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A Mini Review of Fuel Cell: Classifications, Technologies, and Applications

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Abstract: Fuel Cell (FC) is a widely used kind of energy source in industry and there are six main types, which are Solid Oxide Fuel Cell (SOFC), Alkaline Fuel Cell (AFC), Phosphate Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC), Direct Methanol Fuel Cell (DMFC), and Proton Exchange Membrane Fuel Cell (PEMFC). This research review the application, technology, and bottleneck of different FC. Also, the future research target is also introduced.

Keywords: Fuel Cell, classification, application, technology, bottleneck

1. Introduction

Fuel Cell (FC) is a widely used kind of energy source in industry [1, 2]. As the development of industry, people care about the pollution a lot. Thus, the application of fossil energy has been reduced and oppositely, fuel cell has been widely used in both industry and research. There are six state-of-art of most widely used fuel cells, which are Solid Oxide Fuel Cell (SOFC), Alkaline Fuel Cell (AFC), Phosphate Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC), Direct Methanol Fuel Cell (DMFC), and Proton Exchange Membrane Fuel Cell (PEMFC) [3-6]. In this research, six different types of FC are summarized. Their working principles, core performance advantages and current main application scenarios are sorted out systematically, to clarify the development status of different fuel cell technologies in current industrial practice and academic research. On this basis, this review also summarizes the key technical bottlenecks that restrict the large-scale promotion of each type of FC at this stage, and prospects the future development direction of FC technology, aiming to provide a clear reference for subsequent related research and application transformation.

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2. Classifications of FC

In this section, a detailed and separate introduction to each of the six distinct types of FC will be provided, exploring their individual characteristics and applications. This kind of FC has been widely used since its safety and high-efficient.

2.1. Phosphate Acid Fuel Cell (PAFC)

PAFC is considered the first generation of modern FC. It uses liquid phosphoric acid as an energy electrolyte [7]. In the research of Nie's group, liquid polymer precursor was found that can perfectly infiltrate into the voids and the cracks at $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ and cathode interfaces and then polymerize after the heat treatment, which will increase the stability for the practical application of high-voltage All-solid-state lithium batteries [8]. Wu et al. Summarized the roles of ionic liquids in solid-state batteries focusing on the interface, with insights into their functionality, and this work concluded that PAFC is limited in industry applications, which more efficient and useful FCs need to be generated [9]. In order to increase the safety of PAFC, the research group of Yusuf from Spain used $LiFePO_4$ cathode in PAFC [10]. And the result showed that fluorinated phosphazene-based electrolytes with content up to 6% (by vol.) cannot be deemed non-flammable, because it will also burn in high-temperature atmosphere.

Therefore, how to optimize the electrolyte formula to improve the high-temperature safety performance of PAFC while maintaining its original power generation efficiency is still the core research direction of PAFC technology at this stage. At present, the most common application scenario of PAFC is medium and small-scale stationary power generation, because its operating temperature is between 150℃ and 200℃, which has good tolerance to carbon monoxide impurities in fuel, and the system construction cost is lower than that of many emerging fuel cell technologies. Its main technical bottlenecks at present include low overall energy conversion efficiency, large volume of the device caused by liquid electrolyte, and potential corrosion risk of phosphoric acid to core components of the cell, which makes it difficult to be applied in large-scale high-power scenarios and mobile power supply fields such as new energy vehicles.

2.2. Molten Carbonate Fuel Cell (MCFC)

MCFC is a kind of high-temperature FC that uses an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminum oxide matrix [11]. The stability in high-temperature atmosphere is the key advantage of MCFC, which enables it to directly use fossil fuels such as coal gas and natural gas for power generation without the need for additional complicated fuel purification and reforming devices. Tang et al. investigated an experimental and modeling study of ammonia oxidation in a jet stirred reactor, and they found the limit of it, which the performance of the FC is strongly influenced by equivalence ratios [12]. In the research of Contreras's group, MCFC can operate as standalone units to improve the transportation

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system in vehicles, ships and provide energy efficiently to meet energy needs in residential and commercial areas [13].

Compared with low-temperature FCs, MCFC does not need expensive precious metal catalysts, which effectively reduces the manufacturing cost of the cell stack [14]. However, the long-term operation of MCFC under high-temperature and molten salt environments also brings obvious technical problems: the cathode material is prone to dissolution and corrosion during long-term operation, and the electrolyte will gradually volatilize and degrade, which directly reduces the service life of the whole cell [15]. At present, the commercialization process of MCFC is still in the demonstration and promotion stage, and its main application fields are large-scale stationary power generation projects and distributed energy supply systems, while further technical verification is still needed for mobile power supply scenarios. How to improve the long-term structural stability of cell core materials and inhibit the performance degradation caused by high-temperature corrosion is still the main research focus of MCFC technology at this stage.

2.3. Solid Oxide Fuel Cell (SOFC)

SOFC represents a major category of FC technology. It inherits the distinctive advantages of high efficiency and low emission inherent to FC technology, and additionally features unique merits including an all-solid-state structure and substantial flexibility in fuel selection [16]. Xie et al. did research on iron-based double perovskite cathode materials for SOFC, this study investigated the effects of three modification strategies, namely element doping, surface modification, and composite cathode construction, on electrochemical performance [17]. In the research of Lu's study, investigates the B-site engineering in the perovskite material $Pr_{0.4}Sr_{0.6}Co_{0.2}Fe_{0.8}O_{3-\delta}$ (PSCF) through niobium (Nb) doping, in which iron (Fe) is partially substituted to elucidate the influence of Nb on cathode performance [18].

