Analysis of Related Technologies Used in Fuel Cell Vehicles

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Abstract—Nowadays, many types of fuel cells have made significant progress. In 2014, they were applied to the production model Toyota's FCHV-Adv. With their high efficiency and low pollution, fuel cells have gradually started to replace some traditional technologies in many energy applications and production industries and have become a hot topic of interest in recent years. Depending on the type of fuel, there are various types, and different fuel cells work on different principles, leading to differences in their performance. This paper lists the different fuel cells and their application scenarios in the automotive industry. In addition, the use of hydrogen in fuel cell vehicles is also a major concern. This paper briefly discusses the current hydrogen production and four different types of fuel cell vehicles and their energy management strategies. All the technical advantages of fuel cells and hydrogen energy are ultimately reflected in fuel cell vehicles, and this paper describes the current challenges and future possibilities.

1. Introduction
As the world environment continues to change, sea levels are gradually rising, and problems such as the destruction of the ozone layer are threatening the survival of mankind. Mankind urgently needs to reduce damage to the environment from all aspects, including the treatment of air pollution. In air pollution, motor vehicle exhaust pollution accounts for more than 50%. So it is very important to solve the exhaust gas problem. The use and promotion of clean energy vehicles has become one of the important methods to solve the problem of exhaust emissions.

In recent years, new energy vehicles such as pure electric vehicles (PEVs), hybrid electric vehicles (HEVs), and fuel cell vehicles (FCVs) have emerged. Among them, PEVs are regarded as a key development target in China in the near future, and are expected to replace traditional fuel vehicles in the next few years. However, in the power generation process, the large number of pollution emissions and battery problems contained in it make it impossible to become a candidate for emission-free vehicles. As a vehicle that can achieve completely no emissions, FCVs have attracted much attention in recent years. People combined with clean hydrogen energy production technology, such as the use of solar energy to produce hydrogen, to make the use of hydrogen FCVs a completely pollution-free cycle. At the same time, it has a refueling time similar to that of conventional vehicles (CVs), and it does not need to spend several hours to fully charge the vehicle like a PEV. Although it is superior to the CVs on the market in these aspects, it is still rarely seen on the road, because hydrogen fuel cell vehicles are currently facing many problems. The first is the production and manufacturing of fuel cells. Metal
platinum will be used in the process, under such a condition, if hydrogen fuel cells are produced in large quantities, then a large amount of platinum will be used, which requires a lot of cost. Secondly, the problem of the source of hydrogen in the process of use is also tricky. The current hydrogen production method is not only uneconomical but also has a great energy loss. In addition, it is not convenient for the customers to drive a hydrogen fuel cell vehicle. As of the end of March 2021, only 131 hydrogen refueling stations have been built throughout China, of which only 108 are in operation [1-3].

This means that hydrogen fuel cell vehicles cannot be used in most places. Although the temporary large-scale use of hydrogen fuel cell vehicles is still facing great challenges, with the completion of more hydrogen refueling stations and the continuous reduction of hydrogen production costs, hydrogen fuel cell vehicles as the most environmentally friendly vehicles will eventually become the mainstream transportation vehicles in the future.

2. Principles and applications of fuel cells
A fuel cell by definition is an electrical cell, which unlike storage cells can be continuously fed with a fuel so that the electrical power output is sustained indefinitely [4]. Its basic principle is a redox reaction, an electrochemical process in which no mechanical or thermal processes are involved [5], so its energy conversion efficiency can be very high. The specific structure of a fuel cell is shown in Fig. 1 below, which consists of two electrodes, positive and negative, and an electrolyte. During operation molecular hydrogen (H₂) is transported from the gas stream to the anode, where an electrochemical reaction occurs. The hydrogen is oxidized to produce hydrogen ions and electrons, which migrate through the acidic electrolyte, while the electrons are forced through an external circuit to the cathode. At the cathode, the electrons and hydrogen ions react with the oxygen provided by the external gas stream to form water [6].

