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Proton Exchange Membrane Fuel Cells: An Overview

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Abstract
As per the growing concerns on the depletion of petroleum-based energy resources and climate change, fuel cell technologies have become a big area of research in recent years owing to their high efficiencies and low emissions. Polymer electrolyte membrane fuel cells have the advantages of high efficiency, low operating temperature, and fast start-up, are being involved in various applications. Though many technical and associated fundamental breakthroughs have been achieved during last couple of decades, many challenges such as reducing cost and improving durability while maintaining performance remain prior to the commercialization of proton exchange membrane fuel cells. In this review, we discussed a number of aspects such as various types of fuel cells, their synthesis and applications with a focused account on proton exchange fuel cells.

Keywords: Fuel cell, Proton exchange fuel cells, Electrolytes, Membranes, Oxidation, Reduction, Polarization

Introduction

As per the rising aspects of petroleum-based energy resources depletion and climate change, fuel cell technologies have become a big area of research in recent years owing to their high efficiencies and low emissions. A *fuel cell* is a device designed to convert the energy of a chemical reaction directly to electrical energy. In fuel cells, the primary galvanic cells called batteries and the secondary galvanic cells called accumulators or storage batteries use a supply of gaseous or liquid reactants for the reactions rather than the solid reactants (metals and metal oxides) built into the units; moreover they use a continuous supply of the reactants and continuous elimination of the reaction products are provided, so that a fuel cell may be operated for a rather extended time without periodic replacement or recharging. The efficiency of a fuel cell can reach as high as 60% in electrical energy conversion and overall 80% in co-generation of electrical and thermal energies with >90% reduction in major pollutants. Polymer electrolyte membrane fuel cells have the advantages of high efficiency, low operating temperature, and fast start-up, are being involved in various applications. Though many technical and associated fundamental breakthroughs have been achieved during last couple of decades, many challenges such as reducing cost and improving durability while maintaining performance remain prior to the commercialization of proton exchange membrane fuel cells. This work reviews the literature within the context of Fuel cells with its earlier history and more detailed discussion of Proton exchange membrane fuel cells.

Discussion

The first fuel cell was invented in 1839 by Sir William Robert Grove. A schematic representation of the same is shown in Fig. 1. However, the principle was discovered by Christian Friedrich Schönbein [1].

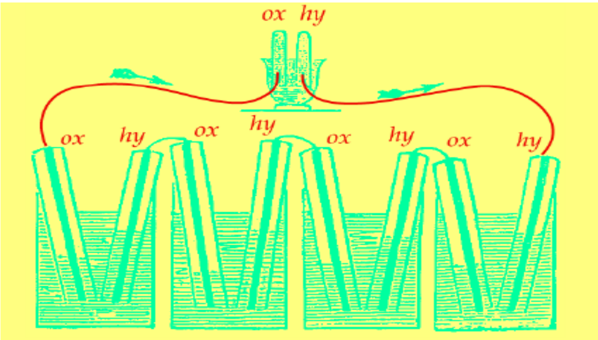

Fig.1: Schematic representation of the first fuel Cell [2] reprinted from Wikipedia.

It was Friedrich Wilhelm Ostwald (1853-1932), who gave relationship between the different various components of the fuel cell viz. electrodes, electrolyte, oxidizing, reducing agent, anions and cations. Emil Baur (1873-1944) conducted extensive research into the area of high temperature fuel cell devices which used molten silver as the electrolyte. Francis Thomas Bacon (1904-1992) performed research and significant developments with high pressure fuel cells. Bacon was successful in developing a fuel cell that used nickel gauze electrodes and operated at pressures upto 3000 psi. Commercial potential first demonstrated by NASA in the 1960's with the usage of fuel cells on the Gemini and Apollo space flights. However, these fuel cells were very expensive. Fuel cell research and development has been actively taking place since the 1970's, resulting in many commercial applications ranging from low cost portable systems for cell phones and laptops to large power systems for buildings.

Basic Parameters of Fuel Cells

There are number of parameters of fuel and are listed below.

a. Operating Voltage
b. Discharge Current and Discharge Power
c. Operating Efficiency of a Fuel Cell
d. Voltage Efficiency
e. Heat Generation
f. Lifetime

Applications of fuel cells

Some of the important areas where fuel cells have tremendous applications are listed below.

a. Power
b. Cogeneration
c. Fuel cell electric vehicles (FCEVs), Automobiles and Forklifts
d. Portable power systems

Type of fuel cells

In this section, we tabulated description of various type of fuels cells [4].

