Applications and Development of Fuel Cells in the Field of New Energy Vehicles

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Abstract. People favor new energy vehicles due to their advantages of low cost and zero emission. However, the current battery technology cannot fully meet the range and charging speed requirements, which restricts the further development of new energy vehicles. Fuel cells are characterized by high energy density and environmental friendliness, showing great advantages in solving energy and environmental problems. It may be able to replace the current lithium battery as the battery choice for the next generation of new energy vehicles. There have been many researchers carrying out related studies and launching mass production models, but there are still many problems to be solved. This paper begins with an introduction of the research background, power generation principle, and classification of fuel cells, and discusses the current problems encountered in lithium battery technology as well as the latest research progress, challenges, and future development direction of fuel cells in the automotive field. Through this article, researchers can gain an understanding of the principle of various types of fuel cells, have a cognizance of the current in-vehicle applications of lithium batteries and fuel cells, and have a certain understanding of the future development of in-vehicle fuel cells.

Keywords: Fuel cells; new energy vehicle; Applications.

1. Introduction

When it comes to new energy vehicles, people tend to think of electric vehicles powered by lithium batteries such as Tesla, BYD, and Ideal, but compared with lithium batteries, fuel cells have higher energy density, higher efficiency, and are more environmentally friendly. At present, lithium battery technology is becoming more and more mature, not only to achieve a significant increase in battery energy density, but also to improve the charging speed of the pure electric car Tesla Model 3, for example, its cruising range of up to 550~660km [1], but compared with the traditional internal combustion engine cars still have a great disadvantage. In recent years, new energy vehicle brands, in addition to continuous research on battery technology, have also turned their attention to hybrid vehicles, hoping to combine the advantages of pure electric vehicles with those of traditional internal combustion engine vehicles, so that users do not need to worry about the charging speed while improving the range, but this is only a kind of compromise due to the limitations of battery technology. In fact, in addition to the common power solutions currently on the market, fuel cells may be the future development direction of new energy vehicles. This paper first introduces the working mechanism of various fuel cells and explains why the Proton Exchange Membrane Fuel Cell (PEM) is more suitable for automotive applications than other types of fuel cells. Then it introduces the working principle of lithium batteries used in new energy vehicles and compares the advantages and disadvantages of lithium batteries and PEM fuel cells. The problems encountered in the application of PEM fuel cells in new energy vehicles are summarized and solutions are proposed in the light of the current research progress.

According to the type of fuel cell electrolyte, fuel cells can be broadly categorized into five types: alkaline fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, solid oxide fuel cells, and proton exchange membrane fuel cells. According to the working characteristics of different fuel cells, due to their high energy conversion efficiency and fast start-up time [2], proton exchange membrane fuel cells are currently the mainstream direction of fuel cell application in new energy vehicles. This paper focuses on the applications and challenges of proton exchange membrane fuel cells in new

energy vehicles and explores battery life, electrode materials, and power systems for the next generation of PEM for onboard applications.

2. Types of fuel cells and how they work

2.1. Alkaline Fuel Cell

The electrolyte solution of the battery is alkaline, and an alkaline aqueous solution such as potassium hydroxide is usually used as the electrolyte. When the battery operates, hydrogen gas, which is used as fuel, is broken down into hydrogen ions (H+) and electrons (e-) at the negative electrode (hydrogen electrode) in the presence of a catalyst. The hydrogen ions enter the electrolyte, while the electrons move to the positive electrode (oxygen electrode) through an external circuit, forming an electric current. At the positive electrode, oxygen combines hydrogen ions from the electrolyte, and electrons arrive at the positive electrode to form water (H2O), a process similar to the reverse process of electrolyzing water [3]. The principle of operation is shown in Fig. 1.

Features

High performance: The theoretical voltage is 1.229 volts; the actual open circuit voltage is less than 1.1 volts [3].

Ambient Start: This can be started at ambient temperature for a variety of environments.

Catalyst Versatility: Platinum-based precious metal catalysts are not always required.

Carbon Dioxide Sensitivity: Carbon dioxide can degrade the electrolyte and affect battery performance.