![Fig.1 Basic principle of a fuel cell](image)

Based on the basic principles of fuel cells people have invented many different fuel cells. They are based on the choice of electrolyte and fuel to classify [8]. The six main categories are as follows.

1. Alkaline fuel cell (AFC);
2. Phosphoric acid fuel cell (PAFC);
3. Solid oxide fuel cell (SOFC);
4. Molten carbonate fuel cell (MCFC);
5. Proton exchange membrane fuel cell (PEMFC);
6. Direct methanol fuel cell (DMFC).

Their specific principles and the current status of their development are described separately below.

2.1. Alkaline fuel cell (AFC)
Fig.2 shows the working process of the alkaline fuel cell. The electrolyte composition used in AFCs is an aqueous solution or a stable potassium hydroxide matrix. The humidified hydrogen is supplied to the anode during operation and reacts with the hydroxide ions in the electrolyte to form water and electrons, while oxygen and water are supplied together to the cathode to be reduced to hydroxide ions, which diffuse through the electrolyte and participate in the hydroxide reaction that occurs at the anode [9]. The end products are water and heat. The specific reaction equation is as follows:

\[
2\text{H}_2 + 4\text{OH}^- \rightarrow 4\text{H}_2\text{O} + 4\text{e}^-
\]
Cathodic reaction, 

\[ O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \]

Fig. 2 Alkaline fuel cell [10]

Alkaline fuel cells are the most mature of all fuel cells because of their early origins, and were extensively studied by many scholars before the 1980s. The initial application was in space missions, where they were used to provide stable power and have the characteristics of small size and light weight to meet the needs of space [11]. In addition, because it operates at a temperature of only 80 degrees Celsius, it can be started quickly, and its technology was used in a four-passenger Austin A40 [12]. But the power density of proton exchange membrane fuel cells far exceeds that of AFCs, so AFCs are inconvenient to use in cars. However, they are by far the least expensive fuel cell to produce and are therefore commonly used in small stationary generators.

In fact, AFCs have not been improved for a long time, probably due to the emergence of more commercially competitive PEMFCs, but there is still a lot of potential to optimize AFCs, such as removing or reducing the impact of CO2 on battery life and performance, etc. The theoretical performance of AFCs is excellent, and further development of AFCs will certainly strengthen their competitive position in applications.

2.2. Phosphoric acid fuel cell (PAFC)

Fig. 3 shows the working process of the phosphoric acid fuel cell. Phosphoric acid fuel cells use an electrolyte of pure phosphoric acid and a catalyst to accelerate the cell reaction. During operation, hydrogen is supplied to the anode, electrons are separated, and hydrogen atoms pass through the phosphoric acid in the form of protons to the cathode, where they form water with oxygen atoms that are charged at the cathode [13]. The specific reaction formula and schematic diagram are as follows:

Anodic reaction, 

\[ H_2 \rightarrow 2H^+ + 2e^- \]

Cathodic reaction, 

\[ O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \]

Fig. 3 Phosphoric acid fuel cell [10]

Phosphoric acid fuel cell technology has been a mature and widely used fuel cell in a number of power plant applications, including the largest fuel cell built to date, an 11 MW PAFC power plant.
belonging to Tokyo Electric Power Co. It operated for over 230,000 hours between 1991 and 1997 [14]. Although phosphate fuel cell technology is relatively well established for commercial applications, there is still a large potential for research using more suitable catalysts and electrolytes that could further increase the power density of fuel cells [15]. In addition, recycling of the heat produced by the fuel cell in combination with the use scenario and system design can improve the overall system performance and profitability in commercial applications [16]. For current application scenarios they are still typically used for on-site stationary applications, such as large power plants.

