INTEGRATED GLYCEROL PROCESSOR AND PROTON EXCHANGE MEMBRANE FUEL CELL (PEMFC) SYSTEMS FOR STATIONARY APPLICATIONS

NOOR AFIQAH BINTI SHARIFMUDDIN

Thesis submitted in partial fulfillment of the requirements
for the award of the degree of
Bachelor of Chemical Engineering

**Faculty of Chemical & Natural Resources Engineering
UNIVERSITI MALAYSIA PAHANG**

JUNE 2015

ABSTRACT

This work presents the performance and efficiency analysis of an integrated glycerol processing and proton exchange membrane fuel cell (PEMFC) system. Glycerol processing as one of the renewable fuel system is employed for hydrogen production. The hydrogen produced from glycerol processing is then fed to the PEMFC system to produce the desired electricity. Here, a PEMFC power generation system composed of two subsystems: fuel reforming and fuel cell stack. A fuel reforming is regarded as a suitable process to produce hydrogen for stationary application of fuel cells because of its high hydrogen yield which subsequently is used to generate electricity through the fuel cell stack by producing a desired power outcome. The system was simulated and optimized into 3 cases. The first one involves the high temperature proton exchange membrane fuel cell (HT-PEMFC) and a glycerol reformer without water gas shift reactor whereas in the second case, a water gas shift reactor is included to improve its overall system efficiency. The third case involves low temperature proton exchange membrane fuel cell (LT-PEMFC) with a glycerol reformer, water gas shift reactor and preferential oxidation reactor. In this study, a direct comparison between the performance of HT-PEMFC and LT-PEMFC systems integrated with a glycerol steam reformer with and without a water gas shift reactor is shown. The target power output of both the HT-PEMFC and LT-PEMFC systems for stationary application is in the range of 1-8 kW, which is sufficient for small household application. Based on result, HT-PEMFC system with water gas shift reactor shows the highest composition of hydrogen that give amount of 80.79% which operates at 1063.15 K and 3 atm with carbon to steam ratio of 2. Compared with HT-PEMFC without water gas shift reactor and LT-PEMFC, both gave 44.76% and 66.26% of hydrogen composition respectively. In term of the system efficiency, it is found that the highest system efficiency is also obtained from HT-PEMFC system with water gas shift reactor followed by LT-PEMFC system and HT-PEMFC system without water gas shift reactor. The highest system efficiency obtained is 59.89% efficiency due to its high energy required to generate for the system.

ABSTRAK

Kertas kerja ini membentangkan analisis teori prestasi dan kecekapan pemprosesan gliserol dan sel bahan api membran pertukaran proton (PEMFC). Pemprosesan gliserol adalah salah satu sistem bahan api yang boleh diperbaharui dan boleh digunakan untuk menghasilkan hidrogen. Hidrogen yang terhasil daripada pemprosesan gliserol ini kemudiannya dijadikan input kepada sistem PEMFC untuk menghasilkan elektrik yang dikehendaki. Di sini, sistem PEMFC penjanaan kuasa terdiri daripada dua subsistem: penjanaan bahan api dan sel fuel jana kuasa. Penjanaan bahan api dianggap sebagai satu proses yang sesuai untuk menghasilkan hidrogen kerana jumlah hidrogen yang dihasilkan adalah tinggi dan kemudiannya akan digunakan untuk menjana tenaga elektrik melalui sel fuel jana kuasa dengan menghasilkan kuasa mengikut pilihan sendiri. Sistem ini disimulasikan kepada 3 kes. Yang pertama melibatkan suhu tinggi sel fuel membran pertukaran proton (HT-PEMFC) dan pembaharu gliserol tanpa gas air anjakan reaktor manakala dalam kes kedua, air anjakan gas reaktor dimasukkan untuk meningkatkan kecekapan sistem secara keseluruhan. Kes ketiga melibatkan suhu rendah sel fuel membran pertukaran proton (LT-PEMFC) dengan gliserol pembaharu, reaktor anjakan gas air dan reaktor pengoksidaan keutamaan. Dalam kajian ini, perbandingan antara HT-PEMFC dan LT-PEMFC sistem dengan pembaharu wap gliserol dengan dan tanpa reaktor anjakan gas air dihuraikan. Kuasa keluaran sasaran kedua-dua HT-PEMFC dan LT-PEMFC sistem untuk aplikasi statik adalah dalam lingkungan 1-8 kW, yang bersesuaian untuk kawasan perumahan. Berdasarkan keputusan, sistem HT-PEMFC dengan peralihan gas air reaktor menunjukkan komposisi hidrogen yang paling tinggi dengan jumlah 80.79% yang beroperasi pada 1063.15 K dan 3 atm dengan nisbah karbon kepada stim 2. Berbanding dengan HT-PEMFC tanpa anjakan gas air reaktor dan LT-PEMFC, kedua-duanya memberikan 44.76% dan 66.26% jumlah komposisi hidrogen. Dari segi kecekapan sistem, didapati bahawa kecekapan sistem yang paling tinggi juga diperolehi daripada sistem HT-PEMFC dengan reaktor anjakan gas air diikuti oleh sistem LT-PEMFC dan sistem HT-PEMFC tanpa anjakan gas air reaktor. Kecekapan sistem tertinggi diperolehi adalah sebanyak 59.89% disebabkan oleh tenaga yang tinggi diperlukan untuk menjana sistem ini.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

