CHAPTER 1

INTRODUCTION AND LITERATURES REVIEW

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1.1 INTRODUCTION

Air pollution is the contamination of air by discharge harmful substance which leads to health problems. Air pollution can also damage the environment and property. Air pollution has thinned the protected ozone layer. So researcher and engineers must find solutions to this problem. The main solution of the above problem is replacing conventional energy sources by clean sources.

A fuel cell is one of the solutions for the mentioned problem because it doesn't produce pollution and noise so it is called clean and silent energy and also ability to increase overall energy efficiency as shown in table (1.1).

As is known there are many types of fuel cells such as alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), and the proton exchange member fuel cells (PEMFC) which considers one of the best types of fuel cells because it is working at low temperature with higher efficiency [1].

Table 1.1 Comparisons between different energy systems [2].

Technology	Size	Fuel	Electrical efficiency (%LHV)
Combustion turbine combined cycle	50-500 MW	Natural gas, liquid fuels	50-60
Industrial combustion turbine	1-50 MW	Natural gas, liquid fuels	25-40
Industrial combustion turbine (reciprocating engine)	1 KW-10 MW	Natural gas, diesel, oil, propane, gasoline ,etc	25-38
Micro turbine	27-400 MW	Landfill gas, propane, natural gas, etc	22-30
Fuel cells	1 KW	Natural gas, H_2,other H_2 rich fuels	35-60
Photovoltaic	1 W-10 MW	Renewable	5-15
Wind turbine	0.2 KW -5 MW	Renewable	< 40
Biomass	Several KW-20 MW	Renewable	20

1.2 FUEL CELL DESCRIPTION

A fuel cell is an electrochemical device that converts the chemical energy of a fuel directly into electrical energy. The basic physical structure of a fuel cell consists of an electrolyte layer in contact with an anode and a cathode on either side. In a typical fuel cell, fuel is fed continuously to the anode (negative electrode) and an oxidant (often oxygen from air) is fed continuously to the cathode (positive electrode). The electrochemical reactions take place at the electrodes to produce an electric current through the electrolyte as shown in Figure (1.1). although a fuel cell is similar to a typical battery in many ways, it differs in several respects. The battery is an energy storage device in which all the energy available is stored within the battery itself (at least the reductant). The battery will cease to produce electrical energy when the chemical reactants are consumed (i.e., discharged). A fuel cell, on the other hand, is an energy conversion device to which fuel and oxidant are supplied continuously. In principle, the fuel cell produces power for as long as fuel is supplied.

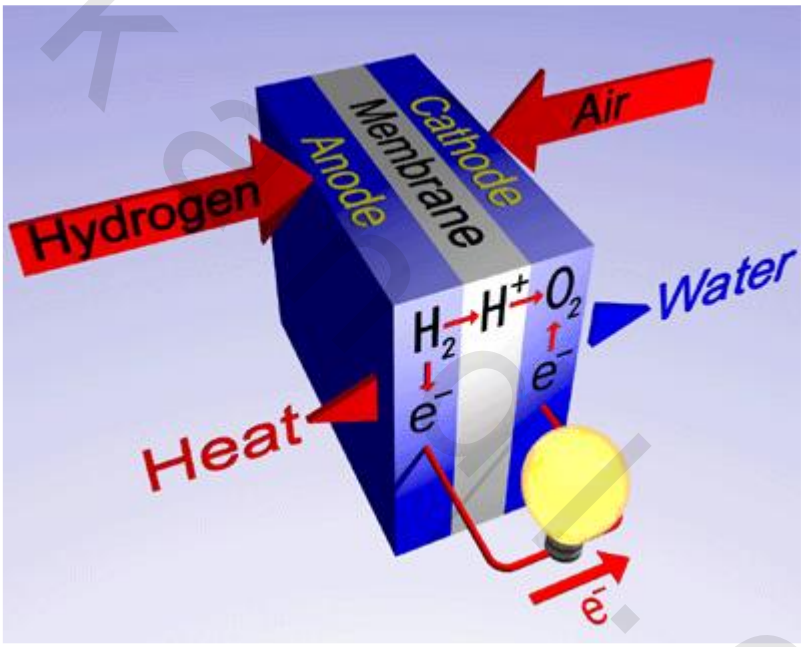


Figure 1.1 Schematic of an individual fuel cell [3].

1.3 FUEL CELL STACKS

A single fuel cell will produce less than one volt of electrical potential. To produce higher voltages, fuel cells are stacked on top of each other and connected in series. As illustrated in Figure (1.2), cell stacks consist of repeating fuel cell units, each comprised of an anode, cathode, electrolyte, and a bipolar separator plate. The number of cells in a stack depends on the desired power output and individual cell performance; stacks range in size from a few (< 1 kW) to several hundred (250 kW).

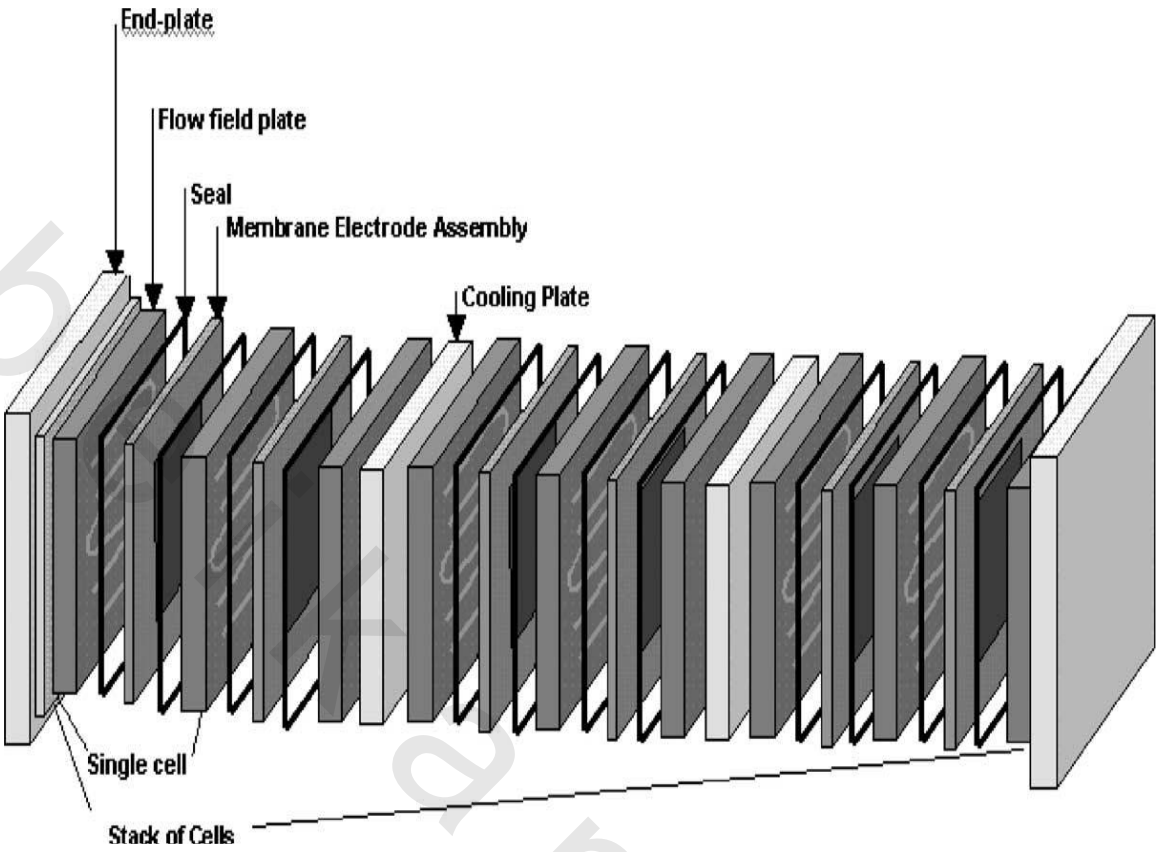


Figure 1.2 Components of a fuel cell stack.