2.3. Solid oxide fuel cell (SOFC)

Fig. 4 shows the working process of the solid oxide fuel cell. The electrolytes commonly used in SOFC are oxide ion-conducting yttrium-stabilized zirconia (YSZ), strontium-doped lanthanum manganate (LSM) as the cathode material, and nickel/YSZ and lanthanum-doped chromite or high-temperature metal interconnects as the anode material [17]. The basic principle in operation is similar to other fuel cells, where the fuel is delivered to the anode, an oxidation reaction occurs, the oxidizer is sent to the cathode and a reduction reaction takes place, and electrons flow along an external circuit from the anode to the cathode. The specific reaction equation and diagram are as follows:

Anodic reaction,

$$0^{2-} + H_2 \rightarrow H_2O + 2e^-$$

Cathodic reaction,

$$\frac{1}{2} O_2 + 2e^- \rightarrow O^{2-}$$

The development of solid oxide fuel cells began in the 1940s and is one of the early categories of fuel cells. In the early days, this type of fuel cell operated at high temperatures between 800 and 1000 degrees Celsius. Some scientists are also working on the optimization of low temperature SOFCs, which can further enhance their practicality. It also enhances its non-polluting and reliable characteristics and enables efficient chemical power generation. Their performance has been demonstrated in several 10-kW class atmospheric pressure power generation systems. In pressurized SOFC-combustion engine combined cycle power systems, power generation efficiencies of more than 70% can be achieved [18]. Much of the current research is directed towards enhancing their applicability and in order to create efficient and durable SOFCs, two SOFC stack designs have been explored extensively in the last few years, the planar design and the tubular design, respectively [19]. In fact, the tubular design is now found to be more widely used than the planar design because of the increase in volumetric power density, and the tubular design is found to be more efficient than the planar design. And now we should try to find new SOFC materials (anode, cathode and electrolyte) in order to develop low-cost, efficient and durable SOFC prototypes [20].
2.4. Molten carbonate fuel cell (MCFC)

Fig. 5 shows the working process of a molten carbonate fuel cell. The electrolyte used in Molten carbonate fuel cells is a mixture of molten carbonates. The hydrogen fuel and the carbonate ions react at the cathode to produce carbon dioxide, water and electrons [21]. At the anode, the primary fuel and water are converted into hydrogen, carbon monoxide and carbon dioxide. The specific reaction equations and diagrams are as follows.

Anodic reaction,

\[ 2H_2 + 2CO_3^{2-} \rightarrow 2CO_2 + 2H_2O + 4e^- \]

Cathodic reaction,

\[ O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{2-} \]

Fig. 5 Molten carbonate fuel cell [10]

The cathode of a fused carbonate fuel cell is composed of a porous ceramic, and many researchers have addressed this structure, and new improvements in cell components have been proposed, particularly in terms of the microstructure and chemical composition of the applied materials [22]. The design of the cathode microstructure can facilitate the reaction rate of the reactions at the cathode and thus enhance the performance of the fuel cell, which is the direction of research for some time to come [23].

2.5. Phosphoric acid fuel cell (PAFC)

Fig. 6 shows the working process of the proton exchange membrane fuel cell. Proton exchange membrane fuel cells (PEMFC) use polymeric membranes that can conduct ions as the electrolyte. The fuel can be pure hydrogen, which is activated by a catalyst to form electron and proton ions at the anode. The protons can pass through the membrane, while the electrons are forced to flow in an external circuit to the cathode. At the cathode, the product water is formed by interacting with oxygen and proton ions [10].

Anodic reaction,

\[ H_2 \rightarrow 2H^+ + 2e^- \]

Cathodic reaction,

\[ O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \]
The proton exchange membrane fuel cell has a relatively short history compared to some other fuel cells, but it is growing at an unprecedented rate and has unprecedented potential for the next progress. This fuel cell can use pure hydrogen as fuel, which means it can achieve high efficiency and zero pollution. This foreseeable benefit has led many countries and companies to invest in the development of marketable hydrogen energy systems for road transport [24]. As a result, PEMFC has been extensively studied in vehicles, and in addition to the emissions benefits, the high energy density and low mass of PEMFC wins out from a crowd of fuel cells as the most suitable fuel cell for vehicles. Although PEMFC has great advantages in theory, there are huge problems in commercial applications. Manufacturing cost, durability, hydrogen fuel replenishment infrastructure and hydrogen storage are among the current challenges [25].