C_{Pt} Concentration on the catalyst surface, mol cm^{-3}

C_{Pt}^{ref} Reference concentration on the catalyst surface, mol cm^{-3}

C_{ref} Reference concentration, mol cm^{-3}

E_c Activation energy, J mol^{-1} K^{-1}

E_{cell} Cell voltage, V

E_r Reversible cell potential, V

F Faraday constant, 96 485 C mol^{-1}

G Gibb free energy, J mol^{-1}

K_m Proton conductivity of LT-PEMFC, S cm^{-1}

L_c Catalyst loading, mg cm^{-2}

LHV   Lower heating value, kJ mol^{-1}

m Molar flow rate, mol s^{-1}

m_{H2} Molar flow of H$_2$, gmol s^{-1}

m_{fuel} Molar flow rate of fuel, gmol s^{-1}

N Molar flux, mol s^{-1} m^{-1}

P Pressure, atm

P_{FC} Power density, W m^{-2}

P_T Target power output, W

Q Heat flow, J s^{-1}

R Gas constant, 8 314 J mol^{-1} K^{-1}

RH   Relative humidity

T Cell temperature, K

T_{ref} Reference cell temperature , K

U_f Fuel utilization

α_c Catalyst surface area, m^2 g^{-1}

i Current density, A m^{-2}

i_0 Exchange current density, A m^{-2}

i_0^{ref} Reference exchange current density, A m^{-2}

l_m Membrane thickness, m

Greek letters

α	Transfer coefficient
γ	Reaction order
λ	Water content
σ_m	Proton conductivity, S cm^{-1}
η_{ohmic}	Ohmic loss, V
η_{act}	Activation loss, V
η_{FC}	Fuel cell efficiency
η_{sys}	System efficiency

Subscripts and superscripts

a	Anode
c	Cathode
m	Membrane
H_2	Water
O_2	Oxygen
N_2	Nitrogen
H_2O	Water
CH_4	Methane
CO_2	Carbon dioxide
CO	Carbon monoxide

1 INTRODUCTION

1.1 Motivation and Problem Statement

Electrical energy is produced from many different sources. Some of these sources are renewable while others are non-renewable. Renewable energy for example, solar, wind, water (hydro), biomass and geothermal is the types of the energy resources that replenished naturally in short periods of time. Differ with non-renewable energy, such as fossil fuel, oil and natural gas are available in limited supplies because it takes a long time for these resources to be replenished (Aust, 2014). Most of the electricity used in this world is made up from power plants that burn fossil fuels to create steam. Based on British Petroleum (BP) Statistical Review in 2013, almost 86.94% of all fossil fuel were used in today's world and it is expected to be increased more in future (Rifkin, 2008). Typically, fossil fuels are contributed into atmospheric pollution and thus, induced global warming. Burning fossil fuels also creates dangerous gases such as carbon dioxide and carbon monoxide that trap heat from the sun and as consequence, make the planet too warm. This is called global warming and it makes the weather or climate change in serious ways. Thus, huge efforts are taken in order to replace fossil fuels with other energy sources and one of the ways is through the adoption of hydrogen fuel cells as energy converting devices (Chandan et al., 2013).

Hydrogen production from biomass has major attention because of the potential application in fuel cells. Enormous amounts of glycerol ($C_3H_8O_3$) produced from biodiesel production by transesterification of vegetable oils are not only available at low cost but also in a large quantity from renewable raw materials. Demand for hydrogen (H_2), the simplest and abundant element, is rising due to the technological advancement in fuel cell industry (Slinn et al., 2008) which can be considered as a potential replacement for current power generation and automobile engine system. Recently, almost 95% of the world's hydrogen is being produced from fossil fuel feedstock (Venturelli et al., 2009).

