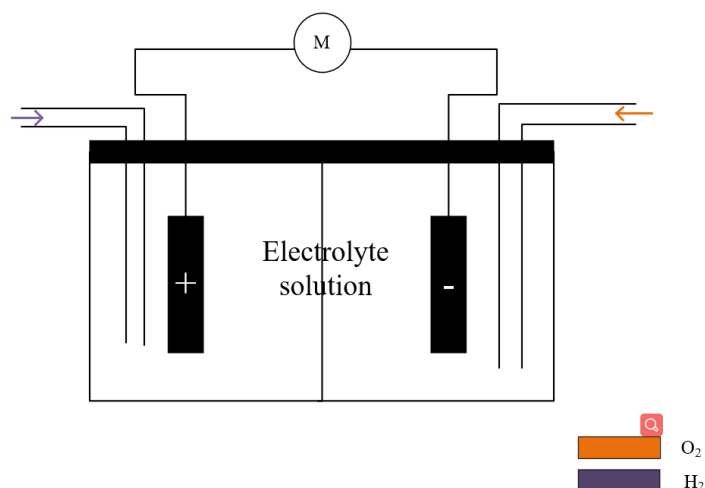
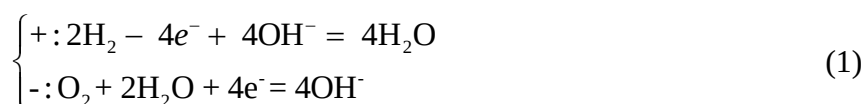


Figure 2. A simple diagram of an alkaline hydroxide fuel cell

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The positive and negative electrodes are both deep into the alkaline electrolyte solution, and the other end is connected to the wire to form a closed loop. There is a large amount of OH^- in the alkaline electrolyte solution. When hydrogen gas is pumped into the negative electrode, it will be catalysed to lose electrons on the platinum electrode and become H^+ , which generates water with OH^- in the solution and releases a lot of heat. Electrons reach the positive electrode through the wire and react with O_2 and water at the positive electrode to generate OH^- and finally add to the solution.

2.2. Proton Exchange Membrane Hydrogen Fuel Cells (PEMFC)

Proton exchange membrane hydrogen fuel cell (PEMFC) is the fifth-generation hydrogen fuel cell developed after alkaline hydrogen and oxygen fuel cell (AFC), hydrogen phosphate fuel cell (PAFC), molten carbonate hydrogen fuel cell (MCFC), solid oxide hydrogen fuel cell (SOFC). It has the characteristics of low working temperature (80°C - 100°C), high specific power (0.1 - 0.2kW/kg), environmental protection and long service life [3-4]. It is mainly composed by proton exchange membrane, porous gas diffusion electrode (including diffusion layer and catalytic layer), bipolar plate, electrode and metal electrocatalyst [5]. The metal catalyst used in PEMFC is platinum in most cases. Its high price has become one of the bottlenecks of PEMFC, and has also become a hot topic in the industry. Figure 3 shows the working principle of proton exchange membrane hydrogen fuel cell.

