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# PEM fuel cell as an alternative solution for clean energy production

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## ABSTRACT/RESUME

***Abstract:****Due to the energy crisis and the rising level of pollution around the world, a new source of clean energy is the fuel cell, as it has no production other than water and heat. PEMFC (Proton Exchange Membrane Fuel Cell) is an electrochemical device that are designed to directly convert, with high efficiency, the chemical energy from the reaction of the fuel (hydrogen in case of PEMFC) and an oxidant (oxygen) into electricity. This study aims to setup a state of the art on PEM Fuel Cell.*

## I-Introduction

Increasing levels of pollution and possible anthropogenic global warming resulting from the combustion of fossil fuels have urged scientists to consider alternative energy conversion and power generation systems that could satisfy the global energy demands in more environmental-friendly ways[1]. Wind, tidal, solar and hydrogen based renewable energy systems are some of the potential areas in this regard. Hydrogen-based renewable energy systems such as fuel cells offer a promising pathway with the prospect of low- to zero-emissions during power generation for sub-watt to megawatt applications in transportation, manufacturing and communications.

The combination of high efficiency, environmental benefits and versatility make fuel cells a suitable power generation device for both terrestrial and space applications. Despite these potential benefits, the commercial deployment of fuel cells faces many challenges such as, high operating cost and a lack of existing hydrogen infrastructure.

The fuel cell was first demonstrated by Lawyer-cum-inventor William Grove in 1839, but no further significant research was carried out in this field until the late 1940s. The first commercial application of a fuel cell was in space and military systems[2]. Among the different types of fuel cells, the polymer electrolyte membrane (PEM) fuel cell is considered a promising approach due to its low operating temperature and simple design configuration. The basic operating principle of a fuel cell is simple, but involves the coupling of complex transport phenomena such as species transport by convection and diffusion, heat transfer, charge balance and electrochemical kinetics[3]. These transport phenomena lead to certain efficiency losses in the fuel cell that affect its overall performance. The performance of a fuel cell can be investigated in two ways; either by experimental techniques or by numerical simulations. Experimental methods have limitations when investigating the complex interaction of transport phenomena taking place inside the fuel cell, whereas numerical modelling provides a better insight into the problem. Furthermore, it is not possible to perform detailed in-situ measurements of a fuel cell during its operation because of its reactive environment. The complex experimental setup of the fuel cell system has stimulated efforts to develop sophisticated numerical models of the fuel cell that can simulate and predict the coupled transport of reactant and product species, heat transfer and charge balance along the fuel cell domain.

A several scientific papers were performed on PEM Fuel Cell system and its application. Theses researches were contributedsignificantly on the improvement of the PEMFC performances and uses.

Sudarshan L *et all*[4]are used identification black box approach system to develop more realistic mathematical model for dynamic behaviour inside a polymer electrolyte membrane (PEM) fuel cell. The performance of each model structure was validated with the data from a $25\,cm^2$ active area practical PEMFC. Their devellped model models can be used to predict polarization behavior under different loading conditions in PEMFC system.

Nanofluid adoption as an alternative coolant for PEMFC thermo-electrical performances improvement was studied by IrnieZakaria et all [5]. In this articl, Thermo-physical properties of $0.1$, $0.3$ and $0.5\%$ volume concentration of $Al_2O_3$ nanoparticles dispersed in water was used.Theirresultwas depicted that the cooling rate improved up to $187\%$ with the addition of $0.5\%$ volume concentration of $Al_2O_3$ nanofluids to the base fluid of water. The obtained improvement was interpreted by the excellent thermal conductivity property of nanofluids as compared to the base fluid.

