# DE[illegible]ACH FOR ONLINE MANAGEMENT OF PEM FUEL CELLS FOR RESIDENTIAL APPLICATION

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# ABSTRACT

This thesis demonstrates a new intelligent technique for the online optimal management of PEM fuel cells units for onsite energy production to supply residential utilizations. Classical optimization techniques are based on offline calculations and cannot provide the necessary computational speed for online performance. In this research, a Decision Tree (DT) algorithm is employed to obtain the optimal, or quasi-optimal, settings of the fuel cell online and in a general framework. The main idea is to employ a classification technique, trained on a sufficient subset of data, to produce an estimate of the optimal setting without repeating the optimization process. A database is extracted from a previously-performed Genetic Algorithm (GA)-based optimization has been used to create a suitable decision tree, which was intended for generalizing the optimization results. The approach provides the flexibility of adjusting the settings of the fuel cell online according to the observed variations in the tariffs and load demands. Results at different operating conditions are presented to confirm the high accuracy of the proposed generalization technique. The accuracy of the decision tree has been tested by evaluating the relative error with respect to the optimized values. Then, the possibility of pruning the tree has been investigated in order to simplify its structure without affecting the accuracy of the results. In addition, the accuracy of the DTs to approximate the optimal performance of the fuel cell is compared to that of the Artificial Neural Networks (ANNs) used for the same purpose. The results show that the DTs can somewhat outperform the ANNs with certain pruning levels.

# ABSTRAK

Thesis ini menerangkan satu kaedah baru dalam pengurusan optimum unit *PEM Fuel Cell* secara online bagi menghasilkan sumber tenaga untuk kegunaan di sebuah kediaman. Pengiraan secara manual teknik pengoptimalan klasik telah menyebabkan ianya tidak dapat memberikan satu proses pengiraan yang cepat seperti yang dikehendaki dalam proses pelaksanaan secara *online.* Dalam kajian ini, satu algoritma *Decision Tree (DT)* telah digunakan dalam rangka untuk mendapatkan satu ketetapan optimum atau kuasi-optimum *FC* untuk digunakan secara *online.* Matlamat utama adalah untuk menggunakan teknik klasifikasi dalam melatih satu *subset* data yang mencukupi bagi menghasilkan satu anggaran ketetapan optimum tanpa mengulangi semula proses pengoptimalan. Satu pengkalan data yang diambil daripada proses pengoptimalan yang dilaksanakan terlebih dahulu dengan menggunakan *Genetic Algorithm (GA)* telahpun digunakan bagi menghasilkan satu *DT* yang bersesuaian dalam konteks merangka satu generalisasi bagi semua hasil proses optimalisasi. Pendekatan ini telah memberikan satu kelonggaran dalam mengubah ketetapan *fuel cell* secara *online* berdasarkan pemerhatian ke atas variasi kadar dan beban permintaan. Keputusan pada tahap operasi yang berbeza juga turut dipamerkan bagi mengesahkan ketepatan yang tinggi bagi teknik generalisasi yang dicadangkan. Ketepatan *DT* telah pun diuji dengan menilai tahap kesilapan relatif berdasarkan nilai optimum. Seterusnya, kebarangkalian untuk mengurangkan cabang *DT* telahpun dikaji dalam konteks untuk memudahkan strukturnya tanpa menjejaskan ketepatan menghasilkan keputusan. Selain itu, ketepatan *DT* untuk menghasilkan penghampiran optimum penggunaan *FC* juga turut dibandingkan dengan *Artificial Neural Network (ANN)*, yang juga digunakan bagi tujuan yang sama. Keputusan walaubagainamanpun menunjukkan *DT* mempunyai prestasi yang baik berbanding *ANN* pada tahap pengurangan cabang *DT* yang tertentu.