1.4 WHY FUEL CELL?

Fuel cells have several advantages that distinguish them from other fuel systems, they are environment friendly, and fuel cell is the best solution to solve the problem between the environment and technology because it produces clean energy and higher efficiency than diesel and gas engine as shown in Figure (1.3), conversely, if we look at the systems of other fuel such as fossil fuels, they produce a large amount of pollution that harm the environment.

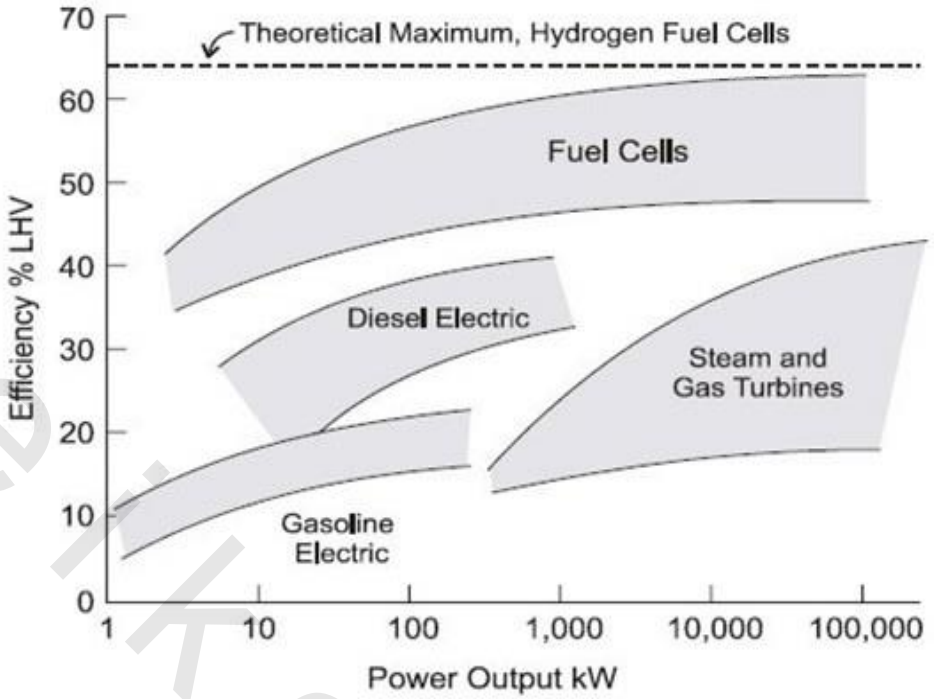


Figure 1.3 Efficiency comparison (www.micro-vett.it).

All fuel cells are supplied by hydrogen and air; hydrogen can be obtained from the electrolysis of water therefore no need to traditional fuel such as oil, gas and thus can eliminate the shortage of fuel in many countries. The other advantage of fuel cells is the very low noise level compared with internal combustion engines because they don't contain any moving parts .In addition, this make their lifetime much longer than internal combustion engines with fewer maintenance problems.

1.5 HISTORY OF FUEL CELL TECHNOLOGY

"The origin of fuel cell technology is credited to Sir William Robert Grove (1811-1896) [4]. Grove was educated at Oxford and practiced patent law while also studying chemistry. Grove developed an improved wet-cell battery in 1838 which brought him fame. Using his research and knowledge that electrolysis used electricity to split water into hydrogen and oxygen he concluded that the opposite reaction must be capable of producing electricity. Using this hypothesis, Grove developed a device which would combine hydrogen and oxygen to produce electricity. Grove had developed the world's first gas battery. It was this gas battery which has become known as the fuel cell.

Ludwig Mond (1839-1909) along with assistant Carl Langer conducted experiments with a hydrogen fuel cell that produced 6 amps per square foot at 0.73 volts. Mond and Langer came across problems using liquid electrolytes. As Mond said "we have only succeeded by using an electrolyte in a quasi-solid form soaked up by porous non-conducting material, in a similar way

as has been done in the so-called dry piles and batteries." Mond used an earthenware plate saturated with dilute sulfuric acid.

It was Friedrich Wilhelm Ostwald (1853-1932), the founder of the field of physical chemistry, who experimentally determined the relationship between the different components of the fuel cell, including the electrodes, electrolyte, oxidizing and reducing agent, anions and cations. Ostwald's work opened doors into the area of fuel cell research by supplying information to future fuel cell researchers.

During the first half of the twentieth century, Emil Baur (1873-1944) conducted extensive research into the area of high temperature fuel cell devices which used molten silver as the electrolyte. His work was performed along with students at Braunschweig and Zurich.

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 up to 3000 psi. Bacon's work lead into World War II as he tried to develop a fuel cell to be used in the Royal Navy submarines. In 1958, his work lead to the development of an alkali cell using a stack of 10" diameter electrodes for Britain's National Research Development Corporation. Bacon's developments were successful enough gain the interest of Pratt & Whitney, and his work was licensed and used in the Apollo spacecraft fuel cells. Similar technology is still being used in spacecraft [4].”

1.6 ADVANTAGE AND DISADVANTAGE OF THE FUEL CELL

1.6.1 Advantage of the fuel cell

a) Efficiency

The conversion from chemical energy into electrical energy require no mechanical interface, such as boiler to turbine and turbine to generator systems, avoiding their losses.

b) Cleanliness

The fuel cell technology is known as (zero pollution) because the outputs of cell are heat and water whereas water can be used in cooling cell when using hydrogen as working fuel.

c) Quiet

The operations of fuel cell systems are very quiet because there are no moving parts in the fuel cell which means no noise generated.

d) Flexibility of location

Due to low emissions and quietness locating fuel cell power plants is easier than locating of conventional power plants. As an example, fuel cells are more easily located in cities where construction of conventional power plants would be difficult.

e) Flexibility in power plant design

It is possible to connect any number of cells in series or parallel to obtain higher voltage or higher current respectively. A series connection of number of cells comprises the stack. The individual cells may be connected by a ribbed, bipolar plate which has two functions: (a) Working as a current collector that provides the electrical series connection between the cells. (b) Gas barrier –separates the fuel and oxidant streams in adjacent cells. Thus, the bipolar plates must be both an electrical conductor and impermeable to gases. The ribbed channels when used provide more uniform gas distribution to the back side of electrodes and they also serve to mechanically support of electrodes.

f) Easy to operate and maintain

Fuel cells are simple to operate because there are few moving parts. Hence, operation and maintenance costs are likely to be low.

g) Reliability

The fuel cell is a device that reliability equivalent to the storage battery at its best conditions.

1.6.2 Disadvantage of the fuel cell

1- Fuelling fuel cells is still a problem since the production, transportation, distribution and storage of hydrogen is difficult.

2- Reforming hydrocarbons via a reformer to produce hydrogen is technically challenging and not environment friendly.

3- The refueling and the starting time of fuel cell vehicles are longer and the driving range is shorter than in a “normal” car.

4- Fuel cells are in general slightly bigger than comparable batteries or engines however; the size of the units is decreasing.

5- Fuel cells are currently expensive to produce, since most units are hand-made.

6- Some fuel cells use expensive materials.

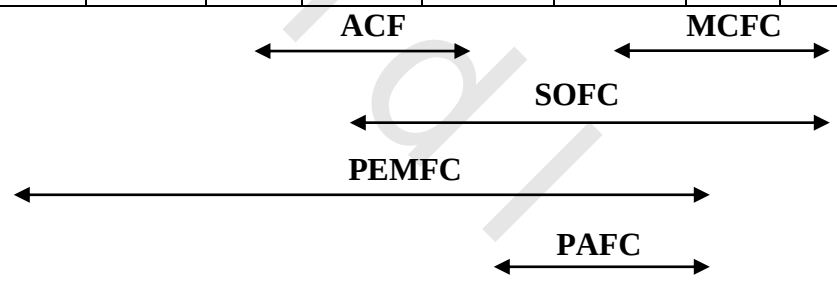
7-The technology is not yet fully developed and few products are available.

1.7 FUEL CELL APPLICATIONS

The characteristics, advantages, and disadvantages summarized in the previous section form the basis for selecting of the candidate fuel cell types to respond to a variety of application needs. The major applications for fuel cells are as stationary electric power plants, including cogeneration units; as motive power for vehicles, and as on-board electric power for space vehicles or other closed environments.