a. Reactant type
b. Electrolyte type
c. Working temperature

Fuel cell	Temperature (°C)	Efficiency (%)	Application	Advantages	Disadvantages
Alkaline fuel cell (AFC)	50–90	50–70	Space application	High efficiency	Intolerant to CO_2 in impure H_2 and air, corrosion, expensive
Phosphoric acid fuel cell (PAFC)	175–220	40–45	Stand-alone & combined heat & power	Tolerant to impure H_2, commercial	Low power density, corrosion &sulphur poisoning
Molten carbonate fuel cell (MCFC)	600–650	50–60	Central, stand-alone & combined heat & power	High efficiency, near commercial	Electrolyte instability, corrosion &sulphur poisoning
Solid oxide fuel cell (SOFC)	800–1000	50–60	Central, stand-alone & combined heat & power	High efficiency & direct fossil fuel	High temperature, thermal stress failure, coking &sulphur poisoning
Polymer electrolyte membrane fuel cell (PEMFC)	60–100	40–50	Vehicle & portable	High power density, low temperature	Intolerant to CO in impure H_2 and expensive
Direct methanol fuel cell (DMFC)	50–120	25–40	Vehicle & small portable	No reforming, high power density & low temperature	Low efficiency, methanol crossover & poisonous by product

Proton Exchange Membrane Fuel Cells (PEMFC)

They also termed as Polymer Electrolyte Fuel Cells. A schematic representation of the same is shown in Fig.2.

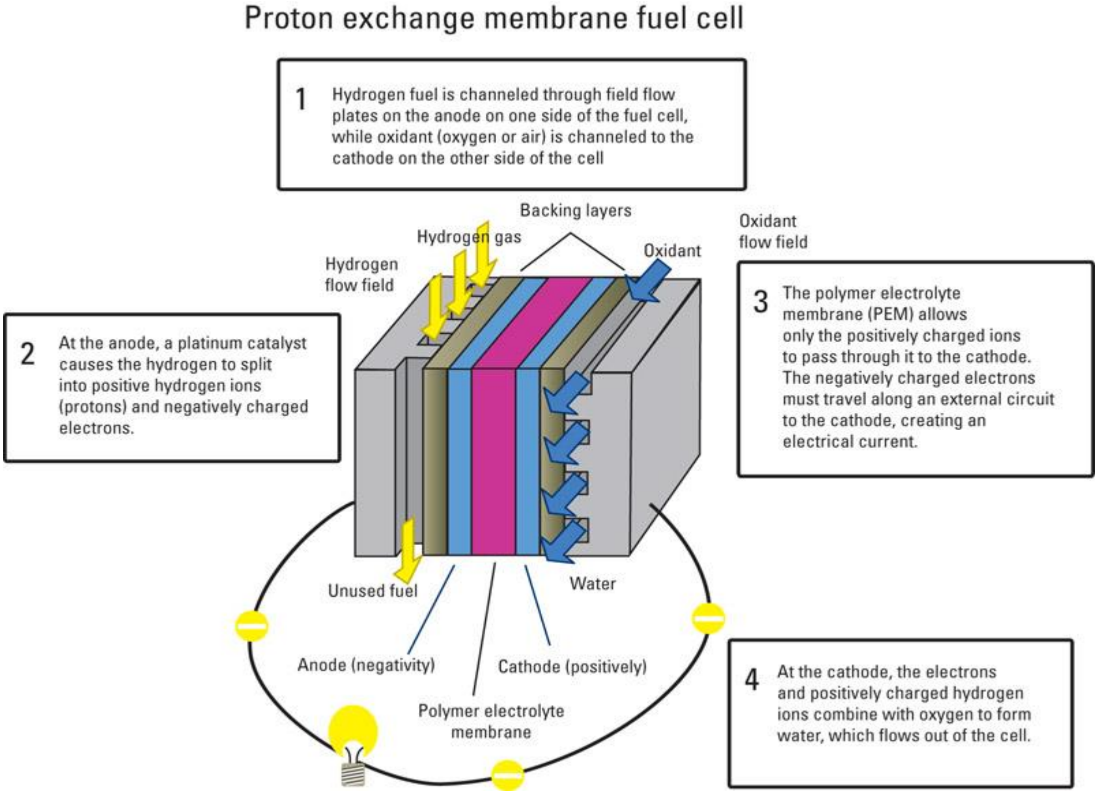

Fig. 2: Schematic representation of the PEMFC. Reprinted from Wikipedia

The proton exchange membrane fuel cell (PEMFC) is a rugged, quite, clean and efficient energy conversion means for transportation application. Because they are lightweight, have such high power density, and cold start capability, they qualify for many applications, such as stationary power, transport, portable power and application in space. Furthermore, PEM fuel cells offer the most efficient and hassle-free way of recovering energy from hydrogen produced as a by-product in chloro-alkali plants. Their distinguishing features include lower temperature/pressure ranges (50 to 100 °C) and a special polymer electrolyte membrane. PEMFCs operate on a similar principle to their younger sister technology PEM electrolysis.

PEM Fuel Cell Design

Membrane-electrode Assembly

A membrane-electrode assembly consists of a membrane, a dispersed catalyst layer, and a gas diffusion layer. The membrane allows the protons to pass through to complete the overall reaction while forcing the electrons to pass through an external circuit. The catalyst layer stimulates each half reaction. Design and manufacturing alternatives for each of these components are analysed as follows.