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## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| FC | - | Fuel Cell |
| PEM | - | Proton Exchange Membrane |
| PEMFC | - | Proton Exchange Membrane Fuel Cell |
| ANN | - | Artificial Neural Network |
| DT | - | Decision Tree |
| AC | - | Alternating Current |
| DC | - | Direct Current |
| DG | - | Distributed Generation |
| NASA | - | National Aeronautics and Space Administration |
| AFC | - | Alkaline Fuel Cell |
| PAFC | - | Phosphoric Acid Fuel Cell |
| MCFC | - | Molten Carbonate Fuel Cell |
| SOFC | - | Solid Oxide Fuel Cell |
| DMFC | - | Direct Methanol Fuel Cell |
| SPFC | - | Solid Polymer Fuel Cell |
| CHP | - | Combined Heat and Power |
| EPRI | - | Electric Power Research Institute |
| MATLAB | - | MATLAB software package |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| KOH | - | Potassium Hydroxide |
| $H_2O$ | - | Water |
| $O_2$ | - | Oxygen |
| OH | - | Hydroxide |
| $H_2$ | - | Hydrogen Gas |
| $H^+$ | - | Ion Hydrogen |
| $e^-$ | - | Electron |
| CO | - | Carbon Monoxide |
| $CH_3OH$ | - | Liquid Methanol |
| $H_2SO_4$ | - | Sulfuric Acid |
| $^oC$ | - | Degree Celsius |
| W | - | Unit Watt |
| kW | - | Kilo Watt |
| % | - | Percent |

# LIST OF APPENDICES

# CHAPTER I

# INTRODUCTION

## 1.1 Overview

With the increasing demand on electrical energy, driven both by rapidly evolving deregulatory environments and by market forces, distributed generation can offer an important support to the conventional centralized power sources. It is certainly true that government public policies and regulations have played a major role in the rapidly growing rate at which distributed generation is penetrating the market. However, it is also true that a number of technologies have reached a development stage allowing for large-scale implementation within existing electric utility systems [1]. Therefore, distributed generation is predicted to play a significant role in electric power systems in coming years [1-3]. A study reported by Electric Power Research Institute (EPRI) indicates that, about 25% of the new power generation will be in distributed mode by the year 2010 [4].

Distributed generation technologies can be categorized as renewable and non-renewable distributed generation. However, distributed generation should not only be confused with renewable generation. Meanwhile, the need to overcome air pollution, global warming, fuel shortages, and problems with nuclear power in densely populated urban has motivated the researchers to investigate the advent of distributed generation in electric power production industries. In fact, some distributed generation could, if fully deployed, significantly contribute to reduce air pollution problems [5-6].

Among the distributed electricity production, fuel cells contribute significantly to the cleaner environment. They produce dramatically fewer emissions, and their byproducts are primarily hot water and carbon dioxide in small amounts [5-7]. Fuel cells provide a promising technology that would be utilized either integrated into distribution systems or in the stand-alone mode. Among the different types of fuel cells, the proton exchange membrane (PEM) fuel cells have approved good features especially for low-capacity applications. One main characteristic of this fuel cell is its low operating temperature, which is about 80°C [8]. This means that it warms up quickly and does not require expensive containment structures. Hence, they are candidates to be used in a wide field of applications because of their quick start-up characteristics and high power densities, which reduced the required accommodation place.

One of the important applications of distributed generating units, where fuel cells are particularly suitable, is the utilization of small-modular commercial or residential units for onsite service. In this case, the capacity of the fuel cell can be chosen to cover most of the load most of the time, where the surplus/shortage is exported to/imported from the main grid system [9].

Despite the benefits offered by fuel cell, the high cost of the electricity produced in the fuel cells represents the main barrier for the unit to be in competition with other energy sources. Although the capital cost forms the major part of the energy price, reduction of operating cost may be considerable. A significant reduction can be achieved if the appropriate setting of the unit is chosen to get optimized operation [10]. Therefore, the operation of the fuel cell has to be properly managed to reduce the operating cost to the minimum level. This reduction in the operating cost can significantly contribute in decreasing the total energy price and improving the economic feasibility of these units.