Horng-Wen Wu et all [6] was performed a numerical study on the effect of flow field designchnagement by the arrangement pattern of the protrusive gas diffusion layer (GDL) on the cell performance for a full-scale serpentine channel. This paper showed that the arrangement pattern of protrusive GDL affects the electric power, pressure drop, and the net power of the PEM fuel cell. In different paper, Horng-Wen Wu [7] is reviewed the transport phenomana and performance modeling of proton exchange membrane (PEM) fuel cells during the past few years. He defined the PEM fuel cell as a set of distinct devices and a series of transport phenomanenthrough gas porous channels, electric power production through membrane electrode assembly and electrochemical reactions. It can be conclude from thispaperthat there are a lot findings and enhancement of PEMFC system performance through numerical modelling and simulation studies.

The PEM fuel cell is exposed to different mechanical stresses due to the different assembly procedures, operational and environmental working conditions. Ahmed MohmedDafalla and Fangming Jiang [8] are carried out a review research on the mentioned problem. These stresses include the compressive clamping stress, hygrothermal stress, freeze-thaw stress, and the stress due to vibration conditions. The review depicted that the combination of these stresses may be lead to PEMFC performance degradation and structural damage. As consequence, avoiding generated stress are necessary for improving PEM fuel cell permanence and durability.

A numerical simulation using Matlab–Simulink environment was performed by Z.Abdin et all [9]. The adopted model was based on parameters with direct physical meaning, with the aim to get empirically describion on the characteristics of the fuel cell. The impact of different parametres namely pressure, temperature, humidification and reactant partial pressure on cell performance are studied. The proposed simplifying assumptions led to fairly light in computational demand of the adopted model and it getout a result with well corcordance with experimental data especially at high current density.

This paperaims to review PEM fuel cell system, itsworkingprincipalsandits applications.

## II. Fuel Cell Types

There are different types of the fuel cell systems have been investigated by researchers to improve their performance and promote their commercialization. Theses classes of fuel cells have emerged as viable power systems for the present and near future applications. Each type of fuel cell has some merits and drawbacks. A brief description of the major types of fuel cells is presented in the following sections.

### II.1 Polymer Electrolyte Membrane (PEM) Fuel Cell

The polymer electrolyte membrane (PEM) fuel cell is regarded as one of the most promising types of fuel cells due to its simplicity and low operating temperature. This type of fuel cells generally operate between 50 to 100 °C, which makes them suitable for automotive and mobile applications [1].In this type of fuel cells, the electrolyte is a solid polymer which contains mobile protons. The major drawback of the low operating temperature of PEM fuel cells is the low electrochemical reaction rate, which can be addressed using sophisticated catalysts and electrodes.

A lot of research has been done on various aspects of PEM fuel cells. The standard single PEM fuel cell is a combination of two endplates as current collectors, two gas diffusion layers, two catalyst layers and a proton exchange membrane

Generally, the hydrogen is fed in from anode side channel and split in the catalyst layer into protons and electrons. The protons pass through the membrane to the cathode catalyst where they combine with the oxygen fed in from the cathode-side channel and electrons from the external electric circuit to form water. The movement of the electrons in the external circuit is the current generated.

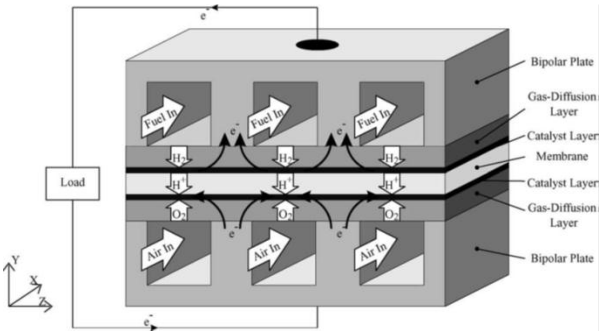

***Figure 1.****Schematic of a PEM fuel cell[3]*

### II.2 Phosphoric Acid Fuel Cell

This type of fuel cells uses liquid phosphoric acid as an electrolyte. Hydrogen is introduced at the anode side and is oxidized to produce positively charged protons and negatively charged electrons. The ionic conductivity of the phosphoric acid is low at low temperatures. Furthermore, it solidifies at temperatures below 40 °C, which makes the initial start-up difficult and restricts the continuous operation of this type of fuel cells . Phosphoric acid fuel cells operate at a temperature of around 220 °C and can tolerate carbon monoxide, which is not acceptable for many other types of fuel cells. Moreover, In this type of fuel cells, the hydrogen fuel problem can be solved by reforming natural gas ($CH_4$, methane) to hydrogen and carbon dioxide, but the equipment required for this adds considerable cost, complexity and size to the fuel cell system[10].