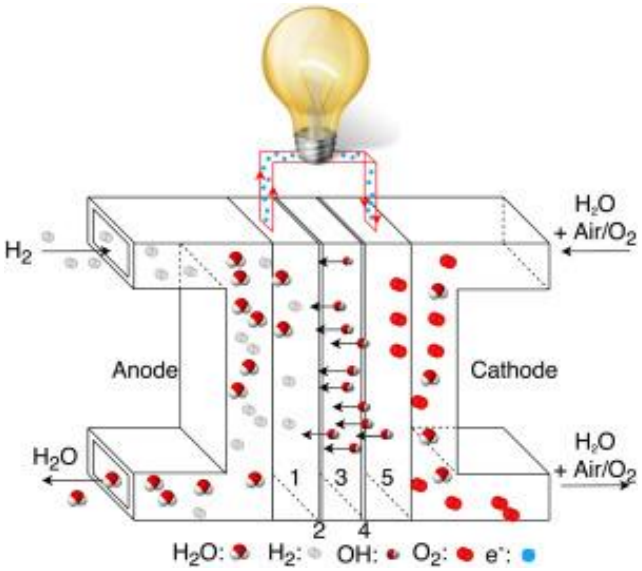


Fig 1. Schematic diagram of alkaline fuel cell, layers 1 and 5 are gas diffusion layers (GDL), layers 2 and 4 are catalyst layers (CL), and layer 3 represents the liquid/polymer electrolyte [3].

2.2. Phosphoric Acid Fuel Cell

Its working principle is similar to that of PEMFC, the main differences being the composition of the electrolyte and the operating temperature. Phosphoric acid fuel cell (PAFC) undergoes an oxidation reaction at the anode, where hydrogen is oxidized into protons under the action of a catalyst, and two free electrons are released at the same time. The resulting hydrogen proton combines with phosphoric acid in the electrolyte to form a phosphoric acid-bound proton, which moves toward the cathode through the phosphate electrolyte. A reduction reaction occurs at the cathode, where electrons, hydrated protons, and oxygen produce water molecules in the presence of a catalyst. Compared to PEMFC, the reaction rate at the cathode is faster than that at the PEMFC cathode due to its higher operating temperature. However, due to the high operating temperature and its slow start-up speed, it is mostly used in power plants and has no onboard applications yet.

2.3. Molten Carbonate Fuel Cell

Molten carbonate fuel cell, abbreviated as MCFC, its electrolyte is molten carbonate, the cathode is composed of porous ceramics, the anode is composed of porous metal, and the electrolyte is isolated by porous ceramic electrolyte diaphragm. MCFC has the advantages of higher working temperature and faster reaction speed; the requirement of fuel purity is relatively low, so it can be in-cell reforming of fuel; it is low cost because it does not need precious metal catalyst; it adopts liquid electrolyte, which is easier to be operated. The cost is low because no precious metal catalyst is required, and the use of liquid electrolytes makes it easier to operate. Despite these advantages that make it seem like a perfect battery choice, its biggest drawback is that the liquid electrolyte is difficult to manage at high temperatures and corrodes and leaks badly during long-term operation, reducing the battery's life.

2.4. Solid Oxide Fuel Cell

Solid Oxide Fuel Cells, or SOFCs, belong to the third generation of fuel cells. SOFCs are high-temperature fuel cells that operate using a solid electrolyte, usually dense yttria-stabilized zirconia. In addition, compared with other fuel cells, SOFCs can use a variety of fuels, such as hydrogen, hydrocarbons, and carbon monoxide. In addition to these advantages, SOFCs operate at high temperatures, are slow to start, costly, and are not sulfur tolerant [4]. They are particularly unsuitable for large fluctuations in load demand, which is why the large and medium-sized power sector is their main area of application [5], and there are significant limitations in onboard application scenarios. Fig. 2 shows the operating schematic of SOFC.