The management of fuel cells can be accomplished by optimizing the setting of these units depending on the operating conditions to minimize the overall operating cost. Obviously, the optimized settings will be valid only for certain operating conditions and have to be recomputed after each variation. However, the optimization process, which can be carried out only in the offline mode, is a complicated and a time-consuming task, and hence requires high computational capabilities. It is important to standardize a simple management method, which is probably adapted by the manufacturer and has to be online and locally updated by the operator. Therefore, a generalization framework has to be applied to extend the optimization results in a generic form. The decision-tree methodology can be employed as a nonparametric learning technique, which is capable of deducing solutions for new unobserved cases.

## 1.2 Background and Motivation

As a result of the energy crisis, renewed considerations in the energy sector have among other things significantly revived interest in fuel cells. Especially, in the scope of systems concerned with hydrogen as a fuel, the discussion on utilising the fuel cells as the future power production and vehicular power plants sounds very promising.

Fuel cells are a fast growing technology that is ready to impact many different sectors of industry. Full cells are now on the verge of being introduced commercially, revolutionizing the way we presently produce power [5].

Fuel cells are clean, highly efficient, scalable power generators that are compatible with a variety of fuel feed stocks and can therefore be used in an assortment of power generation applications [5-7]. In particular, fuel cells have a distinct advantage over other clean generators such as wind turbines and photovoltaic in that they can produce continuous power as long as they are supplied with a constant supply of hydrogen.

The ability to produce continuous power makes fuel cells well suited for supporting critical loads for security applications. Another advantage of fuel cells is that the power house of the system, the fuel cell stack, does not contain any moving parts, which typically lead to mechanical breakdowns in traditional generators. In theory, and as the technology matures, fuel cells may become more reliable than conventional engines. Also, in addition to low noxious air emissions, fuel cells can produce significant amounts of power (electrical and thermal) with much less noise than standard generators [8]. These factors are viewed favorably when siting fuel cell systems in populated areas and even inside facilities.

However, fuel cells are not the perfect solution to the world's energy needs. There are several obstacles that need to be overcome before widespread use of fuel cells occurs. In this case, the biggest hurdle for fuel cells is cost. Although some fuel cell systems are in use today, very few are currently cost effective. Therefore, it is necessary to reduce the energy price to a feasible level in order to bring them to competition with other energy sources. In order to provide a cost effective, both the capital cost and operating costs must be reduced. Hence, optimal management of electrical and thermal power in fuel cells can significantly contribute in achieving the required economical operation [11].

## 1.3 Research Goals and Approach

In this work, the project has been focused on developing a new online optimal approach to manage the daily operation of PEM fuel cells for residential applications by using intelligent technique known as Decision Trees. A novel two-phase approach to manage PEM fuel cells for residential applications by using Artificial Neural Network (ANN) was previously suggested by a member in the department. The same database which was used in training and testing ANN has been used in formulating and testing the trees. The database was previously extracted from the offline optimization process at different load demands and natural gas and electricity tariffs by using Genetic Algorithm (GA).

In order to achieve the research goal, six steps are applied. First, basic concepts of the fuel cell technology including their types, characteristics, applications, advantages and disadvantages need to be reviewed. Next, the economic model of the residential system supplied by a fuel cell unit including the electrical and thermal relations should be clearly understood. Thirdly, the results of the optimization process are reviewed in such that to assess the achieved reduction in the operating cost and the impact of different decision variables on the optimal settings. Then, in predicting the target response (output), a decision tree has been created using the MATLAB toolbox based on the database extracted from the optimization process. The capability of the decision tree to redefine the optimal or quasi-optimal settings of the fuel cell using new unobserved cases is evaluated afterwards. Lastly, the structure of the decision tree is reduced to simplify the structure as possible taking into account keeping the accuracy of the results close to that of the full tree. The performance of the reduced trees could also be analysed and compared with all different management methods.

