Review of Fuel Cell Technology: Principles, Components, Types and System

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Abstract: ***Fuel cells, utilizing chemical reactions to produce electricity, offer a clean and efficient energy solution by harnessing the chemical energy of hydrogen or other fuels. They generate power with minimal environmental impact, producing only heat, water, and electricity as byproducts. Their versatility enables applications ranging from large-scale power plants to portable electronics. In transportation, hydrogen fuel cells exhibit high efficiency, contributing to better fuel economy and reduced emissions. These devices play a crucial role in mitigating climate change by eliminating carbon dioxide emissions and improving air quality. Additionally, they provide stable and zero-emission power for decentralized energy solutions in buildings and serve as secondary power sources during grid failures. Fuel cells also contribute to grid stability and reliability through grid- scale storage capabilities. This review explores the basic working principles, components, system architectures, and types of fuel cells, including Proton Exchange Membrane (PEM), Alkaline Fuel Cells (AFCs), Phosphoric Acid Fuel Cells (PAFCs), Molten Carbonate Fuel Cells (MCFCs), and Solid Oxide Fuel Cells (SOFCs). Understanding fuel cells' operation and potential ap- plications is essential for addressing global energy and environ- mental challenges and advancing sustainable energy solutions.***

Keywords: Proton Exchange Membrane (PEM), Alka- line Fuel Cells (AFC), Phosphoric Acid Fuel Cells (PAFC), Molten Carbonate Fuel Cells (MCFC), Solid Oxide Fuel Cells (SOFC), Alternating Curren

1. Introduction

A fuel cell is a device that uses chemical reaction to produce electricity. A fuel cell generates power effectively and cleanly by harnessing the chemical energy of hydrogen or other fuels (Su et al. 2023). The only byproducts if hydrogen serves as the fuel are heat, water, and electricity (Abdul Ghani Olabi and Enas Taha Sayed, 2023). The diversity of potential applications for fuel cells makes them distinctive; they can power both large systems like power plants and small systems like laptops and computers, using a wide variety of fuels and feed stocks. Fuel cells are multipurpose and durable energy production devices featuring applications for transportation, residential, commercial and industrial sectors (Luo et al., 2021). In transport, hydrogen fuel cells possess higher than 60% efficiency, which results in better fuel economy and less fuel consumption (Luo et al., 2021). Hydrogen fuel cells generate only water vapor whereas the climate change is mitigated by the elimination of carbon dioxide emissions and air pollutants as well that enhance the air quality and public health (Iain Staffell et al., 2019). The fact that they are very quiet because they have very few moving components which makes them even more appealing. In buildings, fuel cells supply stable and zero emission power for decentralized energy solutions, and serve as combined heat and power systems to increase the energy efficiency through thermal usage (Iain Staffell et al., 2019). They also serve as secondary sources of power during grid failures, thereby guaranteeing the continuous supply of elec- tricity to critical functions. Moreover, fuel cells also are a key element of grid scale storage, effectively turning excess energy into chemical energy for storage and subsequent conversion back to electricity during peak demand periods, providing grid stability and reliability. Continuous research elements work to further develop the fuel cell technology which encourages the widespread adoption and shape a sustainable energy future.

2. Literature Review

a) Basic Working of Fuel Cells

The fuel cell reactions run on the principle of electro-chemical reaction to directly convert clean chemical energy straight into electrical energy. The process commences with the addition of fuel at the anode part of the cell, which is then oxidized. This oxidation reaction liberates electrons and forms positive ions (Koomson and Lee, 2023). These flows of electrons through an external circuit generate electrical energy and the positively charged ions migrate through an electrolyte to the cathode. At the cathode, the oxidant, usually oxygen from the air, recombines with electrons and ions to form water and other products (Ouyang et al., 2021). As compared with the conventional combustion engines, fuel cells do not burn the fuel, instead they facilitate controlled chemical reactions (Zhang et al., 2021). This perspective enables the fuel cells to reach the high efficiencies and low emissions level so that they are clean and sustainable source of power generation. Through employing electrochemical processes in turn, fuel cells become an appealing alternative for fulfilling energy demands while achieving environmental protection at the same time.

b) Parts of Fuel Cells

The typical fuel cell is made of several key elements that work together to facilitate the electrochemical reactions involved