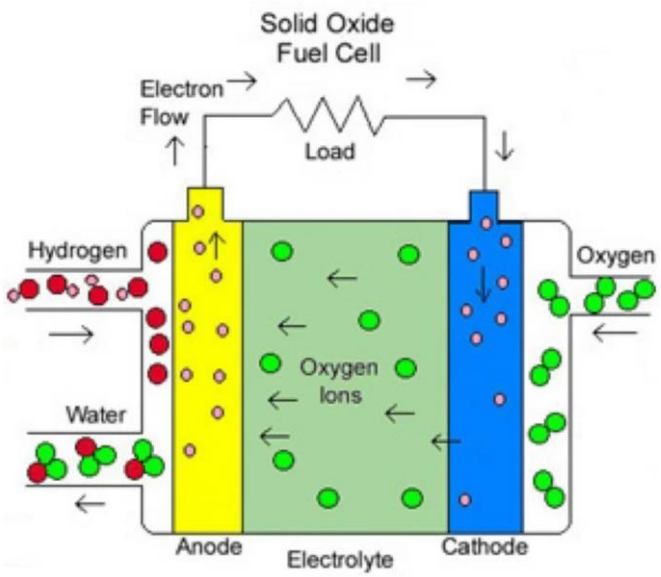


Fig 2. Schematic diagram of the main features of solid oxide fuel cell operation [6]

2.5. Proton Exchange Membrane Fuel Cell

Working Principle: The chemical energy stored in the fuel is directly converted into electric energy through an electrochemical reaction without a combustion process, and the reaction product is pollution-free. Because it is not constrained by the Carnot cycle effect, the energy conversion efficiency is very high, and theoretically, it can reach

Among them, solid oxide fuel cells and proton exchange membrane fuel cells are now more widely used in the field of new energy vehicles.

The working principle of the PEM fuel cell: hydrogen in the anode electrode turns into hydrogen ions and releases electrons. These electrons move to the cathode through the external circuit and generate an electric current. The principle is shown in Fig. 3, and the following reactions occur in the proton exchange membrane fuel cell:

Anode electrode:

$$H_2 \Rightarrow 2H + 2e^+ \quad (1)$$

Cathode electrode:

$$O_2 + 4H^+ + 4e^- = 2H_2O \quad (2)$$

The total reaction is:

$$2H_2 + O_2 = 2H_2O \quad (3)$$

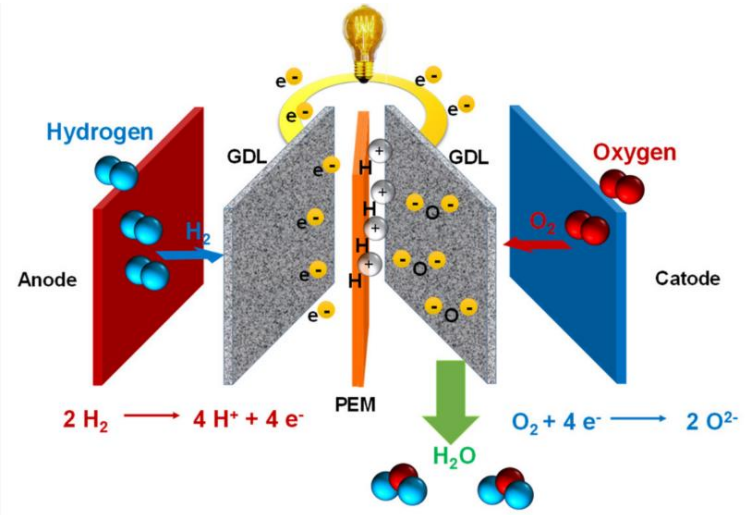


Fig 3. Schematic diagram showing the components of a single PEMFC: anode, cathode, gas diffusion layer (GDL), membrane, anode, and cathode reactions together and products [7].

Compared with other types of fuel cells PEMFC has the following advantages

High efficiency: Proton Exchange Membrane Fuel Cell has a high energy conversion efficiency, which can directly convert the chemical energy of hydrogen and oxygen into electrical energy and reduce energy loss.

Fast startup: it can start up quickly in a short period of time, which is suitable for application scenarios such as automobiles that require frequent starting and stopping.

Low-temperature operation: It is able to operate at lower temperatures without the need for additional heating devices, reducing system complexity and cost.

Compact and lightweight: with its small size and weight, it is easy to install in automobiles without adding too much burden to the vehicle.

High power density: it can provide high power output to meet the power demand of the automobile.