### II.3 Solid Oxide Fuel Cell

Solid oxide fuel cells are made up of four layers, three of which are ceramic. Ceramics do not become ionically active until they reach at very high temperature and therefore the solid oxide fuel cell is only operational in the region of 800-1200 ºC. Oxygen gas enters at the cathode side while fuel enters at the anode side. Light hydrocarbon fuels such as methane, propane and butane are mostly used as fuels in this type of fuel cell. Oxygen is reduced into oxygen ions at the cathode side. These oxygen ions then diffuse through the solid oxide electrolyte to the anode where they electro-chemically oxidize the fuel. This type of fuel cell is generally suitable for large industrial applications because of its high operating temperature range. Due to such high temperatures, a fast reaction rate can be achieved without using any expensive catalysts[11].

### II.4 Molten Carbonate Fuel Cell

This type of fuel cell is a mixture of molten alkali metal carbonates, usually a binary mixture of lithium and potassium, or lithium and sodium carbonates. It should be operate at 650 °C in order toliquefy the carbonate salts and achieve high ion mobility through the electrolyte.Unlike other types of fuel cells; molten carbonate fuel cells do not necessitate any external reformer to extract hydrogen from energy-dense fuels. Due to its high operating temperature, the fuels are converted into hydrogen within the fuel cell itself by internal reforming[12].

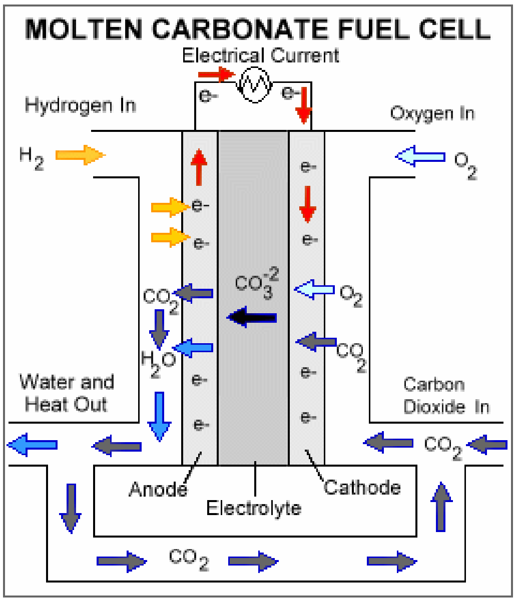

***Figure 2.****molten carbonate fuel cells working principle[3]*

### III. PEM Fuel Cell operating principles

PEM fuel cells consist of three major components: a negatively charged electrode (cathode), a positively charged electrode (anode) and a membrane electrode assembly. The membrane electrode assembly consists of a current collector, a porous gas diffusion layer, a catalyst layer and an electrolyte membrane. The operating principle of a PEMFC is simple and can be considered to be the opposite of electrolysis in wicth the electric current is passed through water to produce hydrogen and oxygen, however in a PEM fuel cell, hydrogen and oxygen gases are passed at either side of the polymer electrolyte membrane where hydrogen is split into its elementary constituents - the positively charged proton ions and the negatively charged electrons.