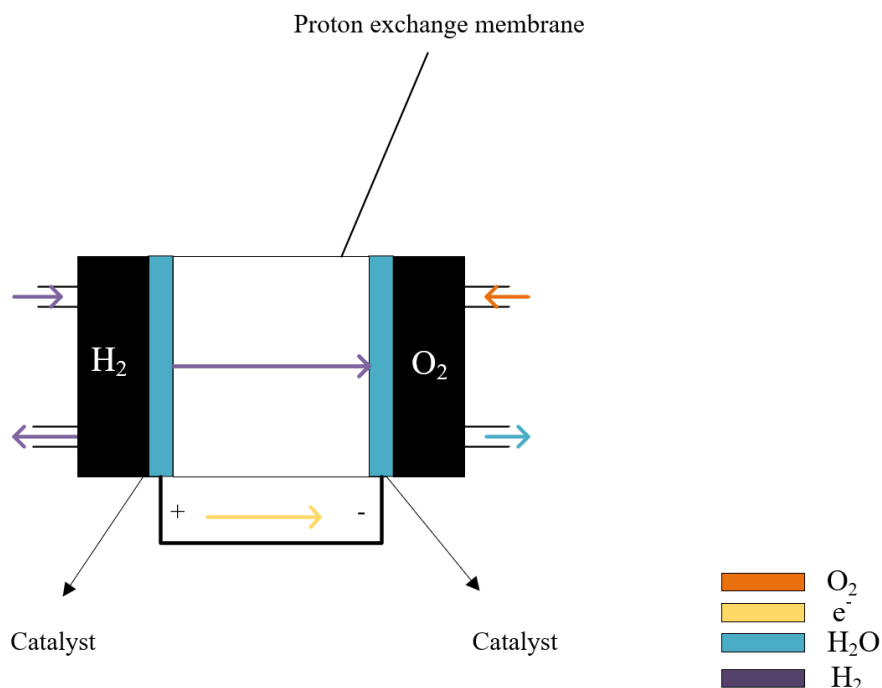


Figure 3. Working principle of proton exchange membrane hydrogen fuel cell

Put hydrogen gas into the anode, it will then reach the surface of the metal catalyst by diffusion, and separates the e^- and proton (H^+) under the catalytic action of the metal electrocatalyst. The proton reaches the cathode through the proton exchange membrane. Under the action of the metal electrocatalyst, the reduction reaction of proton, e^- and O_2 takes place to form water.

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2.3. Hydrogen Phosphate Fuel Cell (PAFC)

PAFC is a medium and low temperature fuel cell (operating temperature 180-210 °C), which has wide application, mature technology and fast development speed, and has the characteristics of high-power generation efficiency, cleanliness and no noise [6]. At present, battery power density, service life, and cost are the problems it is facing [6]. Figure 4 shows the simple working principle of hydrogen phosphate fuel cell (PAFC).

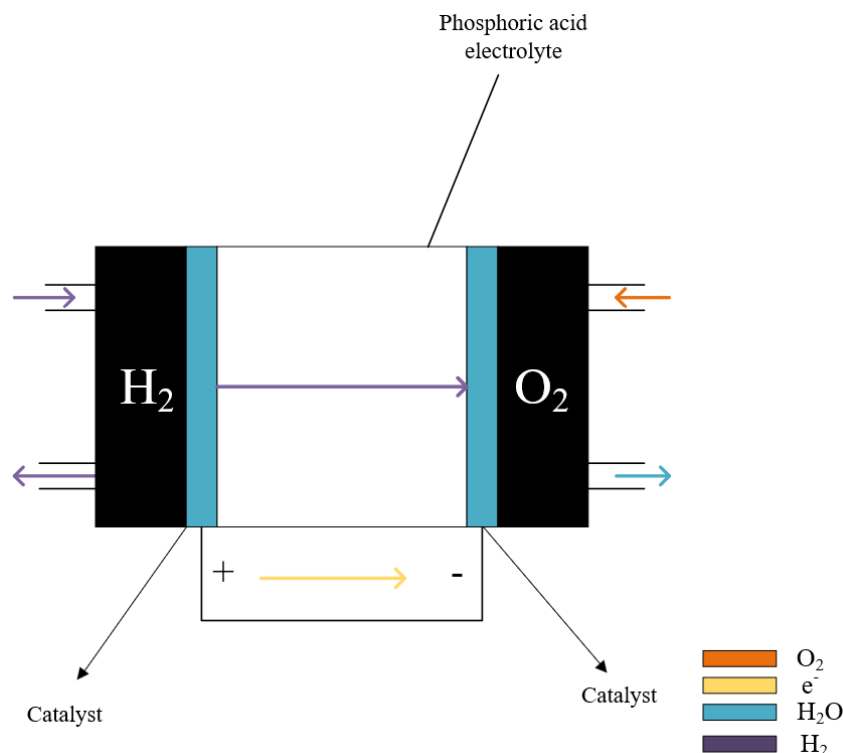


Figure 4. Simple working principle of hydrogen phosphate fuel cell (PAFC)

100% concentration of phosphate electrolyte solution used in PAFC will change its phase at 42°C. H₂ is added to the anode, and the proton (H⁺) separated under the action of the metal catalyst is combined with phosphoric acid to form phosphoric acid complex proton. The separated e⁻ moves to the positive pole, while the hydrated proton moves to the cathode through the phosphate electrolyte in the fuel cell.