## 1.4 Thesis Outline

This thesis consists of six chapters including this chapter. The content of each chapter is outlined as follows:

**Chapter 2** introduces a background study related to fuel cells. An overview of fuel cells and its working principles as well as all types, benefits, obstacles, and applications of fuel cells will be covered.

**Chapter 3** covers the literature review, background, previous research done by other researchers in the same area and relevant issues related to management of PEM fuel cells for residential applications. It includes the description of optimal management of fuel cells for residential application and generalization of the optimization process by using Artificial Neural Network (ANN).

**Chapter 4** describes the proposed of a Decision Tree-Based approach for online management of PEM fuel cells for residential application. The configuration of the full and pruned decision trees including the training and testing are described in detail.

**Chapter 5** presents the results obtained from the proposed approach. Results from the calculation of the cost between the optimal target and different management methods are also discussed and compared in order to validate the performance and capability of the proposed method.

**Chapter 6** provides conclusions and summary of the work undertaken and highlights the contribution of this thesis as well as the recommendations for future research interest.

# CHAPTER II

# OVERVIEW OF FUEL CELLS

## 2.1 Introduction

Since the $19^{th}$ Century was the century of the steam engine and the $20^{th}$ Century was the century of the internal combustion engine, it is likely that the $21^{st}$ Century will be the century of the fuel cell [14-16]. Full cells are now on the verge of being introduced commercially, revolutionizing the way we presently produce power. Fuel cells can use hydrogen as a fuel, offering the prospect of supplying the world with clean, sustainable electrical power.

This chapter will introduce a background study related to fuel cells. To start with, an overview of fuel cells and its working principle is presented. Then, all types, benefits, obstacles, and applications of fuel cells will be introduced.

## 2.2 Overview of Fuel Cells

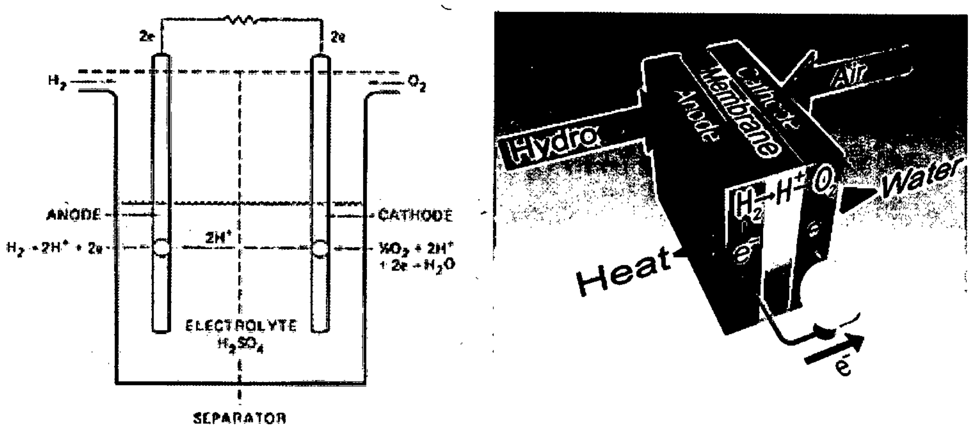
Fuel cells are being considered as one of the promising candidates for automotive propulsion, residential and portable power generation applications due to its high efficiency and extremely clean processes [14-15]. Founded by an amateur .physician, William Grove, in 1839, the technology laid dormant for 120 years before fuel cell again resurfaced when NASA demonstrated potential fuel cell applications in 1960s [17].

However, early research has revealed in the technological and economic constraints on fuel cells development which then has given an impact to the mass production of fuel cells. Nowadays, due to the need to overcome global warming hypothesis coupled with concerns about air pollution, fuel shortages, and problems with nuclear power in densely populated urban, fuel cell has become a serious option for a widespread introduction. As a result, it has motivated the researchers to investigate the utilization of fuel cells in various applications.