This is a unique feature of fuel cells and their potential application ranges from systems of a few watts to megawatts. Table (1.2) illustrates some typical fuel cell applications for the different fuel cell types.

Table 1.2 Typical Applications [5].

TYPICAL APPLICATIONS	**A Portable electronics Equipment**		**Cars, boats, and domestic CHP.**			**Distributed power generation, CHP ,and buses.**	
MAIN ADVANTAGES	Higher energy density to batteries, faster recharging.		Potential for zero emissions, higher efficiency			Higher efficiency, less pollution, quiet operation.	
POWER (W)	1	10	100	1 K	10 K	100 K	1 M	10 M
APPLICATION RANGE FOR FUEL CELL CLASS								

Note: CHP - Combined Heat and Power.

From the previous table the PEMFC has wider range of the applications.

1.7.1 Transportation Applications

Cars

All the world leading car manufacturers have designed at least one prototype vehicle using fuel cells. Some of the car manufacturers (Toyota, Ford) have chosen to feed the fuel cell with methanol; while others have preferred to use pure hydrogen, Opel company used liquid hydrogen.

Since 1994, Daimler-Benz working in collaboration with Ballard, built a series of PEMFC powered cars. The first of such vehicles was fueled with hydrogen, in 1997 Daimler-Benz released a methanol fuelled car with a 640 km range. They planned to offer a commercial vehicle by 2004 [5].

In 1996, Toyota built a hydrogen-fueled (metal hydride storage) fuel cell/battery hybrid passenger car, which was followed, in 1997 by a methanol-fueled car built on the same RAV4 platform. Renault and PSA-Peugeot Citroën are currently working on an improved design based on the results obtained from the FEVER prototype. General Motors, Volkswagen, Volvo, Honda, Chrysler, Nissan, and Ford have also announced plans to build prototype PEMFC cars operating on hydrogen, methanol, or gasoline. International Fuel Cells, Plug Power, and Ballard Power Systems are each participating in separate programs to build 50 to 100 kW fuel cell systems for cars [5].

Buses

In 1993, Ballard Power Systems demonstrated a 10 m light-duty transit bus with a 120 kW fuel cell system, followed by a 200 kW, 12 meter heavy-duty transit bus in 1995. These buses use no traction batteries and operate on compressed hydrogen as the on-board fuel.

In 1997, Ballard provided 205 kW PEMFC units for a small fleet of hydrogen-fuelled, full-size transit buses for demonstrations in Chicago, Illinois, and Vancouver, British Columbia [5].

1.7.2 Portable Electronic Equipment

Many companies are working in development of fuel cells to be as small batteries. this companies aim to use fuel cells in small military devices that need electrical power or use in caller phones or in laptops because when used fuel cell , it needs to recharge after one month. An example of companies developing equipment in this direction are MTI, Motorola, and NEC [5].

1.7.3 Combined Heat and Power Systems

The primary stationary application of fuel cell technology is for the combined generation of electricity and heat, for buildings, industrial facilities or stand-by generators. Because the

efficiency of fuel cell power systems is nearly unaffected by size, the initial stationary plant development has focused on the smaller, several hundred kW to low MW capacity plants [5].

1.7.4 Boats

MTU Friedrichschaffen demonstrated a sailboat on lake Constanze (2004) powered by a 20 kW fuel cell, developed jointly with Ballard [6].

1.8 FUEL CELL TYPES

Fuel cells can be classified according to various parameters:

a) operating temperature

1- Low temperature fuel cells working at about 80-120 °C such as the proton exchange member fuel cells (PEMFC).

2- Intermediate temperature fuel cells working at range of temperatures 120-250 °C, such as alkaline fuel cell (AFC) and phosphoric acid fuel cell (PAFC).

3- High temperature fuel cells working at 600-700 °C, such as molten carbonate fuel cell (MCFC).

4- Very high temperature fuel cells working at temperatures 800-1000 °C, such as solid oxide fuel cell (SOFC).

b) fuel type

1- Direct fuels such as hydrogen, non-methane hydrocarbons and methane.

2- Indirect fuels coal, methanol and ethanol.

c) working electrolyte

There are many types of electrolyte which can be used such as phosphoric acid, ceramic (solid oxide), molten carbonate, sulphuric acid, etc.

The electrochemical reaction of different types of fuel and their operating temperature are shown in Figure (1.4).

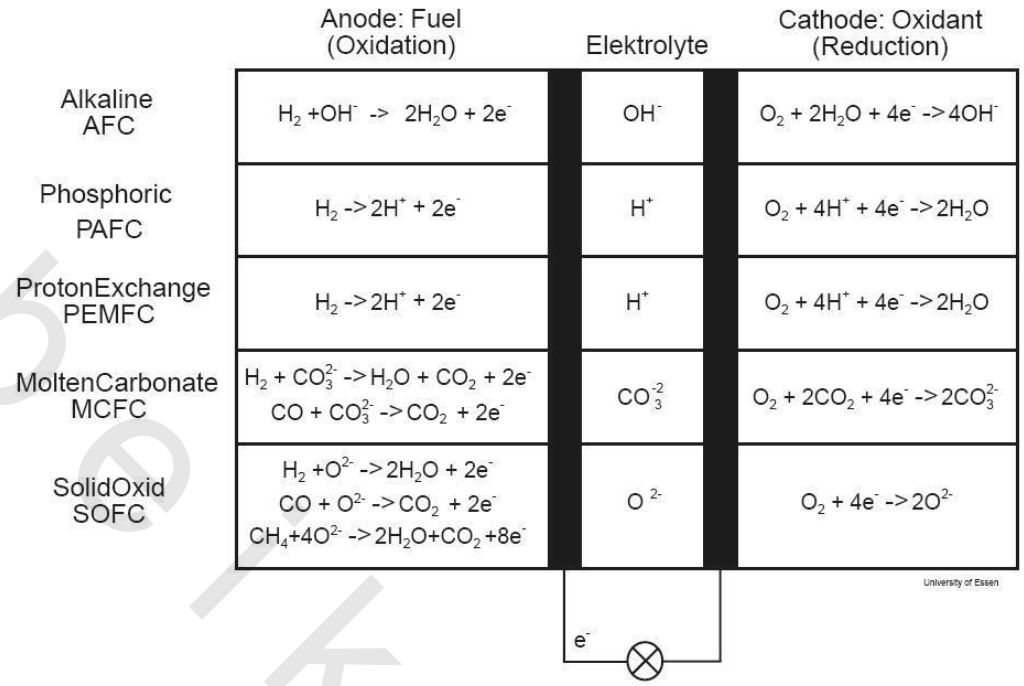


Figure 1.4 Fuel cell electrochemical reactions [7].

The comparison between different types of fuel cells from electrolyte type, electrode, catalyst, fuels, oxidant, conductive ions, system output and electrical efficiency is demonstrate in table (1.3).

Table 1.3 Comparison between different types of fuel cells [1], [8].

Fuel cell type	PEMFC	PAFC	MCFC	SOFC	AFC
Electrolyte	Polymer ion	Phosphoric Acid	Molten Carbonate Salt	Ceramic	Potassium Hydroxide
Electrode	Carbon	Carbon	Nickel and Nickel Oxide	Perovskite and perovskite / metal cermet	Transition metals
Catalyst	Platinum	Platinum	Electrode material	Electrode material	Platinum
Fuels	H2 / Reformate	H2 / Reformate	H2/CO/ Reformate	H2/CO2/CH4 Reformate	H2 Reformate
Oxidant	O2/Air	O2/Air	CO2/O2/Air	O2/Air	O2/Air
Conductive ion	H+	H+	CO3-	O-	OH-
System Output (KW)	1-250	50-200	1-2 MW	1-900	0.6-12
Electrical Efficiency	40-50%	40-50%	50-60%	45-55%	40-50%

Comparison between characteristics of fuel cell types is shown in table (1.4).

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Table 1.4 Fuel cell characteristics [9].