The potential difference between anode and cathode attracts the protons from anode to cathode causing them to travel through the electrolyte membrane, whereas the electrons travel first through an external circuit and then to the membrane catalyst layer interface at the cathode side where they react with the reduced oxygen atoms, following this, the reduced oxygen atoms react with the protons diffusing through the membrane to produce heat and water as by-products [13].The electrochemical reactions for the PEM fuel cell can be stated as follows:

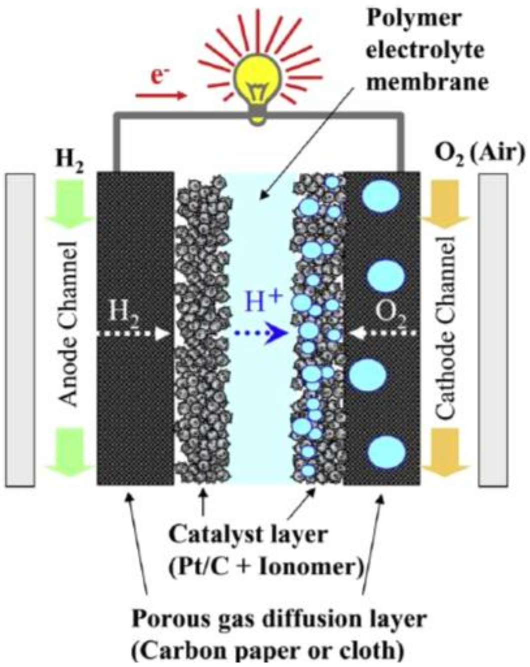

***Figure 3.****Schematic view of a PEM fuel cell and its operating principles[14]*

At the catalyst layer, the hydrogen splits into hydrogen protons and electrons according to:

$$2H_2 \Rightarrow 4H^+ + 4e^- \qquad (1)$$

Cathode Reaction:

$$O_2 + 4H^+ + 4e^- \Rightarrow 2H_2O \qquad (2)$$

The overall reaction is exothermic and can be written as:

$$2H_2 + O_2 \Rightarrow 2H_2O + \text{electricity} + \text{heat} \qquad (3)$$

## IV. PEM Fuel Cell Components

A PEM fuel cell consists of four major components. The following sections briefly describe these components and their role in the operation of the fuel cell.

### IV.1 Polymer Electrolyte Membrane

The polymer electrolyte membrane is the heart of a PEM fuel cell. It has two main functions; firstly, it works as a gas separator, preventing the reactant gases from directly reacting with each other; secondly, it acts as the proton conductor. Typically, the electrolyte membrane consists of a Perfluroinated polymer backbone with Sulphonyl acid side chains [15].Nafion® membranes by Du-Pont are typically used as the de-facto standard for most of the polymer electrolyte fuel cells.

However, there are also other variants of electrolyte membranes, such as Flemion® and Aciplex® membranes, which are well known in the fuel cell industry [16]. Membranes have to be hydrated so as to sustain their protonic conductivity. It is therefore necessary for the membrane to retain a certain amount of water content so as to maintain its ability to transfer protons. This depends on two phenomena; firstly, that of the chemical affinity for water in hydrophobic regions of the membrane, which enables the membrane to absorb and retain water; secondly, that of the electro-osmotic drag phenomena, whereby each hydrogen ion is accompanied by one or two molecules of water [17].The requirement to keep the membrane hydrated restricts PEM fuel cell operation at higher temperatures. In general, to achieve high efficiency, the membrane must possesses the following properties [18, 19]

a) High proton conductivity to support high currents with minimum resistive losses and zero electronic conductivity.

b) Adequate mechanical strength and durability.

c) Chemical stability under operating conditions.

d) Extremely low fuel or oxygen by-pass to minimize crossover current.

e) Reasonable production cost which is compatible with intended application.

### IV.2 Gas Diffusion Layer (GDL)

The gas diffusion layer enables efficient distribution of the reactant and product species along the fuel cell domain. The gas diffusion layer is made up of a sufficiently porous and electrically conductive material. Materials of a typical gas diffusion layer include carbon paper or carbon cloth with typical thicknesses of 100- 300 µm[2]. The GDL is intentionally porous to increase the wetted surface area by hundreds and even thousands times the geometric surface area [13].