Fuel cells can be thought of as continuously recharging batteries. Both batteries and fuel cells operate by using a chemical reaction to produce electricity. However, unlike the battery the fuel cell does not run down or require recharging. It will produce the energy in the form of electricity and heat as long as fuel is supplied [17].

### 2.2.1 Fuel Cells Principles of Operation

There are several types of fuel cells, which each operates a bit differently. But in general terms, the principle of operation is almost the same. A fuel cell consists of two electrodes sandwiched around an electrolyte as illustrated in Fig. 2.1 [19].




(a) (b)

Fig. 2.1 Operation of the fuel cell. (a) A simple fuel cell (b) General construction features of fuel cell

The fuel, which is hydrogen, is bubbled across the surface of one electrode while the oxidant (oxygen) from ambient is bubbled across the other electrode. When the electrodes are electrically connected through an external load, the hydrogen dissociates on the catalytic surface of the fuel electrode will form hydrogen ions and electrons as presented in (2.1).

$$2H_2 \Rightarrow 4H^+ + 4e^- \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1)$$

While the hydrogen electrochemically oxidized on the anode, the oxidant is electrochemically reduced on the cathode surface, represented by (2.2).

$$O_2 + 4H^+ + 4e^- \Rightarrow 2H_2O \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.2)$$

The ions created by the electrochemical reaction will migrate through the electrolyte to cathode while the electrons take different path to cathode since the membrane will not allow the electrons to pass through it. Instead, the electrons will travel through an external circuit to get to the other side, and delivers its energy to a load along the way before reunited at cathode with hydrogen and oxygen to form molecule of water. The backbone of the process which shows the reaction of the hydrogen and oxidant is presented in (2.3).

$$2H_2 + O_2 \Rightarrow 2H_2O \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.3)$$

In the case of electrochemical reaction taking place in the fuel cell, part of the energy is released in the form of thermal energy when the fuel is oxidized. This thermal is called *heat of reaction* [20]. The whole process, represented in Fig. 2.2, takes place naturally, but reactions occur slowly limiting the power of fuel cells [17]. To facilitate a faster reaction, a catalyst is used. The catalyst is usually a rough and porous powder which thinly coats carbon paper or cloth so that a maximum surface area can be exposed to the hydrogen or oxygen [18].

Meanwhile, the type and chemical properties of the electrolyte used in the fuel cells will determine the operating characteristic of the fuel cells. Because of the differences in some of the operating characteristics, fuel cells are classified in different types, mostly named after the electrolyte used.