Fuel cell type	PMFC	PAFC	MCFC	SOFC
Operating pressure	1–5 atm.	1–8 atm.	1–3 atm.	1–15 atm.
Construction materials	Graphitic carbon	Graphitic carbon	Ni and stainless steel	Ceramics and metals
Cooling media	Water	Boiling water	Excess air	Excess air

Fuel requirements of different fuel cell types is illustrated in table (1.5).

Table 1.5 Fuel cell requirement [9].

Fuel cell type	PEMFC	PAFC	MCFC	SOFC
H_2	Fuel	Fuel	Fuel	Fuel
CO	Poison*	Poison at ≥ 2% (vol.)	Fuel	Fuel
CH_4	-	-	Fuel	Fuel
NH_3	Poison	Poison	-	Fuel
CL_2	Poison	Poison	Poison	Poison?
S_2	Poison	Poison	Poison	Poison
Special problems	Moisture control in the membrane.	High-voltage Operation. Cell life.	High fuel utilization Cell life	High oxidant utilization

* A poison is a substance that harms fuel cell performance or longevity.

1.8.1 Specifications of different types of fuel cells

The advantages and disadvantages of the different types of fuel cells are demonstrated in table (1.6).

Table 1.6 Advantage and disadvantage of different types of fuel cells [1], [10].

Fuel cell type	advantage	disadvantage
PEMFC	• Low temperature. • Quick start. • Less wear. • Better durability. • Solid electrolyte. • High power density.	• Expensive catalyst. • Sensitive to impurities.
PAFC	• More tolerant of impurities than PEMFC. • High efficiency.	• Large size. • Heavy. • Expensive catalyst.
MCFC	• Lower catalyst cost. • High efficiency. • Fuel flexibility.	• High operating temperatures cause breakdown of cell. • Decrease cell life. • Slow start up. • Complex management.
SOFC	• Solid electrolyte. • High efficiency. • Fuel flexibility.	• High operating temperature cause breakdown of cell. • Slow start up.
AFC	• High performance.	• Extremely sensitive to co_2. • Corrosive materials.

1.8.2 Comparison of different types of fuel cells applications

The Potential applications for fuel cell types are shown in table (1.7).

Table 1.7 Different application of fuel cell types [1].

Fuel cell type	PEMFC	SOFC	PAFC	MCFC	AFC
Industrial and municipal cogeneration	No	Yes	Yes	Yes	No
Distributed power	Yes	Yes	Yes	Yes	Yes
Passenger cars	Yes	No	No	No	No
Heavy duty vehicles	Yes	No	No	No	No
Road vehicles – auxiliary power unit	Yes	Yes	No	No	Yes
Commercial Buildings	Yes	Yes	Yes	Yes	Yes
Large scale grid power	No	Yes	Yes	Yes	No
Portable generators	Yes	No	No	No	No
Back up power for small buildings	Yes	Yes	No	No	Yes
Combined heat and power for small bldgs	Yes	Yes	No	No	Yes
Primary power for small buildings	Yes	Yes	No	No	Yes

1.9 FUEL CELL PERFORMANCE

1.9.1 Ideal Performance

The ideal performance of a fuel cell depends on the electrochemical reactions that occur with different fuels and oxygen as summarized in figure 4-1. Low-temperature fuel cells (PAFC and PEFC) require noble metal electro catalysts to achieve practical reaction rates at the anode and cathode, and H_2 is the only acceptable fuel. With high-temperature fuel cells (MCFC, SOFC), the requirements for catalysis are relaxed, and the number of potential fuels expands. Carbon monoxide "poisons" a noble metal anode catalyst such as platinum (Pt) in low-temperature fuel cells, but it serves as a potential source of H_2 in high-temperature fuel cells where non-noble metal catalysts such as nickel (Ni) are used.

The ideal performance of a fuel cell is defined by its Nernst potential, represented as cell voltage. The overall cell reactions corresponding to the individual electrode reactions listed in figure 4-1 are given in Table 1.8, along with the corresponding form of the Nernst equation. The Nernst equation provides a relationship between the ideal standard potential (E°) for the cell reaction and the ideal equilibrium potential (E) at other temperatures and partial pressures of reactants and products. Once the ideal potential at standard conditions is known, the ideal voltage can be determined at other temperatures and pressures through the use of these equations. According to the Nernst equation, the ideal cell potential at a given temperature can be increased by operating at higher reactant pressures, and improvements in fuel cell performance have been observed at higher pressures.

Table 1.8 Fuel Cell Reactions and the Corresponding Nernst Equations.

Cell Reactions[a]	Nernst Equation
$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	$E = E° + (RT/2\mathcal{F}) \ln [P_{H_2} / P_{H_2O}] + (RT/2\mathcal{F}) \ln [P_{O_2}^{1/2}]$
$H_2 + \frac{1}{2}O_2 + CO_{2\,(c)} \rightarrow H_2O + CO_{2\,(a)}$ 3	$E = E° + (RT/2\mathcal{F}) \ln [P_{H_2} / P_{H_2O} (P_{CO_2})_{(a)}] + (RT/2\mathcal{F}) \ln [P_{O_2}^{1/2} (P_{CO_2})_{(c)}]$
$CO + \frac{1}{2}O_2 \rightarrow CO_2$	$E = E° + (RT/2\mathcal{F}) \ln [P_{CO} / P_{CO_2}] + (RT/2\mathcal{F}) \ln [P_{O_2}^{1/2}]$
$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2$	$E = E° + (RT/8\mathcal{F}) \ln [P_{CH_4} / P_{H_2O}^2 P_{CO_2}] + (RT/8\mathcal{F}) \ln [P_{O_2}^2]$

(a) - anode
(c) - cathode
E - equilibrium potential
E° - standard potential
P - gas pressure
R - universal gas constant
T - temperature
F - Faraday's constant

1.9.2 Actual Performance

Useful amounts of work (electrical energy) are obtained from a fuel cell only when a reasonably current is drawn, but the actual cell potential is decreased from its equilibrium potential because of irreversible losses as shown in Figure 1.5. Several sources contribute to irreversible losses in a practical fuel cell. The losses, which are often called polarization, over potential or overvoltage (η), originate primarily from three sources: (i) activation polarization (η_{act}), (ii) ohmic polarization (η_{ohm}), and (iii) concentration polarization (η_{conc}). These losses result in a cell voltage (V) for a fuel cell that is less than its ideal potential, E (V = E - Losses). Expressed graphically as a voltage/current density characteristic (Activation region and concentration region more representative of low-temperature cells):

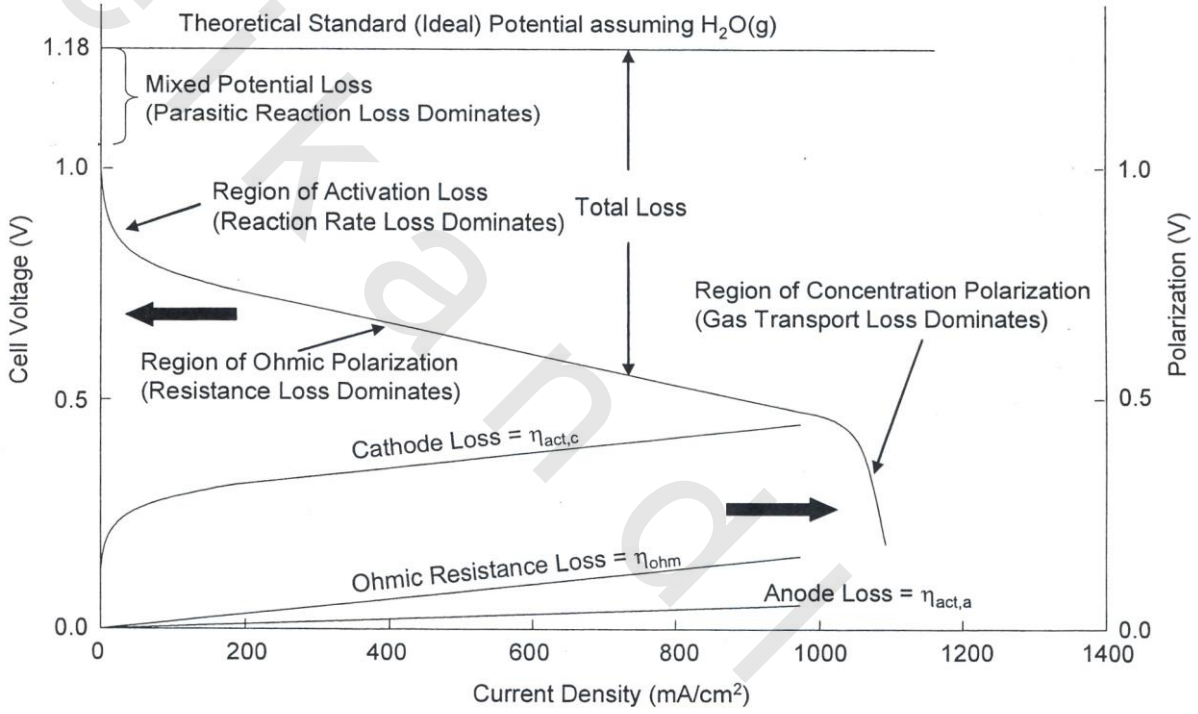


Figure 1.5 Ideal and Actual Fuel Cell Voltage/Current Characteristic [8]

