ISSN 2616-5767 Vol.5, Issue 9: 51-56, DOI: 10.25236/AJETS.2022.050908

Review of Hydrogen Fuel Cell Vehicle Research

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Abstract: *In today's post-epidemic era, how to make the sky bluer, water clearer and human living standard higher has become the current direction of global human exploration and pursuit. In terms of passenger cars, hydrogen fuel cell vehicles have become the object of competitive research in various countries because of their pollution-free, low-noise, and high conversion efficiency features. Based on the collation and summarization of relevant literature at home and abroad, this paper illustrates the basic principle of hydrogen-oxygen engine; describes the current situation of the development of hydrogen-fueled vehicle industry; and puts forward some suggestions for the future development of hydrogen energy technology. The constraints in the development of hydrogen fuel cell are analyzed and its future development trend is predicted.*

Keywords: *Hydrogen fuel cell vehicle; New energy vehicles; Development research; Future outlook*

1. Introduction

Nowadays, with the high-quality development of China's economy and the continuous improvement of residents' living standards, more and more households have passenger cars to travel. However, the high consumption of fossil fuels has caused serious pollution in some areas of China, especially passenger cars, which pollute the environment and have a significant greenhouse effect. As the most effective way to replace traditional internal combustion engine vehicles, pure electric vehicles have attracted widespread attention from governments and relevant research institutions. China's research and development of its late start, but the development rate is very fast. At present, many domestic enterprises have launched their own brand of pure electric vehicle products, and achieved certain results. However, there are still many problems to be solved for pure electric vehicles. In recent years, pure electric vehicles have been poorly experienced by users due to the short single-charge running range, the large impact of battery capacity by temperature, the long charging time, the high cost of sales, the short battery life, and the lack of natural decomposition of used batteries, which makes the investment in the market of pure electric vehicles much more than the return, making its development process quite tortuous.

In order to reach the vision of "carbon peak by 2030 and carbon neutral by 2060", China must make efforts in the automobile market to manufacture environmentally friendly cars with similar performance indexes as traditional internal combustion engine cars and find an environmentally friendly fuel to replace fossil fuels. Since hydrogen fuel cells produce only water in the process of use do not produce other environmentally polluting substances, and have the advantages of low vibration and noise and high conversion rate, they have been listed as a key concern by scientists. As early as the 1960s, fuel cells have been maturely used in the aerospace field. Since this century, fuel cells have been gradually withdrawn from the aerospace field and some military fields, and have been widely used in the civil field. At present, more than 30 countries around the world have invested heavily in developing hydrogen energy technology, including the United States, Europe, Japan and other developed countries. These vehicles can be refueled with hydrogen fuel in just 3-5min and have a range of over 400km per refill. As one of the important means to replace fossil energy with clean energy and advocate low-carbon life, hydrogen fuel cell vehicles play an irreplaceable role in solving the increasingly serious environmental problems nowadays. With the rise of hydrogen energy industry, hydrogen fuel cell vehicles will definitely become one of the important development trends of the future automobile industry. However, there are still some urgent problems in the development of hydrogen fuel cell vehicles, such as the high cost of fuel cell catalysts and diaphragm materials, low storage efficiency and low storage safety factor. These problems have become one of the bottlenecks restricting their development at present and hindering the large-scale application of hydrogen in vehicles. The article will elaborate on the current development status of hydrogen fuel cell vehicles and give an outlook on the future development of hydrogen fuel cell vehicles.

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2. How hydrogen fuel cell cars work

The most important component of a hydrogen fuel cell vehicle is its power supply module, the hydrogen fuel cell (HFC), where a single fuel cell is composed of several reaction chambers connected in series in sequence. The hydrogen fuel cell (HFC) is a chemical cell based on the principle of the reverse reaction of electrolytic water. The hydrogen gas enters from the anode of the fuel cell and the air (whose component is oxygen) enters from the cathode. There is no direct chemical reaction between the two, but only a gentle redox reaction through the directional movement of anions and cations to realize the conversion of chemical energy to electrical energy.