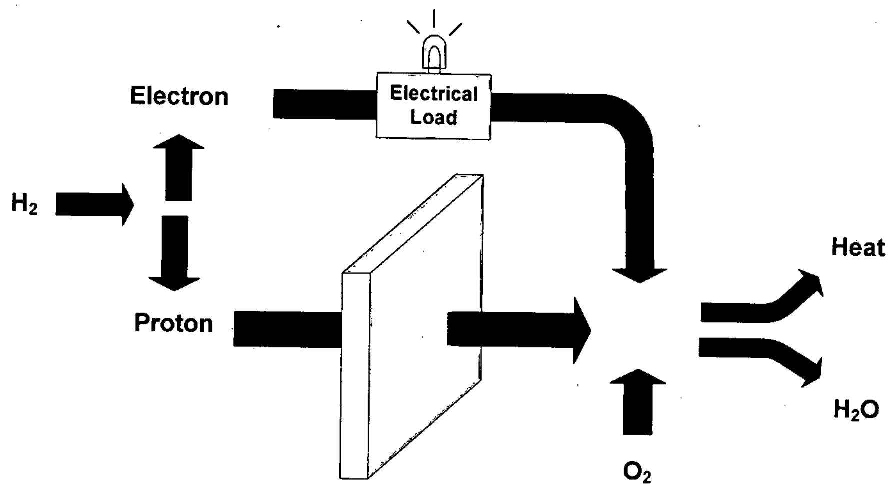



Fig. 2.2 The whole principle of operation of fuel cells

### 2.2.2 Types of Fuel Cells

As a result of the different operating temperature, fuel cells are classified into five types: Alkaline, Proton-Exchange Membrane, Phosphoric Acid, Molten Carbonate, Solid Oxide and Direct Methanol Fuel Cells. These six fuel cell types are significantly different from each other with respect to operating temperatures, materials of construction, and slightly different interactions, but the similar net chemical reactions are backbone of all of them. Because of the differences in some of the operating characteristics, the different types of fuel cells are suited for different potential applications. The following will discuss a brief overview of characteristics, advantages and disadvantages of the main types of fuel cells.

#### 2.2.2.1 Alkaline Fuel Cell (AFC)

Alkaline Fuel Cell (AFC) was the first modern fuel cell to be developed, beginning in 1960 when NASA used it on space missions to produce electricity and water to the astronauts [18]. AFC normally operates on compressed hydrogen and oxygen and use a liquid solution of potassium hydroxide (KOH) in water as an electrolyte. The electrolyte is soaked in a matrix (usually asbestos) that wicks the electrolyte over the entire surface of the electrodes [17]. This will allow the hydrogen to pass through it, while the electrons will be diverted to flow through an external circuit as shown in Fig. 2.3. Equations (2.4, 2.5, and 2.6) represent the anode reaction, the cathode reaction, and the overall reaction of AFC respectively.

Anode : $H_2 + 2(OH)^- \Rightarrow 2H_2O + 2e^-$ ........................ (2.4)

Cathode: $\frac{1}{2} O_2 + H_2O + 2e^- \Rightarrow 2(OH)^-$ ........................ (2.5)

Overall: $H_2 + \frac{1}{2} O_2 \Rightarrow H_2O$ ........................ (2.6)

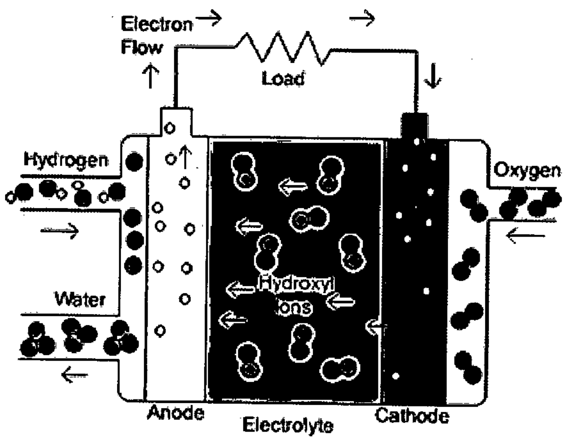



Fig. 2.3 Alkaline Fuel Cell (AFC) [18]

The sluggish of a fuel cell is defined by cathode reaction as the limiting reaction because it takes more time to react than the anode reaction. However, in the AFC, since the potassium hydroxide soaked in a matrix, the cathode reaction occurs much faster than other types of fuel cells, which enhances its overall performance and its electrical response. The lower operating temperature, between 70° - 90° C gives a quick- start advantage for AFC, which can achieve power generating efficiencies up to 70 percent [17-18].

AFCs have problems with carbon dioxide, which it can contaminate the fuel cell and thus ruin the entire fuel cell. Thus, AFCs cannot use normal outside air to provide oxygen, where it has to be employed with a system that can remove the carbon dioxide from the intake air stream. Also, the life span for this fuel cell type is short due to the use of a corrosive electrolyte, which gradually wears out its parts and drive up the operating cost [16]. AFC is believed to be not cost-effective for commercial application since the use of expensive catalyst such as platinum also contributes to a higher cost. However, developments in alternate cell design could generate renewed interest in this fuel cell type for commercial use.