The activation polarization loss is dominant at low current density. At this point, electronic barriers have to be overcome prior to current and ion flow. Activation losses show some increase as current increases. Ohmic polarization (loss) varies directly with current, increasing over the whole range of current because cell resistance remains essentially constant. Gas transport losses occur over the entire range of current density, but these losses become prevalent at high limiting currents where it becomes difficult to provide enough reactants flow to the cell reaction sites.

Activation Polarization:

Activation polarization is present when the rate of an electrochemical reaction at an electrode surface is controlled by sluggish electrode kinetics. In other words, activation polarization is directly related to the rates of electrochemical reactions. There is a close similarity between electrochemical and chemical reactions in that both involve an activation barrier that must be overcome by the reacting species. In the case of an electrochemical reaction with ηact > 50-100 mV, ηact is described by the general form of the Tafel equation

$$\eta_{act} = \frac{RT}{\alpha nf} \ln \frac{i}{i_0} \tag{1.1}$$

Where α is the electron transfer coefficient of the reaction at the electrode being addressed, i_o is the exchange current density, n moles electrons, f Faraday's constant (J/V-mol) and nf amount of charge carried by the movement electrons.

Ohmic Polarization:

Ohmic losses occur because of resistance to the flow of ions in the electrolyte and resistance to flow of electrons through the electrode materials. The dominant ohmic losses, through the electrolyte, are reduced by decreasing the electrode separation and enhancing the ionic conductivity of the electrolyte. Because both the electrolyte and fuel cell electrodes obey Ohm's law, the ohmic losses can be expressed by the equation

$$\eta_{ohm} = ir \tag{1.2}$$

Where i is the current flowing through the cell, and r is the total cell resistance, which includes electronic, ionic, and contact resistance.

Concentration Polarization:

As a reactant is consumed at the electrode by electrochemical reaction, there is a loss of potential due to the inability of the surrounding material to maintain the initial concentration of the bulk fluid. That is, a concentration gradient is formed. Several processes may contribute to concentration polarization: slow diffusion in the gas phase in the electrode pores, solution/dissolution of reactants/products into/out of the electrolyte, or diffusion of reactants/products through the electrolyte to/from the electrochemical reaction site. At practical current densities, slow transport of reactants/products to/from the electrochemical reaction site is a major contributor to concentration polarization

$$\eta_{conc} = \frac{RT}{\alpha nf} \ln \left(1 - \frac{i}{i_l}\right) \tag{1.3}$$

Where i_L is the limiting current.

1.10 FUEL CELL EFFICIENCY

The thermal efficiency of a fuel conversion device is defined as the amount of useful energy produced relative to the change in enthalpy, ΔH, between the product and feed streams.

$$\eta = \frac{Useful\ Energy}{\Delta H} \tag{1.4}$$

Fuel cells convert chemical energy directly into electrical energy. In the ideal case of an electrochemical converter, such as a fuel cell, the change in Gibbs free energy, ΔG, of the reaction is available as useful electric energy at the temperature of the conversion. The ideal Efficiency of a fuel cell, operating reversibly, is then

$$\eta_{ideal} = \frac{\Delta G}{\Delta H} \tag{1.5}$$

The most widely used efficiency of a fuel cell is based on the change in the standard free energy for the cell reaction.

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \tag{1.6}$$

Given by

$$\Delta G_r^o = G_{H_2O(L)}^o - G_{H_2}^o - \frac{1}{2} G_{O_2}^o \tag{1.7}$$

Where the product water is in liquid form. At standard conditions of 25°C (298°K) and 1 atmosphere, the thermal energy (ΔH) in the hydrogen /oxygen reaction is 285.8 kJ /mole, and the free energy available for useful work is 237.1 kJ /mole. Thus, the thermal efficiency of an ideal fuel cell operating reversibly on pure hydrogen and oxygen at standard conditions is:

$$\eta_{ideal} = \frac{237.1}{285.8} = 0.83 \tag{1.8}$$

For convenience, the efficiency of an actual fuel cell is often expressed in terms of the ratio of the operating cell voltage to the ideal cell voltage. As it described in greater detail in the pervious sections , the actual cell voltage is less than the ideal cell voltage because of losses associated with cell polarization and ohmic losses. The thermal efficiency of a hydrogen/oxygen fuel cell can then be written in terms of the actual cell voltage:

$$\eta = \frac{Useful\ Energy}{\Delta H} = \frac{Useful\ Energy}{(\Delta G/0.83)} = \frac{Volts_{actual} \times current}{Volts_{ideal} \times current/0.83} = \frac{0.83 \times E_{actual}}{E_{ideal}} \quad (1.9)$$

Where ΔH is the change in enthalpy, ΔG is the change in Gibbs free energy.

1.11 PROTON EXCHANGE MEMBER FUEL CELLS (PEMFCS)

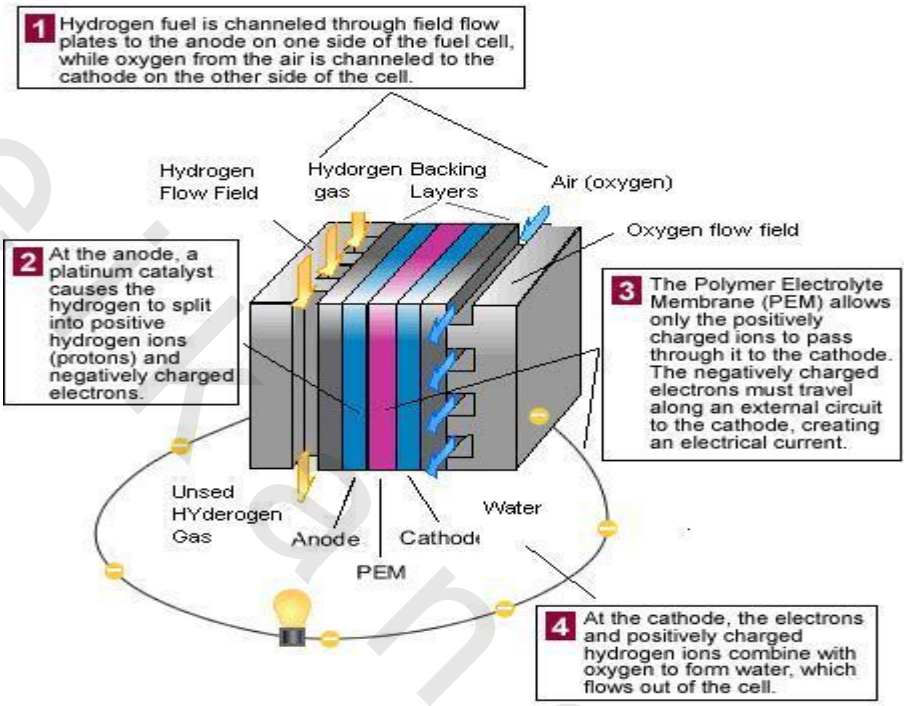
Polymer electrolyte fuel cells have the ability to operate at very low temperatures; this is the main attraction of the proton exchange membrane fuel cell (PEMFC). Since they have the ability to deliver such high power densities at this temperature they can be made smaller which reduces overall weight, production cost and specific volume. Since the PEM has an immobilized electrolyte membrane there is simplification in the production process that in turn reduces corrosion, this provides for longer stack life.