The gas diffusion layer is characterized by its thickness, hydrophobic nature and dry resistance to flow and electric properties [20]. Performance of the PEM fuel cell is immensely influenced by the reactant/product species distribution along the gas diffusion layer since it can lead to issues such as water flooding and poor concentration distribution. To facilitate excess water removal from the fuel cell and minimize water flooding, the hydrophobicity of the GDL is increased by impregnating it with a hydrophobic material. The amount of hydrophobic agent used is a sensitive parameter as excess impregnation can result in the blockage of surface pores and thus a reduction of the GDL porosity [21].

### IV.3 Catalyst Layer

A fine layer of catalyst, usually the noble metal platinum (Pt), is applied to both faces of the electrolyte membrane. A catalyst loading of 0.1-0.3 mg/cm2 per membrane catalyst layer is typically used. The thickness of the catalyst layer is usually in the range 5-15 µm[22]. Due to the high cost of platinum, it must be used sparingly in order to reduce the overall cost of the PEM fuel cell[23].The catalyst layer breaks the bonds between the atoms of the reactant species and promotes higher reaction rates. At the anode side, the hydrogen molecules are absorbed onto the surface of the catalyst and the bonds between the hydrogen atoms are stretched and weakened so that they eventually break. A similar mechanism occurs on the cathode side where the reduction of oxygen is promoted by the action of the catalyst.

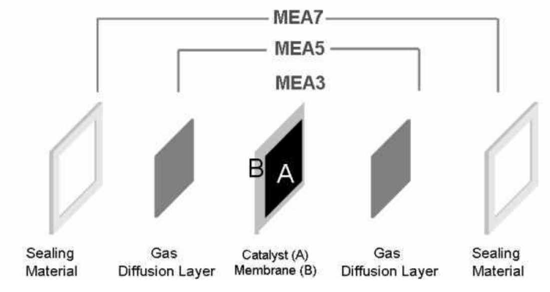

***Figure 4.****fuel cell catalyst construction[16]*

### IV.4 Gas Flow Channel (Bipolar / End Plates)

The interconnection between the fuel cells in a stack is achieved using conductive plates. When machined on both sides, they are normally called bipolar plates. Plates which are fitted at the edges of the fuel cell stack and are machined on one side only are termed end plates. The term electrode plates will be used here to refer to the bipolar and end plates. These plates are an important component of any fuel cell system because they assist the supply of fuel and oxidant to the reactive sites, remove reaction products, collect produced current and provide structural support [24]. Usually, when the electrode plates are made of graphite; they represent about 60 % of the total weight of PEMFC, 30% of its total cost and 80% of its total volume. Hence,the designs of the electrode plates play a significant role in the weight and cost of a fuel cell. The essential requestsof these plates are [2]:

- High values of electronic and thermal conductivity;
- High mechanical strength;
- Impermeability to reactant gases;
- Resistance to corrosion;
- Low cost of production.

Bipolar plates are usually constructed from graphite. However, graphite is porous, fragile, and needs to be thick for the required strength, leading to an increase in weight, size and cost. As such, alternative materials have been under intense study by various researchers [25]. Different design topologies, i.e. straight, serpentine or spiral shapes have been used by the researchers to achieve the aforementioned functions efficiently with the aim of obtaining high performance and economic advantages. Around a 50% increase in fuel cell performance has been reported just by improving the distribution of the gas flow fields [26]. Bipolar/end plates typically have fluid flow channels stamped on their surfaces. Flow channel geometry at both the anode and cathode sides can be different from each other depending on their design requirements. The essential requirements for the bipolar plates with respect to physio-chemical characteristics are the uniform distribution of the reactant species over the active surface of the electrode to minimize the concentration over potential. The choice of flow field configuration strongly affects the performance of a PEM fuel cell, especially in terms of water management and distribution of reactant species. Due to this, the effective design and optimization of the gas flow fields and the bipolar plates remains a very important issue for cost reduction and performance improvement of the PEM fuel cell. The different types of flow field configurations that have been used by researchers are discussed in the following sections.