### 2.2.2.2 Proton Exchange Membrane Fuel Cell (PEMFC)

Proton Exchange Membrane Fuel Cell (PEMFC) is also known as the solid polymer fuel cell (SPFC) or polymer electrolyte membrane fuel cell. PEMFC has gained a lot of attention in the last few years as one of the most promising and certainly the best known of the fuel cell types [16-18]. PEMFC works with a solid polymer electrolyte that allows protons to be transmitted from one side to other as represented in Fig. 2.4. PEMFC requires pure hydrogen and oxygen as inputs, though the oxidant may also be ambient air, and these gases must be humidified. Abovementioned equations (2.1, 2.2, and 2.3) represent the anode reaction, the cathode reaction, and the overall reaction of PEMFC respectively.

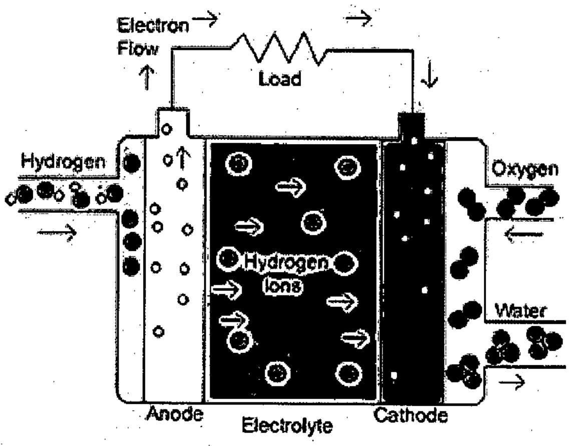



Fig. 2.4 Proton Exchange Membrane Fuel Cell (PEMFC) [18]

These fuel cells operate at relatively low temperature, around 80°C, hence allows them to start quickly (less warm-up time), which makes them particularly suited for transportation and residential applications [8, 16-17]. These fuel cells deliver high power density and offer the advantages of low weight and volume which reduced the required accommodation place compared to other fuel cells. Like other fuel cells, the PEMFC is very efficient, where a stack operating on hydrogen and pressurized air at typical current conditions exceeds 50 percent [15-17].

The use of solid electrolyte adds even more benefits to PEMFC since lower corrosion occurs because PEMFCs utilize a solid non-corrosive solid electrolyte [17]. The solid electrolyte also does not require the liquid management like other liquid electrolytes, which it does not leak or crack and offers further safety to be used at residential and vehicles. This has continued to enable them to stay running for extremely long periods of time and have a large overall life [17].

However, the use of platinum as a catalyst is a significant disadvantage because of the cost of platinum. The platinum catalyst is also extremely sensitive to carbon monoxide (CO) poisoning. In order to compensate for this, the design becomes more complicated, adding cost to the systems. Further reduction of platinum is needed to bring the cost of PEMFC into a range that is competitive with other current technologies. Since it has been targeted as a replacement for conventional internal combustion engine [16], research is very active and cost reduction is expected as the technology matures with experience and a wider market penetration.

#### 2.2.2.3 Phosphoric Acid Fuel Cell (PAFC)

Phosphoric Acid Fuel Cell (PAFC) is one of the most mature cell types and the first to be used commercially, where it has been under development for more than 20 years [15]. PAFC uses liquid phosphoric acid as the electrolyte while its structure resembles the PEMFC as illustrated in Fig. 2.5. The chemical reactions that take place in the cell are represented by equations (2.7, 2.8 and 2.9), respectively.

Anode: $H_2 \Rightarrow 2H^+ + 2e^-$ ......................... (2.7)

Cathode: $\frac{1}{2} O_2 + 2H^+ + 2e^- \Rightarrow 2 H_2O$ ......................... (2.8)

Overall: $H_2 + \frac{1}{2} O_2 \Rightarrow H_2O$ ......................... (2.9)