2.6. Direct methanol fuel cell (DMFC)

Fig.7 shows the working principle of a direct methanol fuel cell. The operating principle of the direct methanol fuel cell is basically the same as that of the proton exchange membrane fuel cell. The difference is that the fuel for the direct methanol fuel cell is methanol (gaseous or liquid) and the oxidizer is still air and pure oxygen.

Anodic reaction,

$$\text{CH}_3\text{OH} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + 6\text{H}^+ + 6\text{e}^-$$

Cathodic reaction,

$$1.5\text{O}_2 + 6\text{e}^- + 6\text{H}^+ \rightarrow 3\text{H}_2\text{O}$$
gas produced on the electrocatalyst surface can lead to reduced performance of the liquid cell [26], which is relatively inefficient due to the fact that the electrochemical activity of methanol is at least three orders of magnitude lower than that of hydrogen. Therefore, future research is needed to stop the toxic effects of methanol and intermediate products (e.g., CO, etc.) on the catalyst, and to find an efficient catalyst to improve the efficiency of DMFC.

3. Hydrogen production

Hydrogen energy is indispensable in fuel cell applications. Fuel cell vehicles using pure hydrogen can be driven without pollution. But the application of hydrogen energy is much more than that; it is a fuel with unlimited potential. But natural hydrogen is only found in compounds, so it is released from organic materials such as fossil fuels and biomass, or from materials such as water, through a thermochemical process that uses heat and chemical reactions [27]. For this reason, many different hydrogen production technologies have been developed. Different hydrogen production methods have different raw materials and efficiency, as shown in the Tab.1 below.

| Technology                      | Feed stock                  | Efficiency | Maturity       |
|--------------------------------|-----------------------------|------------|----------------|
| Steam reforming                | Hydrocarbons                | 70-85%     | Commercial     |
| Partial oxidation              | Hydrocarbons                | 60-75%     | Commercial     |
| Autothermal reforming          | Hydrocarbons                | 60-75%     | Near term      |
| Plasma reforming               | Hydrocarbons                | 9-85%      | Long term      |
| Aqueous phase reforming        | Carbohydrates               | 35-55%     | Med term       |
| Ammonia reforming              | Ammonia                     | NA         | Near term      |
| Biomass gasification           | Biomass                     | 35-50%     | Commercial     |
| Photolysis                     | Sunlight + water            | 0.5%       | Long term      |
| Dark fermentation              | Biomass                     | 60-80%     | Long term      |
| Photo fermentation             | Biomass + sunlight          | 0.13%      | Long term      |
| Microbial electrolysis cells   | Biomass + electricity       | 78%        | Long term      |
| PEM electrolyzer               | H$_2$O + electricity        | 50-60%     | Commercial     |
| Solid oxide electrolysis cells | H$_2$O + electricity + heat | 40-60%     | Med Term       |
| Thermochemical water splitting | H$_2$O + heat               | NA         | Long term      |
| Photoelectrochemical water splitting | H$_2$O + sunlight | 12-4%     | Long term      |

4. Fuel Cell Vehicles

In the history, the research on fuel cells predates their application to automobiles. As early as 1839, Sir William Grove began the research on fuel cells, but it was not until 1932 that an alkaline fuel cell system with porous electrodes was successfully developed by Francis Bacon, an English engineer. However, the first application of fuel cells was not in the automotive field, but in the aerospace field, participating in the Apollo space project. The reason is that fuel cells are safer and lighter than other energy storage devices [29].

Until the last few decades, due to the increasing awareness of people’s environmental protection, the environmental pollution problem of traditional vehicles have gradually been paid attention to. As a result, there have been many new alternative vehicles that can replace traditional vehicles. Among them, fuel cell vehicles (FCV) have huge potential. Fuel cell electric vehicles (FCEVs) in the Fig.8 (a) are powered entirely by fuel cells. Adding a different energy storage system (ESS) is called fuel cell hybrid vehicle (FCHV). Through these auxiliary ESSs and an optimal energy management strategy (EMS), it can provide vehicles with faster dynamic loading, prolong the life of the system and absorb regenerative braking energy [30, 31].