The generated electrical energy is converted to a suitable voltage by a power conversion device to supply the electric motor, which drives the vehicle transmission to drive the power wheel. The abundant electrical energy can be transferred to the battery via the internal circuit and stored in the battery for other modules in the vehicle that require electricity. Basic model of fuel cell application in automobiles is shown in Figure 1.

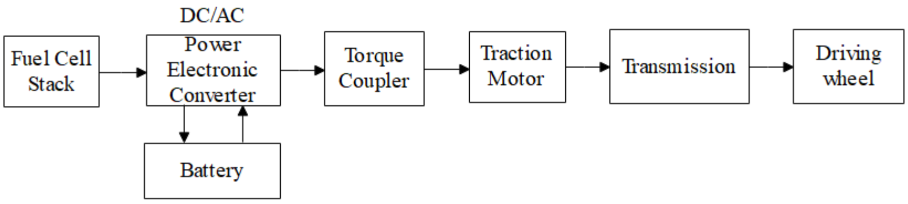

Figure 1: Basic model of fuel cell application in automobiles

Hydrogen fuel cell vehicles differ from ordinary internal combustion locomotives mainly in the vehicle power system. Ordinary internal combustion locomotives use gasoline as fuel, which is burned in the internal combustion engine to drive the piston movement to do work, which is then converted into vehicle power; hydrogen fuel cell vehicles use hydrogen fuel cells to generate electricity to directly drive the electric motor to rotate and drive the vehicle drive wheels.

3. Current Developments in Hydrogen Fuel Cell Cars

3.1 Developments in Hydrogen and Oxygen Fuel Cell

The classification of fuel cells can be divided into (Alkaline Fuel Cell) Alkaline Fuel Cell (AFC), (Proton Exchange Membrane Fuel Cell) Proton Exchange Membrane Fuel Cell (PEMFC), (Solid Oxide Fuel Cell) Solid Oxide Fuel Cell (SOFC) according to the type of electrolyte.

3.1.1 Alkaline Fuel Cell

Alkaline Fuel Cell is an alkaline fuel cell that uses an alkaline solution as the electrolyte (e.g., KOH solution) to generate H_2 and O_2 through electrolysis of water during operation. In addition, non-metals (such as nickel) in the alkaline solution can be used as efficient and stable catalysts, and the stability of the current generated by the cell does not depend on precious metals (such as platinum) as catalysts. The most prominent drawback of using alkaline solution as electrolyte is that if the alkaline electrolyte solution comes into contact with acidic gas (e.g. CO_2), it will acidify and produce salts, which will crystallize and precipitate with the increase of acidic gas concentration, thus reducing the ionic content of electrolyte solution and decreasing the conductivity. This requires the battery to be fed with pure H_2, O_2 during use.

AFC redox reacts as follow.

$$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

$$2H_2 + O_2 \rightarrow 2H_2O$$

3.1.2 Proton Exchange Membrane Fuel Cell

Proton Exchange Membrane Fuel Cell (PEMFC), also known as solid polymer electrolyte fuel cell, uses electron-conducting thin film material as electrolyte because the film is acidic and only hydrogen ions and a few protons can be transferred. does not corrode its own internal structure. Currently, PEMFC is becoming more and more popular among researchers for its compact structure, low operating temperature (80°C), light weight, portability, long working life, rapid start-up, and high energy conversion rate, and has become a mainstream use for hydrogen fuel cell vehicles. The most widely used proton exchange membrane is the sulfonic acid type Nafion membrane produced by DuPont. PEMFC works in an acidic environment and requires the use of precious metals (such as platinum) as a stable and efficient catalyst. Although the amount of platinum used for manufacturing electrodes has been reduced to 0.02 mg/cm2, the cost of Nafion membranes is high. This determines the limitation of PEMFC application.

The redox reaction of PEMFC is as follows.

$$2H2 \rightarrow 4H+ + 4e-$$

$$O2 + 4H+ + 4e- \rightarrow 2H2O$$

$$2H2 + O2 \rightarrow 2H2O$$

3.1.3 Solid Oxide Fuel Cell

SOFC uses solid oxide as the electrolyte, which largely solves the problem of erosion of the internal structure of the battery by the electrolyte solution, and the high temperature waste heat generated during the operation of SOFC can be fully utilized, and the overall utilization rate has been reduced from the original high to the present low. CO, natural gas (CH4), hydrocarbons and other gases can be used as fuel]. It is generally believed that SOFC will become one of the most popular fuel cells in the industry in the future, just like PEMFC. Currently, the common application of SOFC is to provide backup power for signal base stations.