The PEMFC can also operate at elevated air pressure, which allows the cell stack to produce higher power densities. On the other hand, this requires larger compressors and therefore higher power requirements which may decrease this advantage. The solid polymer membrane also can hold substantial differential reactant pressures, which provides some flexibly in cell design and the system design.

The development of PEM faces some challenges in development of the efficient of cell. The main challenges are:

1. Electro catalyst toxicant by short level carbon monoxide concentrations in the fuel.
2. Temperature limits the water management and membrane operation.
3. The cost of membrane and system balance of plant.

The detailed parts of proton exchange membrane fuel cell (PEMFC) is shown in figure (1.6)



Figurer 1.6 The proton exchange membrane fuel cell (PEMFC).

The electrochemical reaction of PEM fuel cell is as follows when the fuel Hydrogen (H_2) is fed to anode side of PEM, H_2 splits into its primary constituent's protons and electrons. Each hydrogen atom consists of one electron and one proton. The electron travels in the electrical current that can be utilized before it return to the cathode side of fuel cell, where oxygen or air fed to cathode, at the same time the proton diffuse in the membrane to the cathode, where (H) atom recombined and react with O_2. Water is created in the electrochemical reaction, and then pushed out of the cell with an excess flow of oxygen. The net result of these simultaneous reactions is a current of electrons through an external circuit – direct electrical current. The reaction which is done inside the cell shown as following:

Anode $$H_2 \longrightarrow 2H^+ + 2e^- \quad (1.10)$$

Cathode $$\frac{1}{2}O_2 + 2H^+ + 2e^- \longrightarrow H_2O \quad (1.11)$$

Cell $$H_2 + \frac{1}{2}O_2 \longrightarrow H_2O \quad (1.12)$$

Schematic diagram of producing an electric for PEMFC is shown in figure (1.7)

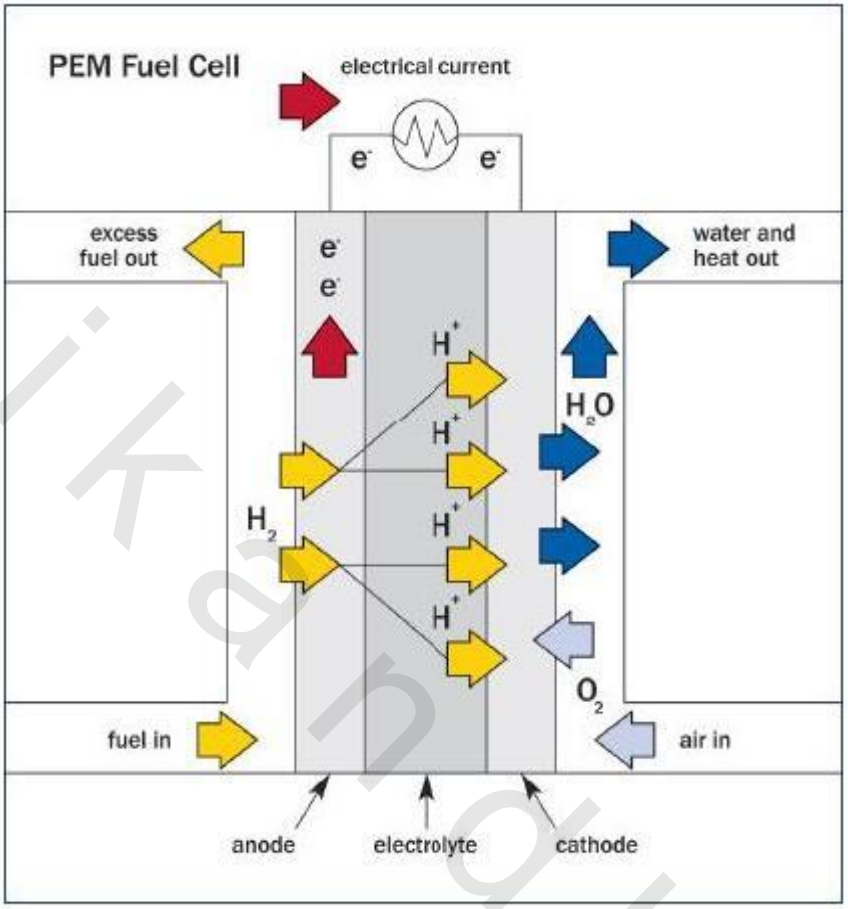


Figure 1.7 Schematic diagram of producing an electric for PEMFC.

1.11.1 PEM Fuel Cell Components

A basic part of a PEMFC is provided in figure (1.8) and consists of four main parts:

i. Membrane.
ii. Electrode.
iii. Gas Diffusion Layer.
iv. Bipolar plates.

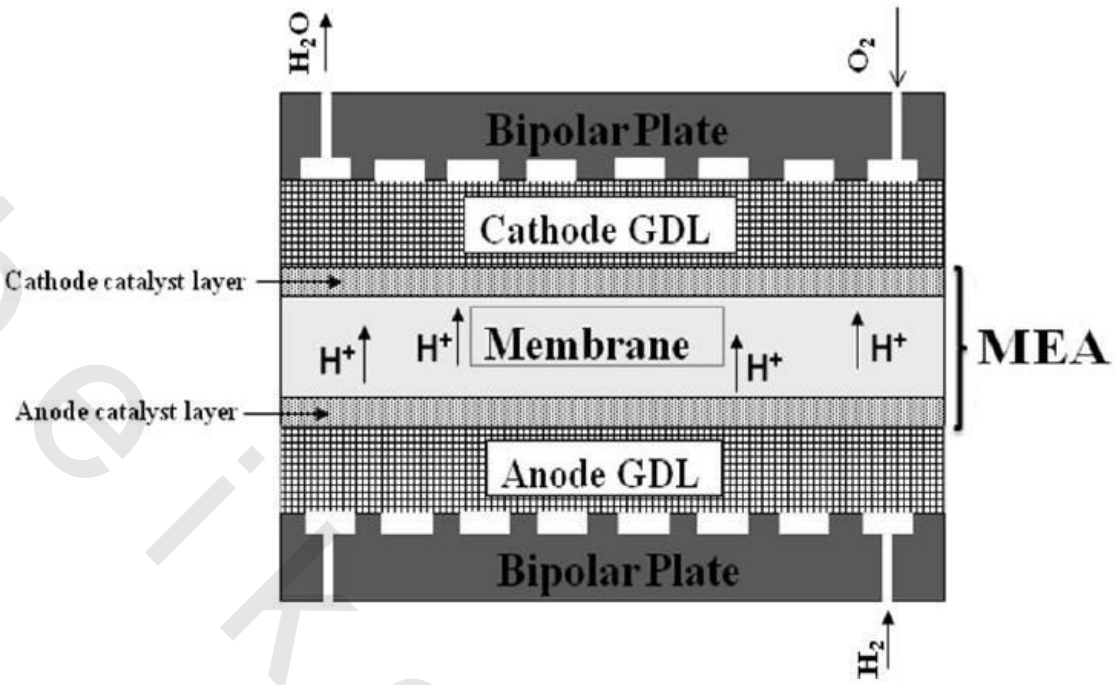


Figure 1.8 Schematic diagram of the basic parts of a Proton exchange membrane fuel cell component [11].

i. Membrane

A fuel cell membrane is one of the vital components of the PEMFC; the desired properties for a membrane to be used as a proton conductor in a fuel cell are listed as follows [11]:

1. Good chemical, mechanical and electrochemical stability in fuel cell operating conditions.

2. Elevated proton conductivity to support high currents with minimal resistive losses and zero electronic conductivity.

3. Thermal and hydrolytic stability.

4. Chemical properties compatible with the bonding requirements of membrane with the electrodes.

5. No permeability to reactant species to maximize efficiency.

6. High durability and low costs membranes.

The different materials of membrane are shown in figure (1.9).