Reaction:



2.4. Molten carbonate hydrogen fuel Cell (MCFC)

Molten Carbonate Fuel Cell is similar to other Fuel cells in structure. It is mainly composed by cathode, anode, diaphragm, bipolar plate and other key materials and components. The cathode and electrolyte diaphragm are generally porous ceramic, and the anode is porous metal. The electrolyte in the separator is carbonate electrolyte in molten state (the temperature is generally between 600°C and 700°C), usually use alkali metal carbonate as electrolyte, such as Li, Na and K, in order to conduct ions and block fuel gas and oxidation gas. Because its operating temperature is relatively high, so it does not need to use precious metal as a catalyst, so that it has many advantages, such as: do not need to use precious metal catalyst, the range of fuel choice is wide and so on. It also has a common problem of high-temperature fuel cells, which is a long start-up time. Figure 5 is a simple diagram of molten carbonate hydrogen fuel cell (MCFC).

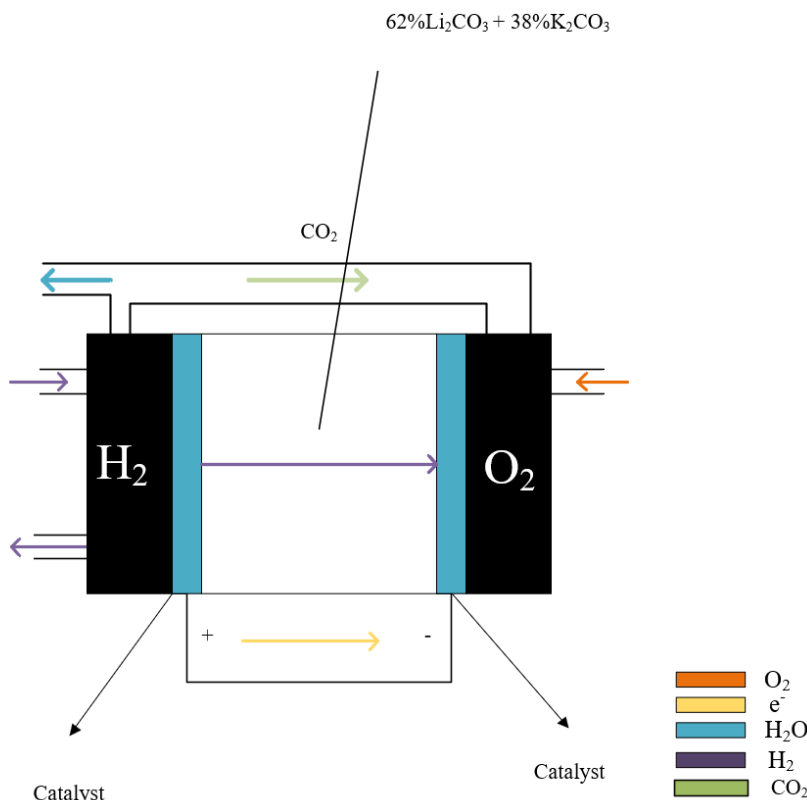
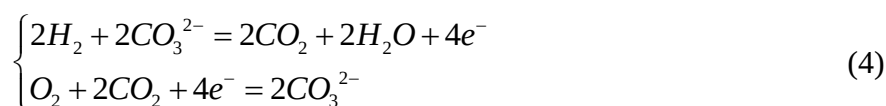


Figure 5. Simple working principle of molten carbonate hydrogen fuel cell (MCFC)

When hydrogen is added, hydrogen will react with CO_2 in the electrolyte solution under the action of catalyst, generating water, CO_2 and e^- , which will go through the external circuit and reach the cathode. At the cathode, O_2 , CO_2 and the e^- from the external circuit combine and react under the action of catalyst to form CO_2 , which then move from the cathode to the anode through electromigration and diffusion, thus forming a cycle. As the diagram shows, the CO_2 also move from anode to cathode at the same time, this is the concentration of CO_2 in the air is not sufficient to sustain the CO_2 reaction at the cathode, and the anode just generates CO_2 in the previous reaction, in order to maintain the stability of the battery, so will the anode CO_2 move to the cathode. The usual method is to separate the incomplete reaction fuel agent (mainly H_2 and CO) from the exhaust gas discharged from the anode chamber by combustion and other treatment methods, and then remove the water, and finally transport it to the cathode.