In summary, proton exchange membrane fuel cells have advantages in energy conversion efficiency, start-up speed, low-temperature operation, compactness, and power density, which are more suitable to meet the needs of hydrogen energy vehicles. Therefore, hydrogen energy vehicles choose proton exchange membrane fuel cells over other types of fuel cells.

3. Current Mainstream Power Battery

3.1. Introduction to Lithium Battery

Currently, mainstream models use lithium batteries, while traditional lead-acid batteries have been eliminated due to their low energy density and large size and weight at the same energy level. As shown in Table 1, compared with traditional lead-acid batteries, lithium batteries are superior to lead-acid batteries in both output voltage and energy density, while nickel-metal hydride batteries have lower energy density, which is why lithium batteries are currently used in mainstream models. The main features of lithium-ion batteries are as follows: high specific energy, lithium-ion battery mass-specific energy, and volume-specific energy reached 120-200 W-h/kg and 300 W-h/L, respectively,

is currently the highest in the energy storage battery, which is also one of the most important reasons for its current large-scale use; discharge voltage is high, generally in the 3.2-4.2 V or more; self-discharge is low, in the normal storage conditions. Low self-discharge, under normal storage conditions, the monthly self-discharge rate of lithium-ion batteries is generally only 5.0%, so for new energy vehicles, there is no need to worry about not being able to start for a period of time without using it like traditional fuel vehicles do; long cycle life, in 100% depth of discharge (DD), ordinary lithium-ion batteries can be charged and discharged up to 500 times more than the lithium-ion batteries, and lithium iron phosphate cycle life is more than 2,000 times [8], but compared to fuel vehicles, its service life is still short, and it is not easy for the battery to be used in a large scale. However, compared with fuel vehicles, its service life is still short board, and the subsequent high cost of battery replacement may deter some consumers. In addition, it has another feature, that is, there is no memory effect, so there is no problem with capacity reduction during repeated use of the battery. High charging and discharging efficiency, the energy conversion efficiency of the battery in the charging and discharging process can reach more than 90%; a wide range of operating temperatures, the general operating temperature range of -20 to 45 degrees [8], but in the low-temperature conditions of the battery's usable capacity decreases, resulting in a decline in the range of new energy vehicles. At present, the widely used power batteries are lithium iron phosphate and lithium ternary batteries, lithium ternary batteries have a higher energy density, but the safety is slightly worse. Lithium iron phosphate battery is just the opposite. In the short term, these two batteries are the mainstream direction of power batteries [9].

The main characteristics of the three types of batteries and their applications are summarized below,

(1) Ternary lithium battery:

Application characteristics: high energy density, long-range, suitable for medium and high-end new energy vehicles.

Advantage: excellent performance, faster charging speed.

Limitations: high cost, safety needs to be improved.

(2) Nickel-metal hydride battery:

Application: There are some applications in early new energy vehicles.

Advantage: mature and reliable, long cycle life.

Disadvantages: relatively low energy density and high weight.

(3) Lithium iron carbonate battery:

Application: widely used in economic new energy vehicles.

Advantages: low cost, good safety.

Disadvantages: limited space for energy density improvement.

Table 1. Properties of the three different batteries.

Battery type	Anode	Cathode	Properties of the battery		
			V	Ah/kg	Wh/kg
Ni-Mi-H	MH	NiO2	1.35	178	240
li-ion	LixC6	Li(1-x)CoO2	4.1	100	410
Lead Acid	Pb	PbO2	2.1	120	252

3.2. Limitations of Lithium Battery Technology

At present, spontaneous combustion incidents of new energy vehicles occur occasionally, and the culprit of this incident is lithium batteries. Under certain circumstances, such as overcharging, over-discharging, short circuits, etc., lithium batteries may undergo thermal runaway, resulting in a sharp rise in battery temperature, triggering a fire or even an explosion. The lithium battery itself also has a safety risk during use, that is, the growth of lithium dendrites. In the process of long-term use, lithium dendrites may grow inside the battery, resulting in piercing the diaphragm and causing the battery to short-circuit. There are many reasons for this, such as electrode polarization, current density, ambient temperature, etc., and the main reason is that the overpotential generated at higher current densities reduces the empirical potential of the anode to a potential conducive to lithium-ion reduction

(i.e., lithium plating). A way to reduce the chance of lithium plating is to increase the absolute capacity ratio between the positive and negative electrodes (often referred to as the N/P ratio) [10].