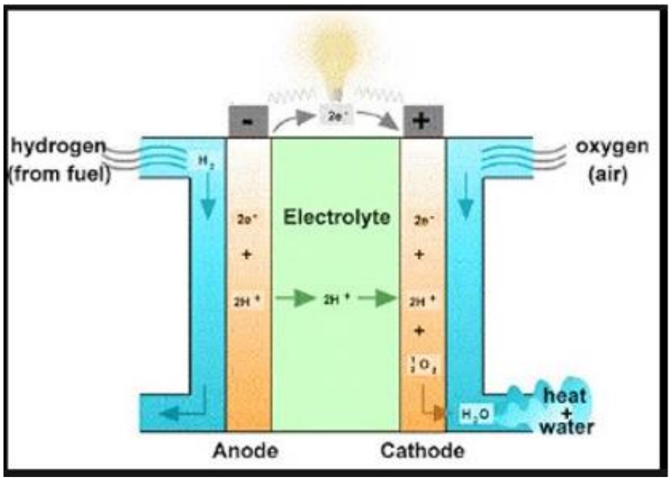

Figure 1: Basic Structure of Fuel Cell

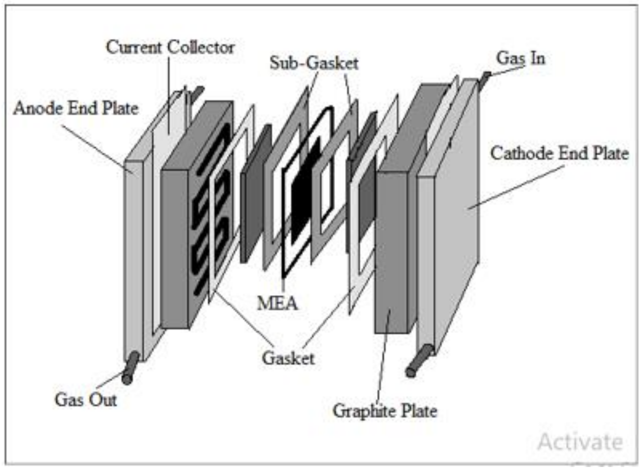

Figure 2: Parts of Fuel Cell

in converting chemical energy to electrical energy. At the core of a typical fuel cell are the anode and the cathode. The anode functions as a place of fuel oxidation, where fuel molecules are subjected to a chemical reaction, as a result, los- ing electrons and forming ions. The cathode effect is produced by reduction of oxidants such as combining with electrons and ions to produce the end products. The electrolyte is placed among the anode and cathode, like a barrier which allows the movement of ions while preventing the merging of fuel and oxidant. This differentiation plays an important part in the preservation of the integrity of the electrochemical reactions and the inevitability of the fuel cell. (Hussain and Yangping, 2020). The electrodes in the fuel cell are crucial for creating surfaces where the reactions are electronically carried out. The overall reactions involve the transfer of electrons between the fuel and oxidant with formation of the electrical energy at the end. Bipolar plates are employed as transporting channels for the reactants and products which also convert the fuel and oxidant for maximum use. Gas diffusion layers, with a porous network type, promote the diffusion of reactant and products to the electrode surfaces which increases the reaction between fuel and oxidant and leads to maximum efficiency (Grigoria Athanasaki, Jayakumar and Kannan, 2023). The balancing of plant components includes systems and mechanisms dedicated to the support of the fuel cell system operation. This includes the fuel supply system, which delivers fuel to the anode, and the oxidizing agent, which supplies the oxidants, such as oxygen, to the cathode. Furthermore, a cooling system is designed to maintain a thermal balance within the fuel cell thus avoiding overheating and optimizing its function. The control mechanisms monitor the operation of the separate components and ensure that the fuel cell system works smoothly and effectively.

c) Fuel Cell System

Fuel cell systems consist of the integration of different types of components which must work together perfectly in order to enable stable and eco-friendly power generation solutions (Mohammad Ali Abdelkareem et al., 2021). These groups target the fuel cell stack, the component consisting of individual fuel cell units assembled either in series or parallel depending on power needs. The central power stack is the place where chemical energy is converted to electrical energy though an electrochemical reaction. The DC power produced by the fuel cell stack is converted to the alternating current (AC) power by the power conditioning units to make it suitable for various applications (Norazlianie Sazali et al., 2020). The conversion mechanism ensures interoperability be- tween different electrical systems and machines which provide additional application possibilities for fuel cell (Norazlianie Sazali et al., 2020). Thermal management system serves not only as an essential part of fuel cell systems, but also as a controlling tool of temperature in the fuel cell stack. Through the constant optimization of operating temperatures, a high operational efficiency is reached and, therefore, the durability of the fuel stack is improved. Thermal management needs to be efficient to ensure the system is always performing as expected and to avoid future degradation of system components due to overheating. Furthermore, the fuel cell system comprises the balance of plant components, such as the fuel processing units, compressors, humidifiers, and controllers (Wang et al., 2018). Fuel processing units are necessary for changing the fuel source into hydrogen, which is essential for the operating of fuel cells. Compressors deliver oxygen and other oxidants such as oxygen to the fuel cell stack, whereas humidifiers appropriately modulate the moisture amount within the unit in order to maximize the system performance (Wang et al., 2018). Supervisors monitor performance of different system components, keep an eye on the functioning of operation and make all necessary adaptations with fluctuating conditions.

