SAVONIA

Fuel Cells in Energy Production

Xiaoyu Huang

Bachelor’s Thesis

____. ____. ________ ____

Field of Study Savonia University of Applied Sciences			
DegreeProgramme Degree Programme in Industrial Management			
Author(s) Xiaoyu Huang			
Title of Thesis Fuel Cells in Energy Production			
Date		Pages/Appendices	
Supervisor(s) Jorma Honkanen			
Client Organisation/Partners			

Abstract

The purpose of this thesis is to study fuel cells. They convert chemical energy directly into electrical energy with high efficiency and low emmission of pollutants. This thesis provides an overview of fuel cell technology.The basic working principle of fuel cells and the basic fuel cell system components are introduced in this thesis.

The properties, advantages, disadvantages and applications of six different kinds of fuel cells are introduced. Then the efficiency of each fuel cell is provided. The EFOY 1600 fuel cell experiment shows that fuel cells are not affected by the temperature. Another experiment of Hydrocar shows that the efficiency of fuel cell is almost the same at different voltages. Finally, the history and future of fuel cell represent the development of fuel cells in China and foreign countries.

The results show that the fuel cell can convert chemical energy into electrical energy without combution. Some energy is lost in the form of heat during the pocess, however, this heat can be utilized for heating or cooling, and it is not wasted.

Keywords
Fuel cell, efficiency,EFOY

Public

CONTENTS

1 1 INTRODUCTION

Energy is the basis of economic development, there is no modern civilization without the development of energy industry. Humans have been conducting efforts to improve high efficiency use of energy resources. There has been a number of revolutionary changes on the way to use energy during the history, from the original steam engine to internal combustion engines. The transformation of using energy has promoted the development of modern civilization in each time.

Fuel cells are energy devices which transfer chemical energy stored in the fuel and oxidant directly into electrical energy. When fuel cells are continuously supplied fuel and oxidant, electricity can be made constantly. According to the different electrolytes, fuel cells can be divided into several types, such as alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), and proton exchange membrane fuel cell (PEMFC), etc. Fuel cells can supply electrical power in centralized or individual ways have advantages of high efficiency of energy conversion, clean, no pollution, low noise, modular structure. (Liisa Heikinheimo2009, 212)

Fuel cells are a significant technology for households and commercial buildings, plus, they are supplemental or auxiliary power to support cars, trucks and aircraft systems. Besides, fuel cells are the power for personal and commercial transportation of new power generation closely tailored to meet growth in power consumption. These applications will be used in a large number of industries worldwide.

A large power plant such as thermal power plant can obtain high efficiency. However, giant units of the power plant are affected by various limitations, so customers can achieve power from an electrical grid in which the power plant makes concentrated power. The big unit's inflexible generation cannot adapt to the family's needs, besides, the grid sometimes goes to the peak or downturn with the user's electrical load change. In order to adapt to the change of electrical load, a water pumped-storage plant has been built for emergency, but it will reduce the benefit of the grid. The traditional coal-fired power plant's burning energy consumes nearly 70% in boilers and steam turbine generators, and a great deal of hazardous substances is emitted out. However, fuel cells transfer chemical energy into electrical energy, without burning and rotating components. Theoretically energy conversion closes to 100%. The actual power generation efficiency can reach 40% - 60%, energy can be transferred directly into enterprises, hotels, families. The comprehensive energy efficiency can reach 80%, and the devices are very flexible. (Zhitong 2004, 34)

Fuel cells are called the fourth electricity power generation after water, nuclear power generation devices. People from the international energy area forecast that fuel cell is the most attractive power generation in the 21st century. There is an important meaning of the development of fuel cell power. It will bring huge economic benefits while combining traditional large units and power grid. (Zongqiang 2005, 28)

Nowadays, the application of fuel cell can be found everywhere in the world. It is related to people's everyday life, for instance, in the electrical products and cells in the vehicles. Fuel cells are used widely in large factories, hotels because of the convenience and safety. There is a bicycle which uses fuel cell as its electrical power which is very popular in China.

In this thesis, the basic knowledge of fuel cells is introduced. The properties, advantages, disadvantages, possible applications will be presented in the second part of my thesis. There are two experiments shown in the thesis, one is EFOY fuel cell, the other is a fuel cell micro car. Experiments are quite necessary for readers to understand how a fuel cell works. There are some calculations and analyse shown in the experimental part. The history and forecasting of the fuel cell will come out in the second part which indicates how important the fuel cell is. There are two kinds of experiments in the thesis. One is the testing of EFOY 1600 fuel cell which is using a fuel cell to load a battery. The other one is fuel cell car which is using a fuel cell to make fuel according to dissolve water.