Glycerol can be used to produce a variety of chemicals and fuels including hydrogen (Authayanun et al., 2011). Conversion of fuels to hydrogen has been carried out by several techniques, such as steam reforming, partial oxidation, autothermal reforming, aqueous-phase reforming and supercritical water reforming. In this paper, steam reforming technique for hydrogen production from glycerol is chosen due to it complete conversion yield with low carbon formation (de Lima et al., 2012). Specifically, glycerol can be used in the field of hydrogen production via gas reforming for fuel cell application.

By definitions, fuel cell is electrochemical cell which can continuously convert the chemical energy of a fuel and an oxidant to electrical energy by a process involving an essentially invariant electrode-electrolyte system (Kordesch and Simader, 1996). For a hydrogen/oxygen fuel cell, the inputs are hydrogen (fuel) and oxygen (oxidant) while the outputs are direct current (dc) power, heat and water.

Compared with other type of equipment that producing energy, fuel cell have many advantages which include higher efficiency, no existence of the mobile parts that result in lack of pollution, no emission of environmental polluting gases such as SO_x, NO_x, CO_2 and etc. However, the only disadvantage of fuel cell is due to the high cost in developing the fuel cell. Nevertheless, this problem can be solved by applying the new technology.

One of the examples of fuel cell is proton exchange membrane fuel cell - (PEMFC). Generally, PEMFC is composed of different fundamental elements namely bipolar plates, diffusion layers, electrodes (anode and cathode) and the electrolyte. The core of a PEMFC is called the membrane electrode assembly (MEA), and it is composed of the proton exchange membrane (PEM) placed between two electrodes. Proton exchange membranes have different functions, such as separating the gaseous reactants, conducting protons from the anode to the cathode, electrically insulating the electrons and supporting the catalyst. In PEMFC, a dense proton-exchange membrane is responsible for proton migration from the anode to the cathode. Hydrogen is catalytically oxidized in the anode to produce protons (Díaz et al., 2014). The membrane is placed between two electrodes. The proton produced can migrate from the anode to cathode where the protons react with oxygen to produce water and heat (Zhang et al., 2006). The complete reactions occurred in the PEMFC are shown in Equations (2.1) – (2.3).

Meanwhile, the liquid electrolyte systems can be overpowered by solid proton exchange membranes due to the unique features of the solid proton exchange membrane, which include easy handling, compact and excellent resistance to the permeation of gaseous reactants.

In general, PEMFC can be divided into two types which are low temperature PEMFC (LT-PEMFC) and high temperature PEMFC (HT-PEMFC). Both LT-PEMFC and HT-PEMFC has its own advantages and disadvantages, so it is important to understand how they compare (Table 2.3). The operating temperature for LT-PEMFC is within 50°C to 80°C and has been developed using Nafion as it membrane which uses a water-swollen MEA. All LT-PEMFC requires a very high purity of hydrogen fuel to operate; this requirement will result of low operating temperature of the fuel cell. At relatively low temperature, the electrocatalyst at the anode can causes catalyst poisoning due to contaminants which includes carbon monoxide (CO), unsaturated hydrocarbon and organosulphur compounds. The operating temperature of a PEMFC plays an important role. Since proton conduction is through MEA for LT-PEMFC, the upper operating temperature is highly depending on the concentration of water that remains in the MEA. This is to ensure the current to be smoothly generated. The impact of too little water in the electrolyte layer may lead to irreversible failure of the electrolyte. However, too much water may result in limited blockage of the cathode but it does not lead to irreversible cell damage. A schematic of the effect of too little and too much water is shown in Figure 1.1.
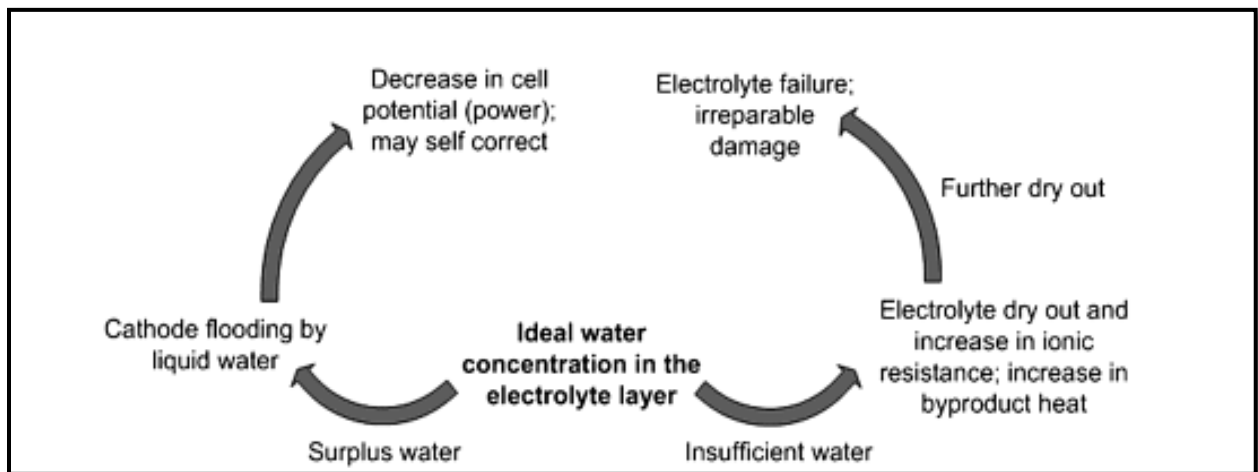