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2.5. Solid oxide hydrogen fuel cells (SOFC)

Solid Oxide Fuel Cell (SOFC), has a high temperature operating temperature (600°C - 1000°C), the main components are electrolyte, anode, cathode, connector. The electrolyte, cathode, anode are ceramic materials. Unlike other fuel cells, they are solid-state structures. It has many advantages, such as the fact that it no longer needs to be pure hydrogen, but can use other flammable hydrocarbon gases as fuel. At the same time, it does not need precious metals as its catalyst, can use ceramic catalyst. Because of its high temperature reaction, also can make various internal reduction of hydrocarbon gases come true, so as to simplify equipment. In addition, the clean and high-quality hot gas produced in the high temperature environment is very suitable for the cogeneration of heat and power. If the electric energy and heat energy are comprehensively utilized, the utilization rate can

reach about 80%, so it is a very efficient and clean energy system. However, due to the extremely strict requirements for battery materials, the development of solid oxide hydrogen fuel cells is relatively slow [7].

3. Hydrogen fuel cell application status

Although there are many types of fuel cells, proton exchange membrane hydrogen fuel cells have lots of advantages, for instance, good low temperature performance, low operating temperature, high power generation efficiency, cleanliness and no noise [6]. Therefore, it is widely used in all kinds of fuel cells. Therefore, the following article takes proton exchange membrane hydrogen fuel cells as an example to review the application status.

3.1. Power system

3.1.1. Civil power system

Nowadays, many famous automobile companies have developed Hydrogen fuel cell vehicles, such as Toyota's Mirai, Hyundai's NEXO, and BMW's I Hydrogen NEXT. Since 2021, China's pure electric vehicle subsidy policy began to decline, and the policy gradually tilted toward fuel cell vehicles. At the same time, China is actively setting up hydrogen demonstration city clusters and rewarding enterprises that have made significant scientific and technological contributions. In January 2022, Hyundai Motor Hydrogen Fuel Cell System Co., Ltd. was established in Huangpu, Guangzhou as China's first large-scale hydrogen fuel cell system production factory. Most of the batteries produced by the factory will be supplied to Hyundai's NEXO fuel cell vehicle. Hyundai Motor Group plans to officially introduce the NEXO in China in 2022. Toyota-funded United Fuel Cell System Research and Development Co., Ltd. and Huafeng Fuel Cell Co., Ltd. will begin selling TL Power 100, the first fuel cell system developed and produced in China for commercial vehicles, which is based on Toyota's second-generation Mirai fuel cell system. The rated power is 101kW, and some parts made in China are used to improve the power and durability of the system in line with the use environment of domestic commercial vehicles. Through local research and development in China, the system has achieved the industry's top power density and 30,000 hours of durability. During the Beijing 2022 Winter Olympics, 816 hydrogen fuel cell vehicles participated in the transportation service. On May 25, 2021, Hyundai Motor's hydrogen Fuel Cell heavy truck XCIENT Fuel Cell model was officially released. The vehicle is equipped with a 180kW hydrogen fuel cell system consisting of two 90kW hydrogen fuel cell stacks. It is equipped with seven large hydrogen storage tanks and can store about 31kg hydrogen fuel. The vehicle has a maximum endurance of about 400km, making it the world's first hydrogen fuel cell heavy truck. It can be seen that hydrogen fuel cells are developing rapidly in civil power system and have broad prospects.

3.1.2. Military power system

The Type 214 is based on the streamline hull of the first generation of the Type 212 fuel cell submarine. It was commissioned on 2 November 2010, and there are about 11 of them in service in Greece, South Korea, Portugal and Turkey. It is powered by two sets of Siemens' new PEM proton exchange membrane fuel cell system modules with a maximum output of 240kW, a sprint speed of eight knots, a range of 480 nautical miles, a range of 1,248 nautical miles at a speed of four knots, and a range of 12,000 nautical miles at six knots using a snorkel. Its use of hydrogen fuel proton exchange membrane has obvious advantages, the only by-product of the battery is water, so it will not produce waste gas and heat, reduce the noise and infrared characteristics when submarine is operating. The fuel-cell system allows the submarine to patrol at speeds of 2-6 knots for more than three weeks, allowing it to be deployed for long periods of time without having to come up for air after a certain time.

Both the British and Dutch ministries of Defense have evaluated the application of fuel cells, and both believe that hydrogen fuel cells are the most preferred option for the power system of warships, so fuel cell technology has a wide application prospect in warships [8].