In addition to this, it is difficult to improve the energy density of lithium batteries, which is still relatively low compared to other types of batteries, limiting the range of electric vehicles. To further improve the energy density of lithium batteries, they face many technical challenges, such as material selection, and electrode structure design. Raw material prices: Lithium, cobalt and other key raw material prices are high, resulting in the relatively high cost of lithium batteries.

Lithium batteries also face aging problems, with the increase in the number of charge and discharge, the capacity of lithium batteries will gradually decline, affecting the service life of the battery. After long-term use, the performance of the battery will gradually decline, there is no choice but to replace the battery.

Recycling difficulties: lithium battery recycling technology is not yet fully mature, the recycling cost is high, and there is a certain environmental pressure. Automotive lithium battery recycling is still in its infancy, and there is no clear method available. It is expected that by 2030, the world will accumulate about 11 million tons of waste lithium batteries, of which automotive batteries account for a large part [11]. Those with a storage capacity of 50-70% contain toxic and environmentally hazardous materials and need to be recycled or reused.

4. Challenges and Future Directions for Fuel Cell Applications

(1) High cost: The core components of fuel cells, such as catalysts and membrane electrodes, are expensive, resulting in higher overall vehicle costs.

(2) Inadequate infrastructure: The construction of supporting facilities such as hydrogen refueling stations is lagging behind, limiting the convenience of using fuel cell vehicles.

(3) Durability and reliability: In actual use, the life and stability of fuel cells need to be further improved.

(4) Hydrogen source problem: There are certain difficulties and costs in the production, storage, and transportation of hydrogen.

Fuel cell life is the primary problem faced by fuel cell vehicles. At present, the battery life of fuel cell buses has been improved, such as in 2011, the U.S. fuel cell hybrid bus life of more than 11,000 h, and the life of a fuel cell forklift reached the level of 12,500 h. The life of the second generation of wheelside motor-driven fuel cell buses introduced by the German Daimler Group in 2009 has reached 12,000 h [12]. Therefore, how to extend the life of fuel cells is still the focus of the next generation of technology research and development. There are many factors affecting fuel cell life, from electrode materials to the structure of the electric stack, from the fuel cell system to the fuel cell vehicle power system, and finally to the fuel cell vehicle, and the reasonableness of the design of each link has a direct impact on the final life of the fuel cell. The next generation of mainstream technology will continue to focus on the following aspects: electrode materials: changes in catalyst activity and membrane proton conductivity; stack structure: heat dissipation, internal resistance, gas diffusion, water vapor exchange, etc.; fuel cell system: air recirculation technology, stable working condition control, start-stop strategy, etc.; fuel cell power system: design and optimization of the powertrain configuration, determination of the power indexes of the whole vehicle, and start-stop strategy. Fuel cell power system: powertrain configuration design and optimization, vehicle dynamics index determination, DC/DC control logic, power battery matching, etc. [13]. Fuel cell power system: power system configuration design and optimization, vehicle dynamics index determination, DC/DC control logic, power battery matching, and so on. The ultimate goal is to increase the power density of the PEMFC, i.e., from the current power density of about 4 kW l-1 to a short-term goal of 6 kW l-1 and a long-term goal of 9 kW l-1 [14]. At the same time, costs are to be reduced and durability increased to facilitate large-scale commercialization. These three criteria are largely interrelated and constrained by each other, and finding the optimal balance between them is the key to achieving further commercialization in the future.

5. Conclusion

PEMFCs have attracted much attention due to their advantages in new energy vehicle propulsion and the remarkable technological advances made in recent years. This paper compares lithium-ion batteries and PEMFCs and focuses on the development direction of PEMFCs, in which optimizing the design of PEMFC stack structure, achieving higher power density, lowering cost, and improving durability will directly contribute to the large-scale commercialization of PEMFCs for in-vehicle applications. In conclusion, considering the existing fuel cell technologies, the design of the stack structure is a key direction, while the development of new electrode materials will be crucial for the improvement of various PEMFC performances as well as for the prolongation of fuel cell lifetime.

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