Figure 1.1: Schematic diagram of the effect of water in PEMFC electrolyte layer

In HT-PEMFC, it does not use water-swollen MEA. Thus, water is not essential as a proton conducting compound. HT-PEMFC is another type of PEMFC that used polybenzimidazole (PBI) as it membrane and it is swollen with phosphoric acid. This was commercially introduced in 2004 and it targeted at operating within the range of 120^oC to 180^oC. The major advantage of HT-PEMFC is that it can tolerate a substantial concentration of CO in hydrogen fed to the anode. Platinum, Pt is used as anode and cathode catalyst on the carbon, same as for the LT-PEMFC. The degree of CO tolerance is strongly depends on the temperature at the anode. Acceptable electrochemical performance is obtained with up to 1% CO at 140^oC, but this increase to 3% CO at 180^oC. Another advantage of HT-PEMFCs is that there is no need to humidify the cathode air supply. Since the electrolyte layer does not require water to maintain good proton conductivity, the humidity of the cathode and anode stream is not necessary. However, as mentioned above, it is important to avoid liquid water from being contact with MEA in order to prevent phosphoric acid to be leached out from the MEA.

PEMFC system for stationary application consists of a steam reformer and fuel cell, which in our case is PEMFC either LT-PEMFC or HT-PEMFC. A reformate gas derived from steam reformer is the preferred fuel for PEMFC operation before hydrogen transport and storage are readily available. Among the various type of fuel available, glycerol is one of the most potential feedstock for producing hydrogen (Byrd et al., 2008). This hydrogen will later be used as a fuel for PEMFC.

Hydrogen considered as an important energy carrier for future since it can be used in fuel cells to generate electricity through electrochemical reaction without releasing any pollution gases. Most hydrogen is produced from reforming process of natural gas and these natural gases are cost-effective feedstock which is consumed a non-renewable resource. Renewable sources such as biomass and bio-ethanol will be the most important source for production of hydrogen (Byrd et al., 2008). One of the attractive and feasible hydrogen productions from renewable resources is using glycerol. This is due to the fact that glycerol is indeed a by-product of the production of biodiesel, which utilizes vegetable oils or fats as a feedstock. Recently, the consumption of biodiesel for transportation has increased, resulting in an increased amount of glycerol generated (da Silva et al.,2009). Therefore, glycerol can be considered as a promising renewable source of hydrogen production.

Hydrogen can be produced from glycerol by many ways and one of the approaches is by using steam reforming process. Steam reforming is commonly used in producing hydrogen in the chemical industry. In this process, the substrate is reacted with steam in the presence of a catalyst to produce hydrogen, carbon dioxide, and carbon monoxide. The steam reforming process is highly endothermic. Reforming process mainly involves splitting of hydrocarbons in the presence of water and water gas shift reaction as given in the Equation (2.4) and (2.5).

1.2   Summary

As a whole, it can be concluded that fuel cell is one of the possible solutions in resolving issues relates with climate change since it is a new green technology that is about to develop. PEMFC can be classified as one of the type of fuel cell that operates at temperature between 80-130°C. There are two types of PEMFC which are LT-PEMFC and HT-PEMFC. Both type of fuel cell have its own advantages and disadvantages which also operate at different parameters.

1.3   Objectives

The main objective of this research is to develop a systematic framework of PEMFC for stationary application. Through this framework it is possible to conduct:

- Design and analysis of LT-PEMFC and HT-PEMFC.
- Determine the optimal condition for LT-PEMFC and HT-PEMFC.
- Compare the performances between LT-PEMFC and HT-PEMFC based on the optimal condition for LT-PEMFC and HT-PEMFC.
- Compare the performances of HT-PEMFC with water gas shift (WGS) reactor and without WGS reactor.