Currently, the main technical challenge of SOFC is the high operating temperature requirement, which demands high-temperature resistance and good interfacial compatibility for all cell components [19]. The mismatch of thermal expansion coefficients between different materials is prone to causing performance degradation and structural damage during repeated start-stop cycles. Currently, the main development trend of SOFC technology is to reduce the operating temperature to the medium-low range of 500°C-800°C [20], so as to relax material performance requirements, cut system manufacturing costs, and expand application scenarios to distributed energy supply and even auxiliary power supply for transportation. How to maintain the high electrochemical activity of electrolyte and cathode at medium and low temperatures is still the key problem to be broken through in current SOFC research.

2.4. Alkaline Fuel Cell (AFC)

In AFC, potassium hydroxide (KOH) is used as the electrolyte [21], and this kind of FC has a high efficiency and can reduce the pollution [22]. In the research of Ferriday's group, AFC technology was summarized and they concluded

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that the average rate of degradation is notably high, which is friendly to the environment [23]. Jiang et al. studied the oxygen reduction reaction in both acidic and alkaline electrolytes [24]. This work present a new idea toward designing and developing low-cost, high-performance electrocatalysts for FC applications.

However, AFC still faces a critical inherent limitation that cannot be ignored: it is extremely sensitive to carbon dioxide (CO_2) in the air and fuel [25-28]. CO_2 will react with the alkaline electrolyte KOH to generate carbonate, which gradually reduces the alkalinity of the electrolyte and degrades the electrochemical performance of the electrode, thus greatly limiting the long-term stable operation of AFC. Due to this characteristic, early AFC can only be applied to specific closed scenarios with pure hydrogen and oxygen as reactants, such as on-board power supply systems for spacecraft and submarines.

2.5. Direct Methanol Fuel Cell (DMFC)

DMFC is powered by pure methanol, which is usually mixed with water and fed directly to the FC anode [29]. Tountas's group investigated the use of renewable methanol in DMFC and found that the efficiency was increased 38% to 112% [30]. This research pointed at a new method to reduce pollution caused by FC waste. Artificial Intelligence (AI) has been widely used in industry [31-33], and AI was applied in Xu's research, and the performance of DMFC was enhanced by the assistance of AI [34].

DMFC is rapidly developing because of its simple structure, convenient fuel storage and transportation, and high energy density [35]. It is particularly suitable for small portable electronic devices, such as mobile phones, laptop computers and miniature unmanned aerial vehicles, which have broad application prospects in civilian portable energy scenarios [36]. At present, the main technical bottlenecks restricting the large-scale application of DMFC are the low catalytic activity of anode methanol oxidation reaction, serious methanol crossover from anode to cathode through the proton exchange membrane, and the high cost of platinum-based catalysts commonly used at this stage [37]. How to develop low-cost high-efficiency non-platinum or low-platinum catalysts, improve proton exchange membrane modification processes to reduce methanol permeability, and optimize single-cell structure design to improve overall energy conversion efficiency are the core research directions of DMFC technology at present.

2.6. Proton Exchange Membrane Fuel Cell (PEMFC)

The proton exchange membrane is the core component in a FC [38]. Huang's group did a comprehensive experimental analysis of performance parameters to determine dynamic voltage characteristics for PEMFC [39], This study provides valuable insight into PEMFC dynamic performance and guidance for system control optimization. Ban et al. did a research on covalent organic frameworks modified composite proton exchange membranes towards advanced FC and pointed out the future research method in this area [40].

PEMFC uses perfluorosulfonic acid proton exchange membrane as the electrolyte, which has the advantages of fast startup, high power density, low operating temperature, and good zero-emission characteristics [41], making it the preferred technology route for new energy vehicle power systems and distributed stationary power generation at present. The membrane electrode assembly, which is composed of proton exchange membrane, catalyst and gas diffusion layer, directly determines the output performance and service life of the fuel cell [42]. At present, the main challenges for PEMFC large-scale commercial application include the high cost of core components caused by the large dosage of platinum-based catalysts, the insufficient durability of membrane materials and catalysts under complex operating conditions, and the lack of a complete hydrogen storage and transportation infrastructure matching the fuel cell system. Improving the utilization rate of platinum to reduce catalyst loading, developing high-stability proton exchange membrane materials, and optimizing the system design of fuel cell engines to improve durability and reduce overall costs are the key research directions of current PEMFC technology [43].

3. Conclusions

In summary, FC, as a clean and efficient new energy conversion device, has shown huge application potential in multiple fields such as transportation, stationary power generation and portable electronic equipment, and different types of FC have their own unique applicable scenarios and technical characteristics. High-temperature FC represented by PAFC, MCFC and SOFC have good fuel adaptability and high energy conversion efficiency, but they face challenges in material durability and system cost due to their high working temperature; AFC has high catalytic efficiency, but its sensitivity to CO_2 limits its large-scale promotion in open scenarios; DMFC is outstanding in the field of small portable energy due to its convenient fuel supply, but it still needs to break through technical bottlenecks such as methanol crossover and high catalyst cost; PEMFC has now become the mainstream technical route for new energy vehicle power systems, and its large-scale commercial application still needs to solve the problems of high cost, insufficient durability and supporting infrastructure construction. In the future, targeted breakthroughs in key technologies such as core electrode catalysts, electrolyte membrane materials and system structure optimization for different types of fuel cells, combined with the cross-application of emerging technologies such as artificial intelligence, are expected to further promote the industrialization process of fuel cell technology, and make greater contributions to the global energy transformation and the realization of carbon neutrality goals.

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