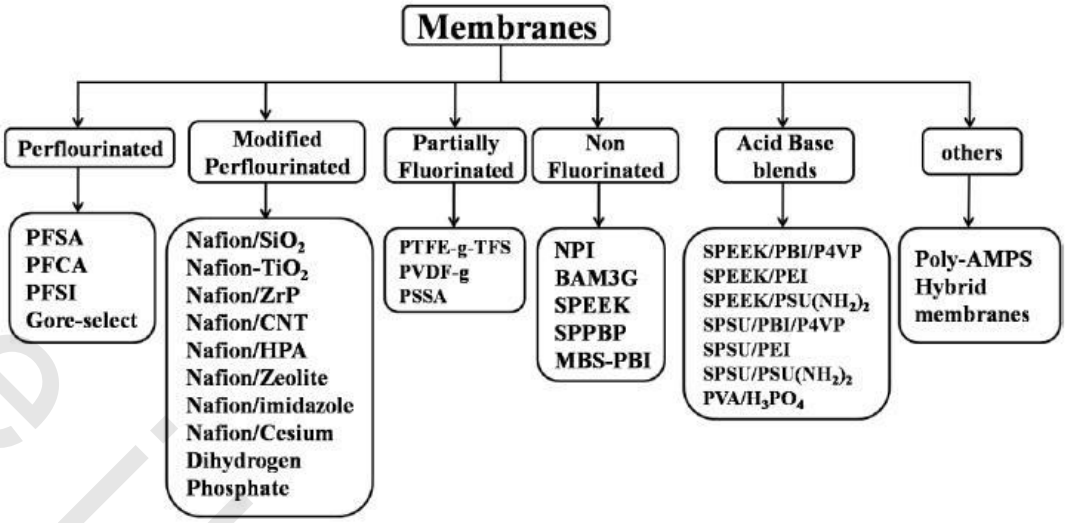


Figure 1.9 Classification of membrane materials [11].

ii. **Electrode**

A fuel cell electrode is essentially a thin catalyst layer pressed between the membrane and a porous, electrically conductive substrate. It is the layer where the electrochemical reactions take place. The best catalyst material for both anode and cathode PEM fuel cell is platinum. Since the catalytic activity occurs on the surface of the platinum particles, it is desirable to maximize the surface area of the platinum particles.

Essential demands on electrodes materials are:

1- High electronic conductivity.
2- High catalytic activity.
3- High density of active sites.
4- High porosity.
5- Thermal and chemical stability.

To minimize the cell potential losses due to the rate of proton transport and reactant gas permeation in the depth of the electro catalyst layer, this layer should be made reasonably thin. At the same time, the metal active surface area should be maximized, for which the Pt particles should be as small as possible. For the first reason, higher Pt/C ratios should be selected (>40% by wt.); however, smaller Pt particles and consequently larger metal areas are achieved with lower loading (as shown in Table (1.9).

Table 1.9 Achievable Pt Active Area for Various Pt/Carbon Compositions Using Ketjen Carbon Black-Supported Catalyst [12].

wt.% Pt on Carbon	XRD Pt Crystallite Size, nm	Active Area* m^2g^{-1} Pt
40	2.2	120
50	2.5	105
60	3.2	88
70	4.5	62
unsupported Pt black	5.5-6	20-25

In general, higher Pt loading results in voltage gain (Figure 1.10) [13], assuming equal utilization and reasonable thickness of the catalyst layer. However, when current density is calculated per area of Pt surface then there is almost no difference in performance, that is, all the polarization curves fall on top of each other (Figure 1.11) [13].
The key to improving the PEM fuel cell performance is not increasing the Pt loading, but rather in increasing Pt utilization in the catalyst layer.

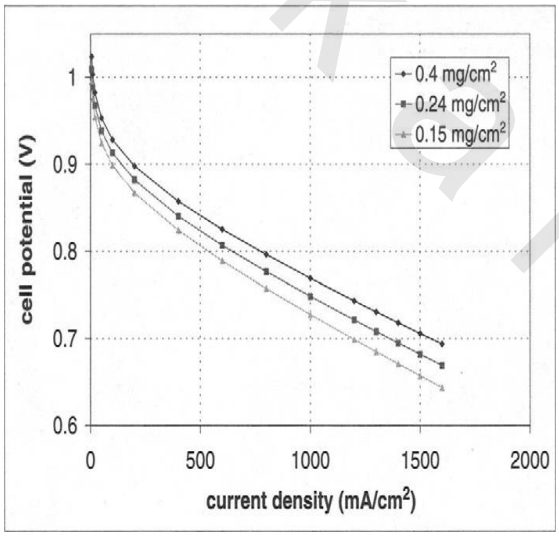


Figure 1.10 Effect of Pt loading on fuel cell polarization curve (H_2/O_2 fuel cell)[13].

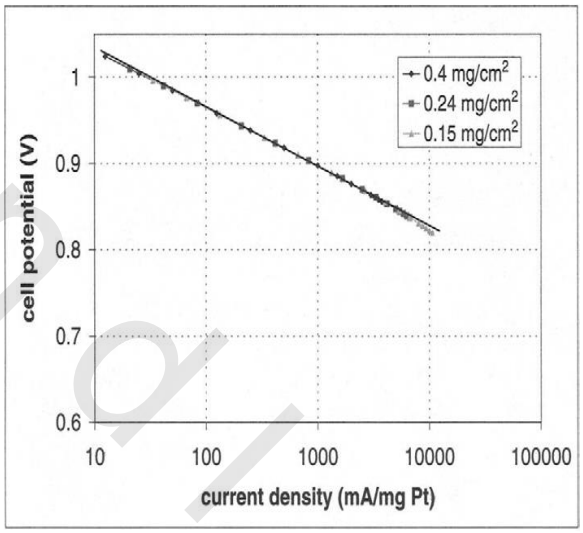


Figure 1.11 Cell performance per unit of Pt. Electro catalyst [13].

iii. Gas Diffusion Layer

The typical materials for gas diffusion layers are carbon paper and carbon cloth. These are porous materials with typical thickness of 100-300 μm. The functions of the gas diffusion layers are to provide structural support for the catalyst layers, passages for reactant gases to reach the catalyst layers, transport of water to or from the catalyst layers, electron transport from the catalyst layer to the bipolar plate in the anode side and from the bipolar plate to the catalyst layer

in the cathode side, and heat removal from the catalyst layers. Gas diffusion layers are usually coated with Teflon to reduce flooding which can significantly reduce fuel cell performance due to poor reactant gas transport.

The required properties of the gas diffusion layer can be deduced from its functions:

1- It must be both electrically and thermally conductive, again both through plane and in plane. Contact resistance is typically more important than bulk conductivity

2- It must be sufficiently porous to allow flow of both reactant gases and product water.

3- Since the catalyst layer is made of discreet small particles the pores of the gas diffusion layer facing the catalyst layer must not be too big.

4- It must be sufficiently rigid to support the "flimsy" MEA. However, it must have some flexibility to maintain good electrical contacts.

iv. Bipolar plates

The functions of the bipolar plate are to provide the pathways for reactant gas transport, and electron conduction paths from one cell to another in the fuel cell stack, separate the individual cells in the stack, carry water away from the cells, and provide cooling passages.

The bipolar plate required properties can be deduced from their functions, namely:

1- They connect cells electrically in series – therefore they must be electrically conductive.

2- They separate the gases in adjacent cells – therefore they must be impermeable to gases.

3- They provide structural support for the stack – therefore they must have adequate strength, yet they must be lightweight.

4- They conduct heat from active cells to the cooling cells – therefore they must be thermally conductive.

The bipolar plate has several designs as shown in figure (1.12)

Figure 1.12 Several designs of bipolar plates.

1.12 LITERATURES REVIEW

1.12.1 Literatures review of PEMFC

A full three-dimensional, non-isothermal computational fluid dynamics model of a tubular-shaped proton exchange membrane (PEM) fuel cell has been developed by Maher A.R Sadiq Al-Baghdadi [14]. A parametric study has been performed for three critical parameters: the GDL porosity, the GDL thermal conductivity, and the membrane thermal conductivity. The effects of different operating parameters on the performance of proton exchange membrane (PEM) fuel cell have been studied experimentally using pure hydrogen on the anode side and air on the cathode side by Lin Wang et al [15]. The dynamic performance is a very important evaluation index of proton exchange membrane (PEM) fuel cells used for real application, which is mostly related to water, heat and gas management. A commercial PEM fuel cell system of Nexa module is employed to experimentally investigate the dynamic behavior and transient response of a PEM fuel cell stack have been developed by Yong Tang et al [16].