1.4 Scopes of the Work

Firstly, the systematic framework of PEMFC is developed where the step-by-step procedures of the framework are highlighted. In the framework, the fuel processing equipment for hydrogen production using glycerol as well as mathematical model needed for PEMFC is analyzed. The application of this systematic framework of PEMFC will be highlighted through three different case studies. The first case study is LT-PEMFC system with a steam reformer, a WGS reactor and a preferential oxidation (PROX) reactor. Second case study is HT-PEMFC system with only a steam reformer whereas for the last case study is HT-PEMFC system with a steam reformer and a WGS reactor. Based on these case studies, the optimal operating performances such as inlet temperature, hydrogen operation and reformate gas operation are determine in order to produces hydrogen efficiently. Lastly, based on the optimal operating condition, the performance for LT-PEMFC and HT-PEMFC systems for stationary application are compared for producing power of 3kW as well as the overall efficiency.

1.5 Main Contributions of the Works

According to latest analysis of PEMFC, the efficiency comparison between LT-PEMFC and HT-PEMFC with fuel processor is investigated without considering the effect of the operating parameter on the processes of the fuel cell. The operating parameters are important in determining the overall performance in term of efficiency. In this research, the performance of the integrated processors and PEMFC is determined through these parameters which include the inlet temperature, hydrogen operation and reformate gas operation.

1.6 Organization of Work

The structure of the remaining thesis is outlined as follows:

Chapter 2 provides the different type of fuel cell that has been developed in the latest green technology world. From this chapter, the advantages and the disadvantages of each fuel cell are summarized and compared. Furthermore, the application of PEMFC and different type of PEMFC is also elaborated and compared. The glycerol operation is reviewed in order to analyze the necessary equipment needed (for example WGS reactor, reformer etc.) in the glycerol operation for LT-PEMFC and HT-PEMFC applications.

Chapter 3 reviews on the integrated glycerol processor and PEMFC framework methodology. This is the step-by-step modeling procedure where it is capable to handle a wide range of the whole system problems. Here, each step is explained and the outcomes from each step are indicated. There were 5 steps involves in this model.

Chapter 4 is to discuss the result obtained from glycerol processor and PEMFC modeling. For glycerol processor modeling, all three cases are compared in term of the hydrogen composition produced based on different parameter used. In term of PEMFC modeling, the output power is calculated based on the current density and cell voltage obtained from the hydrogen composition produced. Finally, the overall system efficiency is obtained and compared between all cases. A software has been developed based on the proposed integrated glycerol processor and PEMFC methodology. In Chapter 5, the step-by-step implementation in the software is demonstrated using case study.

Chapter 6 is to conclude the framework that has been proposed.

2 LITERATURE REVIEW

2.1 Introduction

Fuel cell is one of a leading alternative technology that has the potential to be a future sustainable energy system with low CO_2 emission. A fuel cell has the potential to provide efficient, clean and quiet energy conversion that can reduce in greenhouse effect and local pollution (Edwards et al., 2008). As mentioned in the first chapter before, a fuel cell is an electrochemical apparatus that converts chemical energy to an electrical energy by using hydrogen or hydrogen fuel together with oxygen from air. The chemical energy relating to chemical reaction will change the fuel into water, electricity and heat without any fuel combustion (Peighambardoust et al., 2010). In summary, the reaction in fuel cell can be explained in following:

$$Anode: 2H_2 \rightarrow 4H^+ + 4e^- \tag{2.1}$$

$$Cathode: O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \tag{2.2}$$

$$Overall\ reaction: 2H_2 + O_2 \rightarrow 2H_2O \tag{2.3}$$
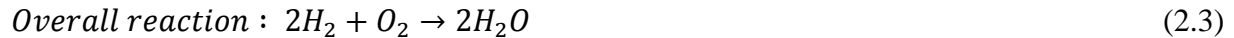
Based on the above equation, reaction occurs at anodes when the hydrogen atom split into electrons and catalyzed ions in order for the electrons to migrate to the cathodes through an external circuit and which finally generate electricity. Meanwhile, the ions will migrate through the electrolyte and reunite with electrons and oxygen at the cathode to produce heat and water. A schematic representation of fuel cell with overall reaction is shown in Figure 2.1.
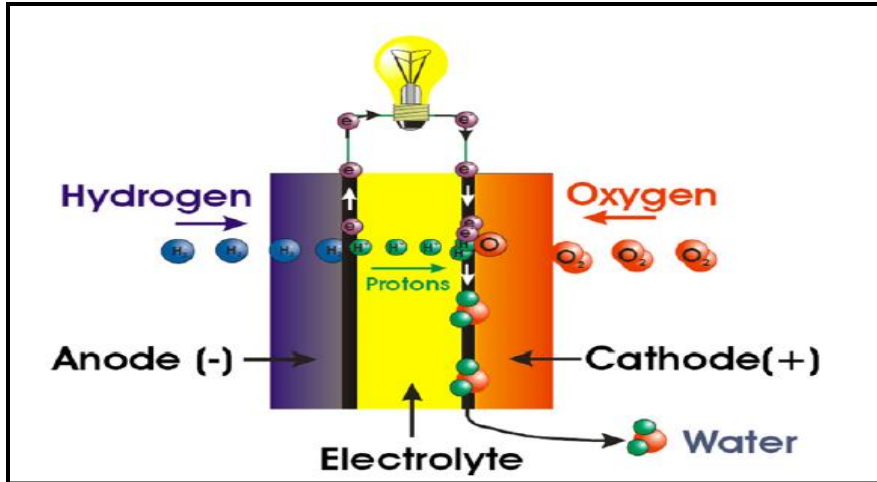
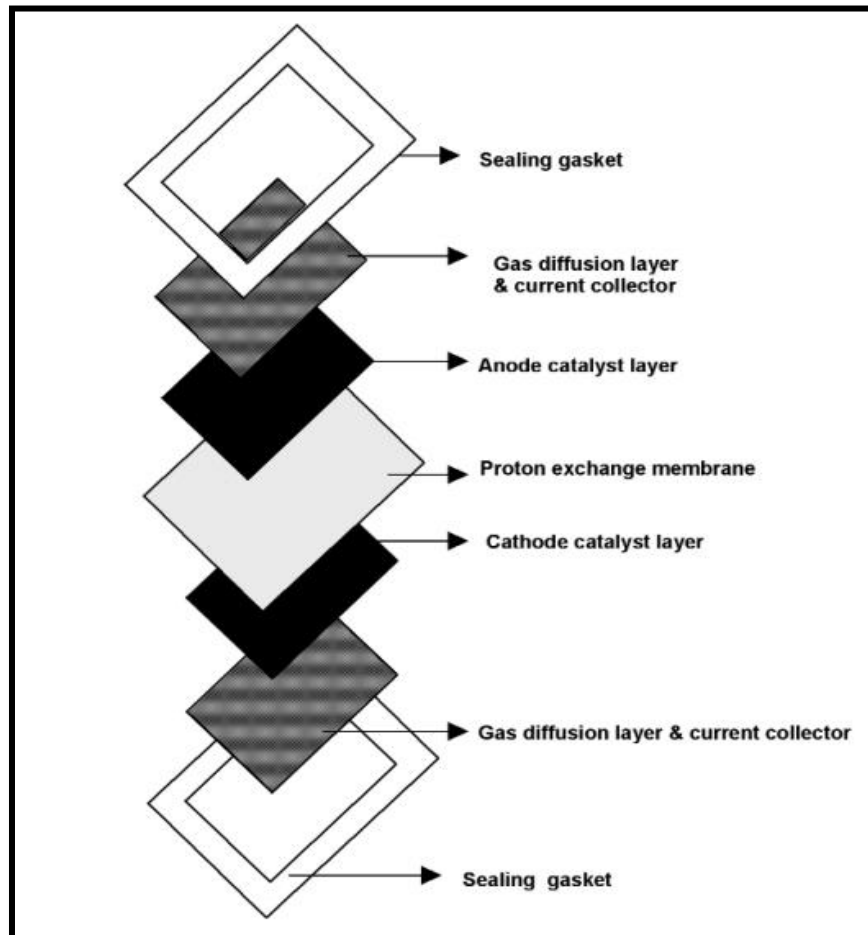Figure 2.1: Schematic design of fuel cell

Figure 2.2: Schematic design of Membrane Electrode Assembly (MEA)

In a fuel cell, the most important part will be the membrane electrode assembly (MEA). A complete form of MEA consists of seven layers: a proton exchange membrane (PEM), three-phase anode and cathode catalyst layers (CL), two gas diffusion layers (GDL) and two sets of sealing gaskets, as shown in Figure 2.2. Every layers of the MEA perform a different role however; if there is any change that occurs in any layer, it might effects the performance of the others.

For the first layer, a PEM from polytetrafluoroethylene (PTFE), support with perfluorinatedvinyl-polyether side chains which consist of sulphonic acid end groups. When these membranes become hydrated, the protons will later become highly mobile. These perfluorosulfonic-acid membranes were originally developed for the chlor-alkali industry and so the fuel cell environment is relatively insignificant. However, the need for high power densities has led to much thinner membranes than those developed for the chlor-alkali industry.

As for the second layer which is the CL, it consists of composite structure that is proton conducting polymer and carbon supported metal catalyst in both cathode and anode. Platinum is the best catalyst however, the choice of the anode catalyst and loading levels also depends on the fuel source. When operating with pure hydrogen, a small amount of Pt is required since the hydrogen oxidation reaction is superficial and the resulting over potential is small. If the fuel is reformate or methanol, then catalysts such as a PtRu, PtRh, or PtNi alloys can be used to minimize the effect of CO poisoning.