The redox reaction of PAFC is as follows.

$$2H2 + 2O2- \rightarrow 2H2O + 4e-$$

$$O2 + 4e- \rightarrow 2O2-$$

$$2H2 + O2 \rightarrow 2H2O$$

Comparing FC with different electrolyte types, it is easy to see that the efficiency of each FC is generally high, the lowest can reach more than 30%, and the reaction product basically contains only water, with low pollution, high conversion rate, environmental protection and other characteristics. Moreover, the fuel used is not limited to hydrogen, but natural gas, biogas and gas can be used as fuel. It shows that the fuel cell is suitable for the equipment to supply energy for new energy vehicles in the future.

3.2 Use of Hydrogen Fuel Cell Vehicles

At present, many car companies in the world have launched fuel cell models, such as the "Mirai hydrogen fuel cell car" produced by Toyota Motor Corporation in Japan, the "Clarity hydrogen fuel cell car" produced by Guangzhou Honda Motor Co. Ltd. and the "Hongqi H5 FCVE" produced by China First Automobile Group Corporation, and the GLC F-CELL produced by Mercedes-Benz. Among them, Toyota's research and development is more systematic and large-scale, and Toyota focuses on hydrogen fuel cell vehicles for long-mileage use. Through long-term effective investment, Toyota has achieved considerable success by product innovation and selling well in both domestic and overseas markets. The price of Toyota's hydrogen fuel cell car (Mirai) has been reduced to 400,000 RMB. Since its launch, the Mirai has sold more than one million units in total. The car uses hydrogen as its power source and is stored in on-board tanks. Although the price is still expensive, it is already a benchmark in the industry.

In addition to passenger cars, Toyota commercialized the Hino hydrogen fuel cell bus during the Aichi Expo in Japan back in 2005. Recently, Toyota again demonstrated the next-generation hydrogen fuel cell bus SORA. SORA consists of the initials of the four words Sky, Ocean, River and Air, the technology of the Earth's water cycle. As seen in the SORA cutaway schematic, a number of hydrogen storage tanks are placed directly above the bus, and the fuel cell stack, power motor battery and other components are also located at the rear of the bus. It is understood that the current power density of the fuel cell stack is as high as 3.1kW-L-1, with a maximum output power of 114kW, and because the output voltage of each fuel cell unit is only 0.6~0.7V, it needs to be matched with a DC boost converter and power cell. Thus, the voltage can be adapted to the high voltage of 650V and drive the power motor to rotate. Among these technologies, a significant part of them comes from the hydrogen fuel cell passenger

ISSN 2616-5767 Vol.5, Issue 9: 51-56, DOI: 10.25236/AJETS.2022.050908

car (Mirai). (A cross-section of the SORA is shown in Figure 2).

Figure 2: SORA's cutaway

3.3 Analysis of Advantages and Shortcomings of Hydrogen Fuel Cell Cars

3.3.1 Advantages of hydrogen fuel cell cars

The hydrogen fuel cell has a wide source of hydrogen, and there is no need to worry about the problem of energy depletion because of the abundant reserves on the earth, while traditional internal combustion engine vehicles use fossil fuel - petroleum as fuel, and fossil fuel is at risk of depletion. The fossil fuels burned in traditional internal combustion engine vehicles, i.e. petroleum, produce greenhouse gases, sulfides, nitrogen compounds and other harmful gases that pollute the environment; hydrogen fuel cells provide electricity for the on-board electric motor to drive the vehicle and power the on-board electrical appliances, and do not use internal combustion engines, pistons and connecting rods, etc., which greatly reduces the vibration of the engine. The process of driving will be smoother seat belt to give users a better experience, internal mechanical loss will also be reduced, and some parts of the vehicle can be used for a longer period of time to reduce replacement costs.