2 HISTORY AND FUTURE OF FUEL CELLS

2.1 Fuel cells in China

The research and development of fuel cell have made a considerable progress in recent years in China, especially proton exchange membrane fuel cell (PEMFC), which reached close to the advanced world level. Certain progress of MCFCs and SOFCs has also been made during these years. In general, the fuel cells in China compared with foreign countries are still in a scientific research phase of low level. Developed countries have already set large fuel cell development projects as the key research projects and have achieved a number of significant achievements. Moreover, different rank of fuel cell power plants have been built instead of traditional generator and internal combustion engines which are widely used in power generation and car power. Increasing investment, boosting fuel cell power generation technology research should be taken as the first step in China. (Zhitong 2004, 235)

The fuel cell technology is one of the major development projects in China's ninth five-plan period. In order to make China's fuel cell development close to the international level, the PEMFC, MCFC, and SOFC technologies are the main subjects to be carried out. The 5 kW PEMFC is listed as the key development assumed by Chinese academy of sciences. (Zongqiang 2005 167)

The research and development of PEMFC battery in China have reached the high technical level in comparison to developed countries. There is a number of proportions of fuel cell productions in the world market. Since PEMFCs are listed as the key project of the ninth five-plan, varieties of 100 watts, 1 kW to 2 kW, 5 kW, 10 kW and 30 kW batteries have been successfully produced in recent years. The 5 kW batteries had a capacity of 100 W/kg and 300 W/L. The PEMFC bicycle had successfully manufactured, and 200-watts-electric-bicycle fuel cell-systems have been developed. The 30 kW battery systems have been used as the first power supplier for fuel cell light bus. In addition, the output of loading batteries could reach 46 kW, which laid a good foundation for the development of hybrid electric vehicles; the highest speed is 60.6 km/h. (Zongqiang 2005, 169)

There were few institutions in the research of MCFC in China, until the early 1990s when Chinese Academy of Sciences started the research of MCFC. A great progress has been achieved in manufacturing the anode materials. Shanghai Jiaotong University and Changqing Oilfield Company have had cooperation to start the research of MCFC with the target of exploiting 5 kW to 10 kW batteries. (Zhitong 2004, 240)

Scientists from Shanghai institution of ceramics carried out the earliest research of SOFC in 1971. The target focused on SOFC electrode materials and electrolyte materials. Afterwards, the national natural science foundation invested in deliberate cathode and anode materials, which obtained a huge progress. In addition, the electrolyte, anode and cathode materials are studied at Jilin University since 1989. Chinese Science and Technology University began to engage in the research of solid electrolyte in 1992. Two kinds of electrolyte appeared at that time. One was the nanometer zirconium as SOFC electrolyte which has an operating temperature of 450 °C. Another one was made by using new proton conductors as electrolyte, which had gained nearly theoretic electromotive force of the voltage and the current density of 200 mA/cm^2. Moreover, they were doing more research on the new generation of SOFC supplied by porous ceramics. (Zhitong 2004, 256)

2.2 Fuel cells in other countries

Developed countries regarded the development of large fuel cells as key research projects. Enterprises also invested in exploiting and developing the technology of fuel cells. Up to this time, there were varieties of important achievements has been obtained, which made fuel cells replace traditional generators and internal combustion engines to the new areas in power generation and cars. This new power generation reduced air pollution. 2 MW, 4.5 MW and 11 MW fuel cells generation equipment has been produced in the developed countries. (Zongqiang 2005, 180)

The environmental green revolution will benefit due to the advantages of fuel cells, such as high efficiency, less pollution, short construction period, easy maintenance and low cost. Nowadays, the fuel cell power generations are large scale applications in North America, Japan and European countries.

Japan decided to develop various types of fuel cells due to the oil crisis worldwide in 1973, and PAFC as large energy-saving power generation were exploited by NEDO. 1 MW PAFC power generation device has been developed since the year of 1981. 200 kW PMFC power generation devices were studied in order to suit remote areas and commercial use in 1986. For instance, Fuji Electric Corporation is currently Japan’s largest PAFC battery pile suppliers. The company had sold 17 sets of PAFC demonstration units to the world by 1992. 88 different kinds of PAFCs including 50 kW, 100 kW and 500 kW were put into use. (Zongqiang 2005, 183)

A famous Canadian Ballard Company is the leading company in PEMFC technology. The products in the company were from traffic tool applications to fixed power stations. Ballard Generation System as the subsidiary company is in a leading position in the area of development, production and marketing of PEMFC. The primary product is a 250-kW-fuel cell for power generation. Ballard Company had cooperation with many famous companies in order to commercialize the Ballard Fuel Cell. (Zongqiang 2005, 185)

2.3 Future of fuel cells

Nowadays, fuel cells have much wider applications than any other currently available power sources from toys to large power plants, from vehicles to mobile chargers, and from household power to battlefield power. Therefore, there will be an immeasurable future of the fuel cells. There are two tables that show the future trends of fuel cells.