The GDL play the most critical and least appreciated role in MEA. The main purpose of GDL is to allocate the reactants from the gas flow channels uniformly along the active surface of the catalyst layer. In addition, the GDL has to ensure proper transport of product water, electrons, and heat of reaction. It also forms a protective layer over the very thin layer of the catalyst.

Lastly, the integrated seals and gaskets used as a compact design while performing its primary function of eliminating leaks and over-compression. The thickness and the compressibility of these gaskets dictate compression levels on the GDLs. Also, contaminants from the seals can poison the catalysts or degrade over time. So far, there has been little detailed accounting on the effects of various gaskets in the literature.

2.2 Different type of fuel cell

Fuel cell can be classified based on the used criteria to different methods which depend on the different parameter related to operating conditions and it structure. Generally, there are five different types of fuel cell (Acres, 2001).

Firstly, the alkaline fuel cell (AFC), which is a fuel cell with an alkaline solution electrolyte such as potassium hydroxide, and can be either mobile or retained in a matrix material. The AFC has excellent performance on hydrogen and oxygen compared to other candidate fuel cells. The major disadvantage of this fuel cell is that it is very susceptible to CO_2 and CO poisoning and hence its use with reformed fuels and air is limited.

Next is the phosphoric acid fuel cell (PAFC) with acidic solution electrolytes which has achieved the biggest commercial success, particularly in packaged combined heat and power modules for distributed generation applications. The main limited of the PAFC is the lower efficiency realized in in comparison with other fuel cells.

Thirdly, the proton exchange membrane fuel cell (PEMFC) also known as polymer electrolyte membrane fuel cell is very light and also potentially of high efficiency making it attractive for automotive applications. However, due to low temperature operation, catalysts (mostly platinum, Pt) are needed to increase the rate of reaction.

Meanwhile, the solid oxide fuel cells (SOFC) and the molten carbonate fuel cell (MCFC) are both high-temperature cells and can provide high-grade heat suitable for further power generation, making them capable to operate at higher efficiency too. Unfortunately, the high operating temperature of SOFC limits the materials selection and a difficult fabrication processes results. In addition, the ceramic materials used for the electrolyte exhibit a relatively low conductivity, which lowers the performance of the fuel cell. As for MCFC, the main disadvantage is the forming of very corrosive electrolyte which impacts on the fuel cell life, as does the high temperature operation (Nantes and Bp. 2007). Table 2.1 summarizes the operating and applicable properties of five main types of fuel cells (Peighambardoust et al., 2010)

Table 2.1: Operating and applicable properties of five main types of fuel cells.

Type of fuel cell	Operating temperature (^{o}C)	Power density (mW/cm^2)	Fuel efficiency (Chem. to elec)	Lifetime (hr)	Capital cost ($/kW)	Fuel
AFC	60-90	100-200	40-60	>10 000	>200	High purity H$_2$
PAFC	120-220	200	55	> 40 000	300	H$_2$, CO
PEMFC	80-130	350	45-60	>40 000	>200	High purity H$_2$
SOFC	800-1000	240	55-65	>40 000	1500	H$_2$, CO, CH$_4$
MCFC	600-700	100	60-65	>40 000	1000	H$_2$, CO

Most commercialize work has focused more on PEMF and SOFC technologies. In particular, the automobile industry favors PEMFC over other fuel cell classifications, and stationary power generation seems to favors SOFC. Historically, AFC technology has been extremely important in space exploration. Indeed, AFC system is still in use on every space shuttle. PEMFCs have a many advantages compared to other fuel cells. This includes the low operating temperature, short start up time, high efficiency and good power density

2.3 Analysis method for PEMFC

There are many similarities and differences between PEMFC stack and a battery (See Table 2.2). In simple imagination, fuel cell can be describe as a battery in which its fuel and oxidant are stored externally instead of internally that is used in batteries. Both produces direct current electrical power as the output energy. For example, a series of identical batteries can produce a higher voltage while maintaining the output current of a single cell whereas a parallel of identical batteries produce higher current while maintaining the voltage of a single cell. These concepts are also applied for a collection identical fuel cell. Usually, individual fuel cells are arranged in series so that the voltage is maximized and current is held to minimum values.

Table 2.2: Comparison between PEMFC and batteries

	PEMFC stack vs. battery
Similarities	1. Both produce DC electrical power. 2. Voltage "sags" at high current draw. 3. Higher voltage is achieved by arranging electrochemical cells in series. 4. Both use an appropriate electrolyte layer to separate the anode and cathode.
Differences	1. Fuel and oxidant are internal to batteries: external to PEMFC stacks. 2. Batteries self-discharge upon storage; PEMFC stacks do not self-discharge. 3. PEMFC stacks require auxiliary components to supply a flow of air and hydrogen to the stack; batteries are completely self-contained.