3.3.2 Weaknesses of hydrogen fuel cell cars

There is a big difference between the acceleration of a car with a fuel cell and a conventional internal combustion engine piston type car. Although the hydrogen fuel cell can quickly power the electric motor at full load within 1s, it can only withstand short periods of overload operation. Thus, the instantaneous acceleration performance of hydrogen fuel cell cars is not as good as that of internal combustion engine cars.

4. Existential problems

The current problems of hydrogen fuel cell vehicles include the technical problems of hydrogen fuel cell itself, the problems of hydrogen supply chain and the safety problems in the process of their own use.

4.1 Hydrogen-oxygen fuel cells own technical problems

Proton exchange membranes are required in every type of hydrogen fuel cell, but they are expensive. For example, Proton Exchange Membrane Fuel Cell requires the use of proton exchange membranes that have severe restrictions on low ion transport. The most popular proton exchange membrane on the market is the sulfonic acid type Nafion membrane produced by DuPont in the U.S. The price of this special membrane is about $\$4000/m^2$. The price disadvantage causes the price of hydrogen fuel cell vehicles to be higher than that of ordinary vehicles. These catalysts are about twice as expensive as gold. This becomes the second major factor that restricts the development of hydrogen fuel cells.

4.2 Hydrogen storage problem in hydrogen fuel cell vehicles

The current methods of storing hydrogen are mainly divided into two categories: physical methods, such as high-pressure hydrogen storage method and low-temperature liquid hydrogen method, and chemical methods, such as hydrogenated metal storage method.

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4.2.1 Pressurized Tank Storage

High pressure hydrogen storage is the most common method of hydrogen storage, where hydrogen is compressed and then filled into cylinders for storage. There is a wide market for this technology. At a storage pressure of $3.5\times10^{7}Pa$ and a temperature of $298K$, the energy consumed to compress the hydrogen is about $2.2kWh/kg$ and the space provided for storage is $20kg/m^{3}$, which is more energy efficient compared to the cryogenic liquid hydrogen storage method. In the process of making cylinders, it is generally necessary to improve the pressure resistance of cylinders. Ideally, the cylinder material needs to have high tensile strength, low density, light mass for car carrying, and no chemical reaction with hydrogen. So far, cylinder materials are generally made of austenitic stainless steel, aluminum alloy and copper, which are relatively heavy but moderately priced; while the cylinders made of polyethylene, epoxy resin, carbon fiber and aluminum liner materials are lighter but more expensive. Therefore, this storage method cannot effectively reduce the volume and weight of cylinders and provide lower energy density.

4.2.2 Cryogenic Liquid Hydrogen Storage

This storage method involves storing liquid hydrogen in cryogenic tanks for preservation. The operation process starts by compressing the hydrogen using a compressor, cooling the compressed hydrogen with a heat exchanger, transferring the heat of the hydrogen to the cold fluid equipment, and then expanding the hydrogen through a throttle valve, and completing the above process will produce a little liquid, and after separating the produced liquid from the gas, the produced liquid is stored in an insulated cryogenic tank, and the remaining gas continues the above cycle, and the temperature during the cycle is controlled at (-250°C or below), the whole process is called Linde or Joule Thompson Cycle[1]. After reviewing the relevant information, it is understood that the theoretical energy required to carry out the above process is $3.23kWh/kg$,but in practice it needs to reach $15.2kWh/kg$ The whole process consumes a large amount of energy.

4.2.3 Hydrogen Uptake in Metal-Based Compounds

Hydrogen molecules contain hydrogen bonds and metals contain metal bonds, and hydrides can be formed when hydrogen atoms enter the metal valence bond structure. At present, the technology has matured with titanium and iron-based compounds and rare earth-based compounds, and metal hydrides can store hydrogen up to $100kg/m^{3}$ or more at lower pressure. This means that metal hydride is a good hydrogen storage material, just like a dry sponge that can absorb a lot of water, and this storage method can not only store a large amount of hydrogen but also has a stable and safe structure. But its biggest disadvantage is the low mass utilization, 100 kg of metal can only store a few kilograms of hydrogen, these metal materials will generate extra weight for most vehicles and are very expensive. If the mass utilization rate can be improved, this method of hydrogen storage will be the most promising method of hydrogen storage for transportation in the future.