1.12.2 Literatures review of bipolar plate

Bipolar plate (BPP) is one of the most important and the most expensive components of PEM fuel cells and accounts to more than (80%) of the weight and (30%) of the total cost in a fuel cell stack [17]. Bipolar plates based on carbon materials have been the main focus of the development activities so far. However, further cost reduction and increases of power density are beneficial for fuel cell technology. Bipolar plates should require several properties to achieve the desired fuel cell stack performance that are electrical conductivity, gas tightness, chemical stability, lightweight and mechanical strength to withstand clamping forces. Also, an optimal bipolar plate should be low-cost and easily manufactured.

Reiser and Sawyer [18] and Reiser [19] designed the bipolar plate as the flow-field network which formed using many pins arranged in a regular pattern, and these pins can be in any shape, although cubical and circular pins. Pollegri and Spaziante [20] showed a straight flow-field design, which is further exemplified by General Electric and Hamilton Standard LANL No. 9-X53-D6272-1 (1980). Johnson et al. [21] proposed a design with pressure gradients within the channels, such that the resistance to reactant flow differs along the length of the adjacent channels. Spurrier et al. [22] and Granata and Woodle [23] described a modified serpentine gas flow field across the plate surface. Chow et al. [24, 25] released a BPP design, which possesses both reactant gas flow field and cooling flow field on the same plate surfaces, this design is an integrated flow field. As gases flow in the channels, the reactants are transferred into the gas diffusion layer, and thus the concentration of the reactant in the flow channels is reduced along the flow direction. This reduction in concentration can result in non-uniform reaction across the fuel cell active area. Gurau [26] proposed a design for improved mass transfer using interdigitated flow-field design. In this layout the outlet channel volume is less than the inlet channel volume. Rock [27] proposed a stamped BPP for PEM fuel cells from a single metallic

sheet. The plate has a serpentine flow field formed on one side and an interdigitated flow field formed on the opposite side such that a single plate member is usable as an anode and cathode side flow fields for adjacent fuel cells. Jason P et al. [28] evaluate the performance of two new bio-inspired flow pattern designs for bipolar plates in PEM fuel cells. A computational fluid dynamics (CFD) analysis was used to model the flow through the newly designed channels and diffusion into the GDL, a direct 3D micro scale model of a portion of the PEM cathode channel and carbon cloth GDL is used to parametrically investigate local heat and fluid flow at the GDL's pore scale and their effects on condensation of water vapor that leads to flooding by A. Kopanidis et al [29].

Atul Kumar and Ramana [30] studied the effect of gas flow-field design in the bipolar/end plates on the steady and transient state performance of the polymer electrolyte membrane fuel cell (PEMFC). They also studied the use of porous materials in the gas flow-field of the bipolar/end plate was demonstrated. Three different types of porous material were considered: Ni–Cr metal foam (50 PPI), SS-316 metal foam (20 PPI), and carbon cloth [31]. Rajesh Boddu et al [32] studied bipolar plates with different shape, size and pattern of gas flow channels are analyzed using computational fluid dynamic model. Distribution of velocity and pressure are analyzed to show the effect of different serpentine channels with varying number of channel, pattern and sizes .An electric model that simulates flow in bipolar plates and permits the optimisation of gas feeding in PEMFCs is proposed by D. Martín et al [33].

An experimental and numerical study was presented to analyze the gas flow across a GDL from different bipolar plates. It has been shown that the flow through the carbon paper layer is mostly controlled by the pressure gradient across the GDL by A. Lozano et al [34]. Three different bipolar plates, in some way representative of different design models commonly used, with an electrode side area of 49 cm^2 have been numerically and experimentally studied: a set of parallel diagonal channels, a branching cascade type, and a serpentine distribution of parallel-channel blocks by F. Barreras et al [35]. An experimental and numerical research has been performed in order to study the flow distribution in a bipolar plate of a commercial PEM fuel cell by F. Barreras et al. Planar laser induced fluorescence (PLIF) trace tracking has been applied to visualize the flow pattern and to measure the velocity in the plate channels [36]. Hydroforming process is a promising technique to manufacture metal bipolar plates which are cheaper and lighter than traditional graphite bipolar plates, design of experiments (DOE) methods and an adoptive simulated annealing (ASA) optimization method, an optimization model of flow channel section design for hydroformed metal bipolar plate is proposed by Linfa Peng et al [17].

A 3D complete model is simulated using CFD techniques developed by Bladimir Ramos-Alvarado. The fuel cell model includes the gas flow channels, the gas diffusion layers and the membrane-electrode assembly (MEA) [37]. Another study in 2010 presents a Computational Fluid Dynamics (CFD) model developed for a 50 cm^2 fuel cell with parallel and serpentine flow field bipolar plates, and its validation against experimental measurements. The numerical CFD model was developed using the commercial ANSYS FLUENT software, and the results obtained were compared with the experimental results in order to perform a model validation [38].

Alfredo Iranzo et al [39] studied the performance for a 50 cm^2 PEM Fuel Cell under different operating conditions and with different bipolar plate designs. They were also analyzed via experimental measurements. Their results obtained for the cell with serpentine flow field was found to perform better than the cell with parallel flow field. The operation with pure oxygen was improving the performance parameters as well.Kumar and Reddy [40] used the different porous materials in the gas flow-field of the bipolar. Three different types of porous material were considered: Ni–Cr metal foam (50 PPI), SS-316 metal foam (20 PPI), and carbon cloth. Carbon cloth the lowest performance. While the metal foams has the best performance. An additional advantage as that these metal foams can be possibly used for catalyst support for the electrochemical reactions in the fuel cell. Jianhu Nie et al [41] compared numerical simulations of three dimensional water flow together with experimental measurements were performed for the purpose of examining pressure and velocity distributions in the bipolar plate of a PEM electrolysis cell. Barreras et al [42] validate numerically and experimentally three different bipolar plates. In some way representative of different design models commonly used with an electrode side area of 49 cm^2: a set of parallel diagonal channels, a branching cascade type, and a serpentine distribution of parallel-channel blocks. The serpentine-parallel plate distributes the flow with a uniform velocity field, but with an excessively large pressure drop. On the other hand, a homogeneously distributed flow is obtained with the cascade-type flow geometry, together with a quite uniform pressure field over the whole plate. Guilin et al. [43] developed a three-dimensional, non-isothermal and two-phase mathematical model based on computation fluid dynamics is developed to describe flow and heat transfer process of a PEMFC with serpentine fluid channel. The effects of phase change and temperature as well as two-phase flow and transport, electrochemical kinetics, and multicomponent transport on cell performance are accounted for simultaneously in this comprehensive model. San Martín et al. [44] developed models are implemented in Matlab Simulink and validated in a number of operating environments, for steady-state and dynamic modes alike. In turn, the fuel cell models are validated in an actual micro grid operating environment, through the series connection of 4 PEMFC. The simulations of the models precisely and accurately reproduce the fuel cell electrical and thermal performance. Ahmadi et al. [45] presents the results of numerical study with experimental validation, using computational fluid dynamics (CFD) analysis to investigate the species distribution in proton exchange membrane fuel cells (PEMFCs) with deflected membrane electrode assembly (MEA).

1.13 PRESENT STUDY

The performance of the different bipolar plate designs have been studied numerically and experimentally. Detailed 3D model has been developed for different bipolar plate designs. A commercial software COMSOL has been used in this numerical study. Navier–Stokes equation in flow channels and Brinkman's equation in the porous gas diffusion layer by using different bipolar plate designs. The main effective parameters in this study were pressure drop, effective area and residence time.

The objective from this work is to obtain the optimum design and geometry for bipolar plate to improve proton exchange membrane fuel cell (PEMFC) performance.