4.1. Fuel Cell Electric Vehicle (FCEV)

Compared with conventional vehicles (CVs), electric driving has many advantages, such as higher energy conversion efficiency and low negative impacts on the environment. At the same time, there are many new energy storage systems, such as batteries, super capacitors, and fuel cells.

Only the fuel cell is used to generate electricity is the fuel cell electric vehicle (FCEV). Compared with pure electric vehicles (PEVs) whose battery energy density is about 10% of gasoline, FCEVs have higher energy density and can travel longer distances [32]. The power transmission route of FCEVs
mainly includes fuel cell, converter, inverter, electric motor, gear boxes and wheels. Firstly, hydrogen and oxygen are fed into the fuel cell to generate electricity, and then drive the motor after passing through the converter and inverter. Compared with PEVs, FCEVs cannot store the energy during braking [33].

**Fig.8 Four different types of FCV [33]**

### 4.2. Fuel Cell Hybrids Vehicle

#### 4.2.1. Fuel Cell-Battery Hybrids Vehicle

In a Fuel Cell-Battery Hybrids Vehicle, which has been showed in Fig.8 (b), the fuel cell provides constant energy, and the battery is used as an auxiliary to store the energy generated during braking or deceleration and to provide additional energy during the acceleration phase. At the same time, the battery can also be used as power when the vehicle is running at low speed to avoid the inefficient operation of the fuel cell [34].

#### 4.2.2. Fuel Cell-Supercapacitor Hybrids Vehicle

In a Fuel Cell-Supercapacitor Hybrids Vehicle, which has been illustrated in Fig.8 (c), the fuel cell is generally used as the main power source, and the SC is used as the auxiliary ESS, which can capture the regenerative energy during the deceleration, and can respond well to the sudden acceleration of the vehicle to provide extra power. However, due to improvements in specific power, efficiency and cost of lithium batteries in recent years, SC cannot achieve the energy density and fuel economy similar to batteries.

#### 4.2.3. Fuel Cell-Battery-Supercapacitor Hybrids Vehicle

Fuel cells have the advantages of lightness and cleanliness, but they cannot store energy; batteries have the advantage of stably providing energy, but are too bulky; SC has the advantage of dealing with vehicle transient response, but the stored energy is limited. Therefore, in the Fig.8 (d), the combination of these three ESSs can provide higher energy efficiency for the entire power system, improve its durability, and extend the life of each component.

### 4.3. Energy Management Strategies

The objective of the energy management strategy (EMS) is to deplete the fuel consumption, vehicle performance and driver comfort. A FCHV has a variety of energy storage systems, and different systems have different advantages and disadvantages. Therefore, it is necessary to design an excellent control
algorithm to control the energy flow of the vehicle to face different driving conditions. Under such a condition, the development of EMS plays an important role in fuel cell hybrid vehicles.

Fig. 9 shows the classification of EMSs. The EMS can be divided into two different sets of the Rule-Based method and Optimization method. The Rule-Based method can be further divided into Deterministic Rule approach and Fuzzy Rule approach. The Optimization method can be further divided into Global Optimization approach and Real-time Optimization approach.

Fig. 9 Classification of EMSs

Fig. 10 shows the basic flow of the new fuzzy EMS using improved GA, the power demand ($P_{\text{dem}}$) and the state of charge (SOC) as fuzzy inputs. In recent years, a variety of energy management strategies under these two approaches have been put forward to improve the control algorithm in FCHVs. For example, Hamed Farhadi Gharibeh et al. proposes a new online bi-level strategy of energy management for a fuel cell electric vehicle, which could reduce equivalent fuel consumption, reduce power fluctuations of PEMFC output power, and increase the total energy efficiency of energy storage system. Zhang et al. proposed a new fuzzy EMS using an improved Genetic Algorithms (GA) to minimize the consumption of hydrogen as well as the voltage and current fluctuation which is severely affecting the life span of the system components, such as energy storage system.