d) Types of Fuel Cell

Fuel cells are classified as per the type of electrolyte material that is used and the operating temperature, having both unique advantages and drawbacks. The Proton Exchange

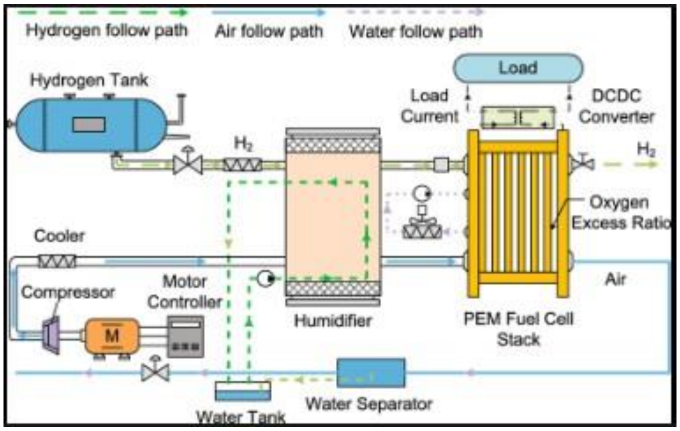

Figure 3: Fuel Cell System

Membrane (PEM) Fuel Cells operate at a temperature less than 100°C and utilizes a solid polymer membrane as an electrode (Do et al., 2022). Alkaline Fuel Cells (AFCs) utilize an alkaline electrolyte (potassium hydroxide) and operate at a moderate temperature range (60-250°C). Phosphoric Acid Fuel Cells (PAFCs) use phosphoric acid as their electrolyte and they work in the temperature range of 150-220°C. The Molten Carbonate Fuel Cells (MCFCs) operate at high temperatures (600-700°C) and have molten carbonate electrolytes as their electrolyte (Mu¨ller-Hu¨lstede et al., 2023). SOFCs are Solid Oxide fuel cells working at relatively high temperatures (800-1000°C), the material of the electrolyte which is solid and ceramic. For a given fuel cell, every type of a fuel cell produces a different strength. For example, low-volume fuel cells such as Polymer Electrolyte Membrane (PEM) are portable, lightweight and can be used in electronic devices with a small power supply PEM mostly utilized in transportation applications and offers several advantages including fast startup times and high power density. AFCs are well known for their good performance and they prove to be ideal for space application use. PAFCs are a good solution in terms of their efficiency and reliability which make them be suitable for stationary power generation. MCFCs and SOFCs have a higher efficiency and can tolerate impure fuel making them appropriate for stand- alone power generation and in large-scale applications like grid power and industrial processes. In general, the variety of fuel cell types make them well suited for use in powering portable consumer electronics, standalone power generation, transportation, and many other uses. The ongoing search is on for more affordable, long-lasting, and effective ways to enhance each fuel cell's performance, which will boost the number of fuel cells available and ensure that sustainable energy sources are adequate for the demands of the future.

3. Conclusion

In conclusion, Fuel cells are highly competitive solutions against power generation based on fossil fuel and with high efficiency rate in many applications. To fully utilize fuel cells and address global energy and environmental concerns,

Table I: Operating Temperatures of Different Fuel Cell Types

Fuel Cell	Operating Temperature (°C)
Proton Exchange Membrane (PEM)	60-100°C
Alkaline Fuel Cells (AFC)	60-250°C
Phosphoric Acid Fuel Cells (PAFC)	150-220°C
Molten Carbonate Fuel Cells (MCFC)	600-700°C
Solid Oxide Fuel Cells(SOFC)	800-1000°C

it is necessary to have a thorough understanding of their principles, components, system architecture, and fuel types. The ongoing studies and advances in the fuel cell department will progress towards the cheaper prices and development of green technologies that will shape our future and be part of environmental sustainability.

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