Membrane Design

Membrane refers to a thin layer of electrolyte (usually ~10-100 µm, for example 18 µm for Gore 18 and 175 µm for Nafion 117), which conducts protons from the anode to the cathode. PEM fuel cell which has advantages of better catalyst tolerance to carbon monoxide and cooling strategy for fuel cell [14]. Gottesfeld and Zawodzinski [15] suggested that perfluorosulphonic acid is the most commonly used membrane material for PEM fuel cells [17].

Catalyst layer

The catalyst layer is where the hydrogen oxidation reaction or oxygen reduction reaction takes place. Catalyst layer is usually very thin (about 10 µm). A recent research mentions the ways to tackle the problem of Platinum nanoparticles degradation [18]. Investigation of the influence of the Pt to carbon ration on the degradation behaviour of Pt based proton exchange membrane fuel cell catalysts was done by utilization of a recently developed colloidal synthesis approach for preparing catalysts with identical Pt nanoparticles, but varying Pt loadings [19].

Gas diffusion layers and Micro-porous layers

They have multiple roles such as provide electronic connection between the bipolar plate with channel-land structure and the electrode, passage for reactant transport and heat/water removal and mechanical support to the membrane electrode assembly [20]. The porous nature of gas diffusion layer material ensures effective diffusion of each reactant gas to the catalyst on the membrane/electrode assembly. The gas diffusion layer allows the liquid water produced at the cathode to leave the cell so it does not flood.

Bipolar plates and Stack

They have been used to distribute the fuel and oxidant within the cell, separate the individual cells in the stack, carry current away from each cell, carry water away from each cell, humidify gases, and keep the cells cool [21]. Topologies can include straight, serpentine, or inter-digitated flow fields, internal manifolding, internal humidification, and integrated cooling. Materials have been proposed on the basis of chemical compatibility, resistance to corrosion, cost, density, electronic conductivity, gas diffusivity/impermeability, manufacturability, stack volume, material strength and thermal conductivity. One of the recent researches shows the effectiveness of carbon-polymer composite coatings for proton exchange membrane fuel cell bipolar plates [22]. At stack level, water and heat management becomes more complex due to interactions of constituent sub-cells. Several fuel cells share one inlet/outlet manifold in a stack. Therefore, a fuel cell with high flow resistance receives fewer amounts of the reactants, causing local reactant starvation which further leads to cell performance decay and material degradation. A third one is heat transfer connection.

Efficiency of PEM fuel cells

Theoretical efficiency: Equation given below is the expression of the maximum efficiency.

$\eta_{th} = W_e / -\Delta H = \Delta G/\Delta H$

Voltage efficiency: The following equation presents the voltage efficiency.

$\eta_v = V(P, T, i)/E$

Faradic efficiency: The faradic efficiency is defined as the ratio of the delivered current and the maximum current which corresponds to the global reaction, we can also have another definition of the faradic efficiency which is the ratio of electrons actually exchanged during the reactions to that of theoretical.

$\eta_F = I/I_{max} = n_{e.ex}/n_e$

The Total Efficiency: if the fuel cell system is the one only considered then we can give the total efficiency can be given by the product of voltage efficiency, theoretical efficiency and faradic efficiency.

$\eta_{tot} = \eta_{th}.\eta_V.\eta_F$

The maximal theoretical efficiency applying the Gibbs free energy equation ΔG=-237.13 kJ/mol and using the Lower Heating Value (LHV) of Hydrogen (ΔH=-285.84 kJ/mol) is 83% at 298 K.

The practical efficiency of a PEM's is in the range of 40–60% using the Higher Heating Value of hydrogen (HHV) [23].

Applications of PEM fuel cells

Proton exchange membrane fuel cells are applicable in following areas:

Transportation applications: The typical power range for this type of applications, such as passenger cars, utility vehicles, and buses, ranges from 20kW to 250 kW. These applications include electric powered bicycles, material handling vehicles such as forklifts, and auxiliary power units including leisure, trucking, marine and unmanned aerial vehicles.

Portable applications: Problems of low energy power capability and long charging time can be well resolved by using portable/micro proton exchange membrane fuel cells. In addition to mobile phones and laptops, portable fuel cells can be used to power toys and utilities such as radio control cars, boats, robot toys, and emergency lights.

Stationary applications: Large scale central power stations have many benefits such as high efficiency, but exhibit several inherent disadvantages, example the waste heat that usually cannot be efficiently utilized and power loss during transmission. Distributed power decentralized generation is a way to resolve these disadvantages, which co-generates heat and power for local usage.

Conclusion

To further overcome the barriers to the wide deployment of fuel cells, fundamental break through outs are needed. Materials used in various cell components influence the operation of the fuel cell. Fuel cell performance, cost, safety are some issues which needed to be accounted for designing a fuel cell assembly. There is a need for development in catalyst layer. Further studies are needed in characterization of pore size distribution as well as hydrophilicity and hydrophobicity distributions and using this information to develop pore level models. The realistic and accurate simulation of liquid water and gas transport through gas diffusion layers with highly non-uniform pore sizes and wettability can be done by such studies. For success in direction of wide areas of applications, a number of important rather complex problems must first be solved including cost, environmental stability and longer lifetime of the cell.

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