5. Future development of hydrogen fuel cell vehicles

At present, there are two major technical difficulties in hydrogen fuel cells, such as high catalyst cost and frequent replacement of diaphragm materials that do not meet the required service life. In order to solve the above problems, this paper reviews the research results and progress achieved in the field of hydrogen fuel cells at home and abroad in recent years from the perspective of improving the catalytic conversion efficiency, and provides an outlook on the future development trend. As far as hydrogen delivery is concerned, the future research directions should be: new storage materials oriented to light mass, high tensile strength and low price, and new delivery solutions oriented to long delivery distance and large delivery capacity. It is reported that Zhang Jinying's research group at Xi'an Jiaotong University applied graphene in hydrogen storage to solve the problem of hydrogen storage and transportation in the first half of 2021. The research results were recently published in the international authoritative journal Nature Communications. After unremitting efforts, Prof. Jinying Zhang's team used highly reactive light metal hydrides (NaH, LiH) as raw materials to regulate the rate of hydrogen release by controlling the encapsulation area of graphene, and achieved a safe, controlled and stable release of hydrogen through an interfacial nano-valve regulation mechanism[2].

The chemical reaction equation of highly reactive light metal hydrides

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$$NaH + H_2O \rightarrow NaOH + H_2\uparrow$$

$$LiH + H_2O \rightarrow LiOH + H_2\uparrow$$

The results of this study have overcome the difficult problem of hydrogen storage and greatly improved the portability and storage density of hydrogen. Also, the use of light metal hydride as a fuel enables higher storage density of hydrogen. It is proved that the method can be used for the storage of many kinds of gases. In addition, the material has good chemical stability as well as excellent mechanical strength and can be used at high temperatures. Currently, the storage method should be functional in the field for emergency power, vehicles, drones and other partially mobile devices.

China has become one of the largest producers of fuel cells in the world. in 2015, the annual production of fuel cell engines produced in China reached about 200,000 units. It is expected that fuel cell vehicles will enter a large-scale commercialization phase in the next few years, and by 2025, more than one million fuel cell vehicles will be in operation worldwide by 2050[3].

China Hydrogen Energy and Fuel Cell Industry Innovation Strategic Alliance mentioned in WHITE PAPER OF HYDROGEN ENERGY AND FUEL CELL INDUSTRY IN CHINA 2020 that hydrogen energy will become an important part of China's energy system in the future, and under the carbon peak scenario in 2030, the annual demand for hydrogen in China will reach By 2060, when the carbon emission reduction target is achieved, it is expected that the nationwide hydrogen generated from carbon neutralization will exceed 130 million tons, accounting for about 20% of the end energy consumption. The industrial sector continues to use the highest percentage of hydrogen, with about 77.94 million tons, accounting for 40.51 million tons of the total demand, the transportation sector with 5.85 million tons, and the construction sector with 6 million tons, for power generation and grid balancing[4].

6. Conclusion

Hydrogen fuel cell vehicles have outstanding advantages such as zero emission, high efficiency, long range, and a wide variety of available fuels, and are one of the most widely used areas of hydrogen energy. on January 11, 2020, the National Development and Reform Commission announced the Opinions on Accelerating the Development of Hydrogen Energy, which included hydrogen energy in the key projects to be supported. This indicates that the importance of hydrogen energy in China has further increased. In the post pandemic era, how to make the sky bluer, the water clearer, and the life of people better has become a direction of global human discussion and pursuit. In this context, the hydrogen fuel cell vehicle industry will have unlimited potential[5].

Currently, the European Union, Japan, Canada, South Africa and other countries and regions have proposed their own carbon neutrality targets; the United States also plans to achieve "net zero carbon emissions" by 2050. Carbon neutrality refers to offsetting the greenhouse gases produced by burning fossil fuels and industrial production through reforestation, energy saving and emission reduction to achieve "zero CO_2 emissions". Countries around the world should take this opportunity to develop fuel cell vehicles as the theme, share the results of scientific research, and jointly develop and utilize new energy sources. All in all, fuel cell vehicles have a broad development space and long-term development significance. The fire of new energy can start a prairie fire, and the green life of the world can be expected in the future.

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