3.2. Portable hydrogen fuel cell

Portable hydrogen fuel cells have not been widely used in the world, mainly in military equipment. On August 4, 2022, Boston Advent Technologies Holdings announced the development of a compact portable fuel cell Honey Badger 50TM ("HB50") system and power supply for off-grid field applications, such as military and rescue operations. It can achieve 50W silent, clean power output, and its hidden design can easily power radio, communication equipment, remote monitoring systems. NEXTER TEYA PEMFC generator, including fuel cell section and chemical hydrogen production unit. Zhejiang top MINEK 100 portable PEMFC power generation system developed by Green Energy Technology Company, 200 W type PEMFC system launched by Shanghai Panye Hydrogen Energy Technology Co., Ltd. and NowoGen S20 type portable PEMFC system launched by Beijing Hydrogen Puchuang Energy Technology Co., LTD. The SFC6600 series portable hydrogen fuel cells exhibited by Beijing Shoubell Technology Development Co., Ltd. at the civil-military integration exhibition have the characteristics of long battery life and no noise [9].

3.3. Comprehensive utilization of energy (cogeneration)

The development of hydrogen heat and power coupling industry is relatively backward, but its excellent performance has exceeded the traditional heating boilers [10]. At present, the market of distributed hydrogen energy supply and cogeneration mainly includes a small household proton exchange membrane fuel cell cogeneration system represented by Panasonic Group of Japan. The European Union mainly followed the Japanese model to develop the household miniature combined heat and power system, and promoted it through ENE-FIELD and PACE demonstration projects. At present, China's scientific research institutions and high-tech industries have already begun to focus on the complete machine research and development of PEMFC-CHP, and the PEMFC-CHP system developed by Shanghai Shenli Technology Company has already been exhibited in 2010 Shanghai World Expo [10]. However, at present, most of the key components of PEMFC in China depend on imports and do not have the ability to produce them independently. Once the export of PEMFC to China is banned, the blow to the whole industry is huge.

4. Main difficulties in present

4.1. Hydrogen storage

Hydrogen has active chemical properties and many unsafe characteristics, such as wide combustion range of hydrogen (volume fraction 4.1%-74.1%), extremely low minimum ignition energy (only 0.02MJ) and easy leakage and diffusion.

At present, high-pressure storage of hydrogen, storage after liquefaction of hydrogen and adsorption of solid hydrogen storage materials are the main research directions and application technologies. High voltage storage is a low difficulty, relatively low cost and also has a low energy consumption, this technology is pretty mature and widely used [11]. However, due to its strict requirements on the strength of hydrogen storage tanks, its storage capacity is small and its safety performance is insufficient.

Currently, Toyota's MIRAI II tank is reinforced with KEVLAR and carbon fiber, which increases the hydrogen storage pressure to 70 megapascals. It can withstand LMG fire, but the cost is high. Liquid hydrogen storage has high energy density and high hydrogen storage density. However, because the boiling point of hydrogen after liquefaction is only 20.37K and the temperature is extremely low, the adiabatic capacity of hydrogen storage tank is required greatly, so the cost is often very high.

4.2. Hydrogen transportation

At present, there are three types of transportation, which are long tube trailer transportation, pipeline transportation and liquid hydrogen tanker transportation.

Long pipe trailer transport, as the name implies, the long pipe trailer transport are constructed by hydrogen storage tank and the front and trailer, hydrogen storage tank's general design pressure is 20-25 mpa, its capacity is generally 3500Nm³. In the process of transportation, it has high safety requirements, it has a very low transportation efficiency and high cost, so it is very suitable for users with short transportation distance and little demand. Hydrogen storage tank strength is one of the most difficult technologies to overcome, and the industry has been working to improve the strength of hydrogen storage tanks to increase the density of hydrogen and improve the efficiency of transport.

Pipeline transportation is generally carried out by high-pressure gaseous or liquid pipeline, which can be used for long-distance transportation. However, it is generally suitable for point-to-point and large-scale hydrogen transportation, which is difficult to construct and requires early investment and construction.

Liquid hydrogen tankers have a high single-vehicle transport capacity, more than ten times greater than long tube trailers. It contains liquefy hydrogen to a volume density of 70.8 kg/m³. But there are three difficulties. First, 30% to 40% of the total energy is used to liquefy hydrogen, second, the storage tanks are expensive, and finally, the evaporation loss (depending on the size of the tank), which is currently 0.1-1% per day.