### a) Serpentine Shaped Gas Flow Channel

The serpentine shaped gas flow channel configuration is a common option for many fuel cell designers. In this design configuration, only one flow path exists for the reactant gases across the flow field plate and any liquid water accumulating in the channel is quickly pushed out of the cell. Watkins *et al.*[27]studied the optimization of serpentine shaped flow channels. This type of flow field configuration results in high pressure losses and therefore needs a high pressure flow.

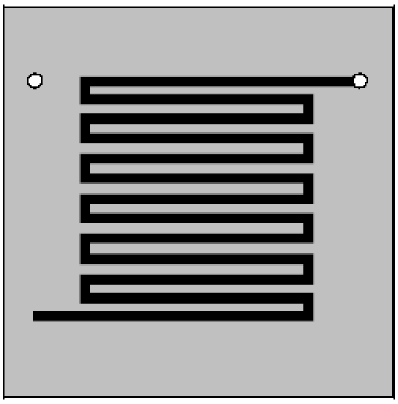

***Figure 5.****Serpentine shaped gas flow channel configuration [27]*

### b) Parallel/Straight Shaped Gas Flow Channel

Pollegri*et al.*[24]introduced the concept of a parallel/straight type gas flow channel configuration. This type of flow field has an advantage over the serpentine shaped channels due to the lower pressure losses; on the other hand, a major drawback is that different paths exist across the bipolar plate for the reactant gases, potentially causing ineffective water removal because of the uneven flow distribution of the reactant flow through the fuel cell domain**.**

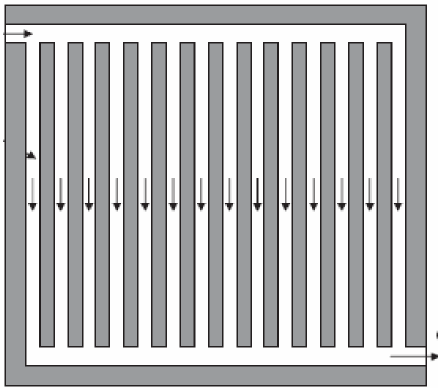

***Figure 6.****Parallel gas flow channel configuration [24]*

### c) Spiral Shaped Gas Flow Channel

Kaskimies et al. [27] proposed a spiral shaped gas flow field configuration. This configuration combines the effective water removal of the single channel geometry with the advantage of having channels containing fresh and depleted cathode gas side by side, leading to better distributions of oxygen and water. However, the manufacturing cost of this type of flow field configuration is significantly higher.

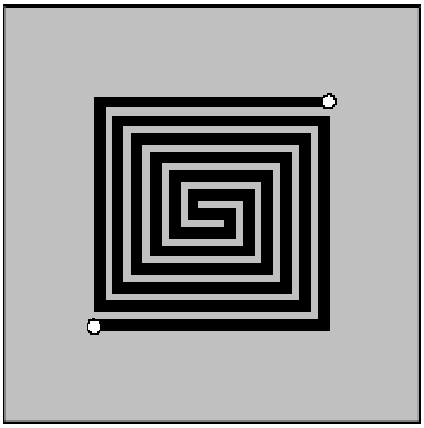

***Figure 7.****Spiral flow field configuration [26]*

## V- Conclusion

This paper reviewed the existing literature on PEM type fuel cells, mainly focusing upon the important type, components and reactions taking place inside its domain. Different materials for bipolar/end plates were also discussed in this research. PEM fuel cells have undeniable advantages, system performance, good dynamics and low operating temperature. Regardless of the problem of availability and supply of hydrogen, many points remain to be addressed (cost, mass and volume, service life, thermal management, fluidic management).

If we look to the great number of studies interest by PEM fuel cell system, we can conclude that this subject is being very important in Clean Technologies and Environmental Sciences.

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