Fig. 10 The basic flow of the new fuzzy Energy Management Strategy (EMS) using an improved Genetic Algorithms (GA)
5. Challenges

5.1. Fuel Cell
The key challenges for fuel cells in vehicles are power density and cost. In the long term, fuel cell vehicles will be an alternative to petrol vehicles, so their performance and price need to be comparable to that of petrol vehicles to promote large-scale commercialization. In terms of cost, the long-term plan should be to develop alternatives to expensive materials in fuel cells or to establish a complete production and supply chain to produce large quantities to reduce the cost per unit. In terms of improving power density, it is also necessary to research and design new materials and structures. In general, within the framework of existing materials, the establishment of finely controlled and easily manufactured structural designs is a key direction, and the emergence of new materials is expected to have a profound impact in the long term.

5.2. Fuel Cell Vehicle
Fig.11 is EV sales in World of 2010-2020. According to the IEA report, in 2020, the global sales of electric vehicles increased by 41% compared with 2019, of which battery electric vehicles (BEV) accounted for about two-thirds, and the sales of fuel cell electric vehicles (FCEV) were negligible [35]. In order to analyze the real environmental benefits of a vehicle, WTW analysis is needed. Well to wheel analysis can be divided into WTT and TTW. The former focuses on energy expended and the associated emissions in the process of manufacturing the final fuel. Primary energy and processing methods are the two major factors in this process. The latter focuses on the energy expended and the associated emissions when the car converts these fuels.

![Fig.11 EV sales in World, 2010-2020](image)

S. Ramachandran et al. analyzed low carbon alternatives, and the results showed that the fuel consumption and emissions of current fuel cell vehicles are higher than those of electric vehicles. The main reason is that the low efficiency of hydrogen production in the WWT process and more carbon dioxide is released.

Hydrogen is a brand-new energy source. Most fuel cell vehicles currently use hydrogen as fuel. However, in order to ensure the sustainable development of fuel cell vehicles, it is also necessary to consider the construction of hydrogen energy infrastructure, such as hydrogen pipeline transport, points of hydrogen production and hydrogen stations. Therefore, it is significant to consider all of these prerequisites before the fuel cell vehicle completely replace the conventional vehicle which is using an internal combustion engine to drive the wheels.
6. Conclusion
In view of the current research progress of fuel cell vehicles (and their additional industries), there are still many problems to be explored and solved, and research should be conducted in the following areas.

(1) The highest efficiency among existing fuel cells can reach 60%, but to further improve their performance in vehicles, higher energy conversion efficiencies and higher energy densities need to be obtained. In addition, in order to achieve mass production and widespread use, it is necessary to further reduce the cost of production and improve its service life.

(2) There are still many challenges with hydrogen as the best energy source for fuel cell vehicles. Most existing methods of producing hydrogen emit polluting gases and are more expensive than fuel. Making hydrogen the primary energy source of the future requires research into low-cost and environmentally friendly ways of producing hydrogen, such as using water (H₂O) to decompose into hydrogen (H₂) and oxygen (O₂) by solar energy, and ensuring its economy. In addition, the transportation of hydrogen is also a challenge, as it is easier and cheaper to transport in its state, but also contains low energy density, while in the liquid state it contains more energy in the same space, but compressing gaseous hydrogen into liquid state requires a lot of energy and is more expensive. So how to produce low-cost liquid hydrogen is also a research direction to make fuel cell vehicles universal.

(3) Four different FCVs powered only by fuel cells and batteries and supercapacitors as auxiliary ESSs were introduced. It also explains that under advanced EMSs, fuel cell hybrid vehicles have more advantages in the fuel consumption, vehicle performance and driver comfort. At the same time, a new online bi-level strategy and the system based on genetic algorithm of energy management are introduced.

(4) Based on WTW analysis, it shows that the fuel cell vehicles, especially the hydrogen energy vehicles, are still slightly inferior to electric vehicles in terms of fuel consumption and emissions. In addition, the number of infrastructure hydrogen refueling stations to support fuel cell vehicles is still not sufficient to support the rapid adoption of fuel cell vehicles in the future.

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