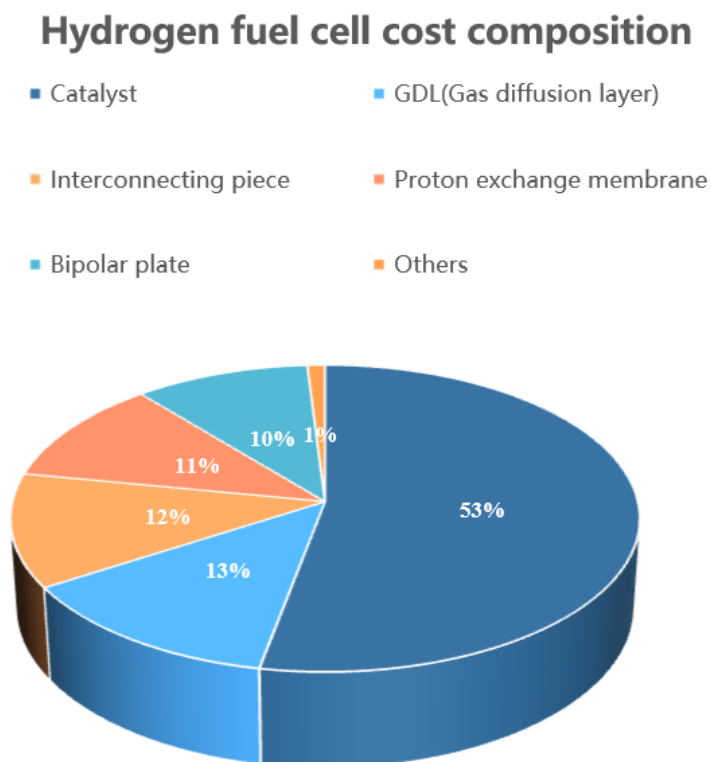


Figure 6. Hydrogen fuel cell reactor cost composition

4.3. Catalyst

Usually, Pt are used to be the catalyst in PEMC. Pt can adsorb hydrogen molecules to facilitate dissociation, which is the first choice for commercial use at present. As shown in Figure 3, Pt/C is generally used at the anode, which disperse Pt nanoparticles on the carrier of carbon particles. Besides Pt/C, the cathode also uses other binary alloys for catalysis. Pt accounts for a high percentage of the cost of the hydrogen fuel cell stack, as shown in Figure 6. The scarcity of Pt is very strong, and the reserves in China are not rich. With the popularization of hydrogen fuel cells in the future, the increased demand will definitely lead to a sharp rise in the price of Pt, which will cause great

resistance to the current research and development of hydrogen fuel cells. Therefore, improving the activity of catalysts and studying low platinum catalysts and non-platinum catalysts become the focus of the industry. At present, the world's average catalyst Pt single volume is 0.3g/kW, China is 0.4g/kW, foreign is 0.2g/kW, the final target is 0.1g/kW, equivalent to the car exhaust purifier Pt consumption.

Pt not only has limited resources and high cost, but also has the problem of catalyst decay under vehicle operating conditions, such as the agglomeration, migration and loss of Pt nanoparticles caused by the potentiodynamic action [12]. Therefore, high stability catalysts should be studied.

5. Conclusion

Hydrogen fuel cells have broad development prospects in many fields. At present, there are very few leading manufacturers, and most of them are in the experimental research stage. In terms of hydrogen fuel cell power system, Toyota and Hyundai have been at the forefront of the world, but the market size is not large and the current technological bottleneck is low on-board hydrogen storage capacity. In general, hydrogen fuel cells are used in a very small range around the world. Despite their good performance, the overall development of the industry is relatively backward. At present, hydrogen fuel cells face three technical bottlenecks. First, the cost and efficiency of hydrogen storage, they directly determine whether hydrogen can be better utilized, three common storage methods have strict requirements on heat insulation and strength of hydrogen storage tanks, and all of them have high costs. In the future, the cost should be gradually reduced and the hydrogen storage capacity of liquid/gas hydrogen storage tanks should be improved. The second is hydrogen transport, which is closely linked to hydrogen storage and is also constrained by the hydrogen storage capacity of the tank. The third is the catalyst, which faces the problem of catalyst decay and high cost. In the future, catalyst's chemical characteristic should be more reactive, and the low platinum catalyst and non-platinum catalyst should be studied.

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