PEMFC is commonly consists of a very simple features that include a water-swollen cation exchange membrane electrolyte layer that separates a catalyzed anode from a catalyzed cathode. Pt on carbon is the catalyst used for both cathode and anode with loading of about 0.1 to 0.2 mg Pt/cm^2 on the anode and 0.2 to 0.3 mg Pt/cm^2 on the cathode. High Pt loading on the cathode is due to the slow reaction that occurs at the cathode (O_2 reduction) compared to reaction at anode (H_2 oxidation) The higher Pt loading on the cathode is because the cathode reactions (O_2 reduction) are slow reactive to the anode action (H_2 oxidation). This combination of electrochemical catalyst deposited onto the electrolyte layer, also known as MEA.

As mention before, PEMFCs have a many advantages which includes the low operating temperature, short start up time, high efficiency and good power density (Costamagna and Srinivasan. 2001). PEMFC operates at temperature 80-130°C which can be considered as low and save operating condition in compared with other fuel cells mention. As for operational efficiency, it is below the theoretical value of 65% but it is more than twice the typical of combustion engines with high sensitivity to operating conditions. Since electrochemical reaction is very sensitive to the temperature change, temperature plays an important role in the efficient and safe operation of PEMFC. As the temperature gets too high, the efficiency of PEMFC will be reduced because of the increase of vapor pressure and membrane water loss. On the other hand, low operating temperature will decrease the electrochemical reaction rate and increase the ohmic resistance (Li et al., 2014). Next is power density. Power density values of PEMFC are around 2-3 kW/m^2. Higher values (4-6 kW/m^2) can be obtained if new membranes and more active cathodes develop. High power density reduces the fuel cell cost, but also increases energy losses and reduces efficiency. An optimum power density minimizes the energy cost, depending on the cost of hydrogen and the fuel cell.

According to previous research, PEMFC has a serious water management challenge and requires pure hydrogen fuel with no CO content to avoid catalyst poisoning (Authayanun et al., 2013). Water management in PEMFC requires careful consideration because it affects the overall system power and system efficiency (Zhang et al., 2006) . Improper water management can lead to electrodes flooding and membrane dehydration. For PEMFC that operates below 100°C, a lack of water in the membrane and gas diffusion electrode decreases their proton conductivity and increases the cell resistance at the same time. Too much water in the cathode can causes "flooding", that limits oxygen transport through the porous gas diffusion electrode. On the other hand, operating a cell above 100°C may reduce potential problems associate with flooding but they can causes issues associated with dehydration.

Water flooding are mainly due to the increase of excess water which can happen at both anode and cathode side of membrane. Flooding leads to instant increase in mass transport losses, particularly at the cathode. Thus, it causes the transport rate of the reactants to the catalyst active site to be reduces significantly.

As for dehydration of membrane, it occurs at the anode side. Three main reasons that may causes membrane dehydration are firstly due the sufficient humidification that cannot be maintained while feeding the cell with low-humidified or dry reactant gas stream. Next is the water formation reaction at the cathode alone is not able to tolerate the lack of water, especially at high operating temperature and lastly is due to the electro-osmotic drag that can also lead to dehydration condition at the anode.

In term of hydrogen fuel, from technology point of view, it is unrealistic to obtain a high purity of hydrogen because high purity hydrogen may not be readily available. It may be preferential to use hydrogen rich gases as fuel. This can be prepared using reforming reactions, such as the water gas shift (WGS) reactor, preferential oxidation (PROX) reactor, membrane separation or methanol oxidation from various organic fuels in order to "stored" hydrogen. As suggested before, reformate gas from fuel processors is a promising alternative hydrogen source for PEMFC whereby glycerol is considered as a potential feedstock for producing hydrogen and one of the most attractive fuels for sustainable development of hydrogen production (Slinn et al., 2008).

Reforming process mainly involves splitting of hydrocarbons in the presence of water and WGS reaction as given below:

$$C_nH_{2n+2} + nH_2O \rightarrow nCO + (2n+1)H_2 \tag{2.4}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{2.5}$$

The first step is highly endothermic which requires more heat than it evolves from water–gas shift reaction. Therefore, overall steam reforming is an endothermic process. Thermodynamically, steam reforming process favors high temperatures and low pressures. The factors affecting the production of hydrogen from steam reforming process are temperature, pressure, water to Glycerol Feed Ratio (WGFR), feed reactants to inert gas ratio and feed gas rate. It has been observed that these factors hold a key role in order to have a high hydrogen yield and a good glycerol conversion.