Table 2.1. National Fuel cell Maturity/Support (2010). [5]

Country	Fuel Cell Manufacturing Infrastructure	Local Adoption of Fuel Cell Systems	Export of Fuel Cell System	Government Support for Growing Fuel Cell Industry
Canada	5	3	4	5
China	3	2	1	4
Denmark	4	3	4	5
Germany	5	3	5	5
India	1	1	1	3
Japan	5	5	1	5
Mexico	3	1	3	1
Russia	1	1	1	1
South Africa	1	1	1	5
South Korea	5	5	1	5
USA	5	4	1	3

The table 2.1 shows eleven different countries which either have policy to support the fuel cell industry or which are outlining some form of medium term support for industry. There is a set of criteria which includes: fuel cell manufacturing infrastructure, local adoption of fuel cell systems, export of duel cell systems and government support for growing fuel cell industry. Each country has been awarded a rating, from 1 to 5, for each of these criteria, with 1 being low and 5 high.

Table 2.2. Projected Levels of National Fuel Cell Maturity/Support (2020). [5]

Country	Fuel Cell Manufacturing Infrastructure	Local Adoption of Fuel Cell Systems	Export of Fuel Cell System
Canada	3	3	5
China	5	3	5
Denmark	3	3	5
Germany	4	3	5
India	5	3	5
Japan	5	5	5
Mexico	5	2	4
Russia	3	2	3
South Africa	5	2	5
South Korea	5	5	5
USA	3	5	2

From the table 2.2, looking forward to 2020, the relative positions of the most active countries have changed. It is apparent that a number of countries are aligning themselves over the next decade to be centres of manufacturing rather than adoption.

3 THEORY OF FUEL CELL

The fuel cell is based on the sample combustion reaction given by the equation:

$$2H_2 + O_2 \longrightarrow 2H_2O$$

The electron can be handled to provide electricity in a consumable form through a simple circuit with a load. Simple fuel cells have a small contact between the electrolyte, the electrode and the gas fuel.

The fuel cell does not require recharging in the same way as a battery. It will produce electricity as long as fuel is constantly supplied. The basic design of fuel cell includes two electrodes and an electrolyte. Hydrogen and oxygen pass over each of the electrodes and through means of a chemical reaction, electricity and water are produced.

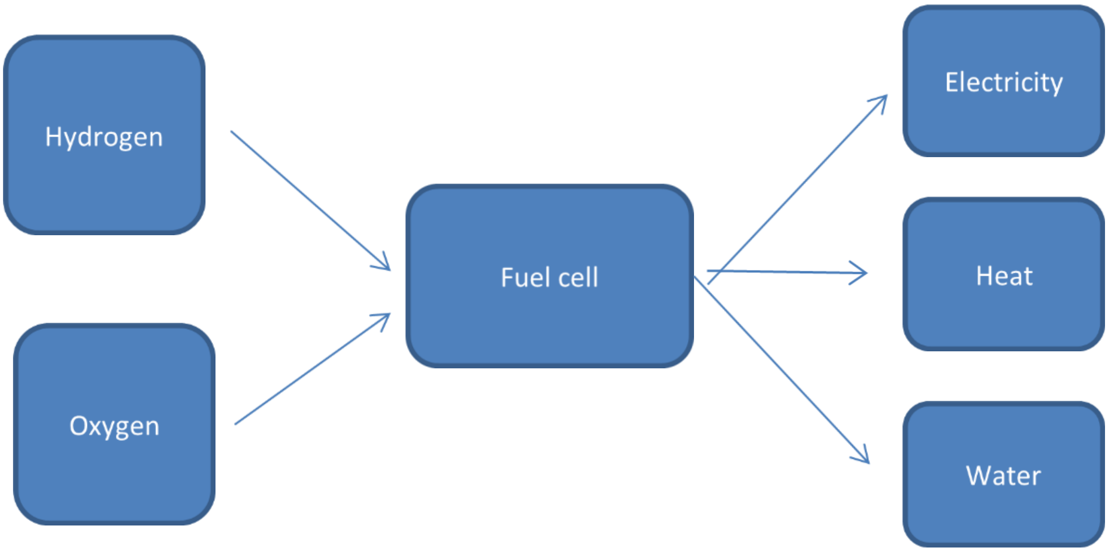


Figure 3.1. The diagram of fuel cell inputs and outputs.

In figure 3.1, hydrogen and oxygen react to get chemical energy. Fuel cell transfers the chemical energy in electricity, heat and water.

Hydrogen is commonly used as a source of fuel for fuel cells. Although methane and carbon monoxide are used as fuel in some fuel cell, they are simply hydrogen carriers. Hydrogen does not appear naturally in a useful form, so hydrogen is produced through the steam reforming of natural gas. However, the costs of steaming-reforming of natural gas are quite expensive, hydrogen will likely be produced from fossil fuel sources. Another way to produce hydrogen is solar hydrogen production by electrolysis.

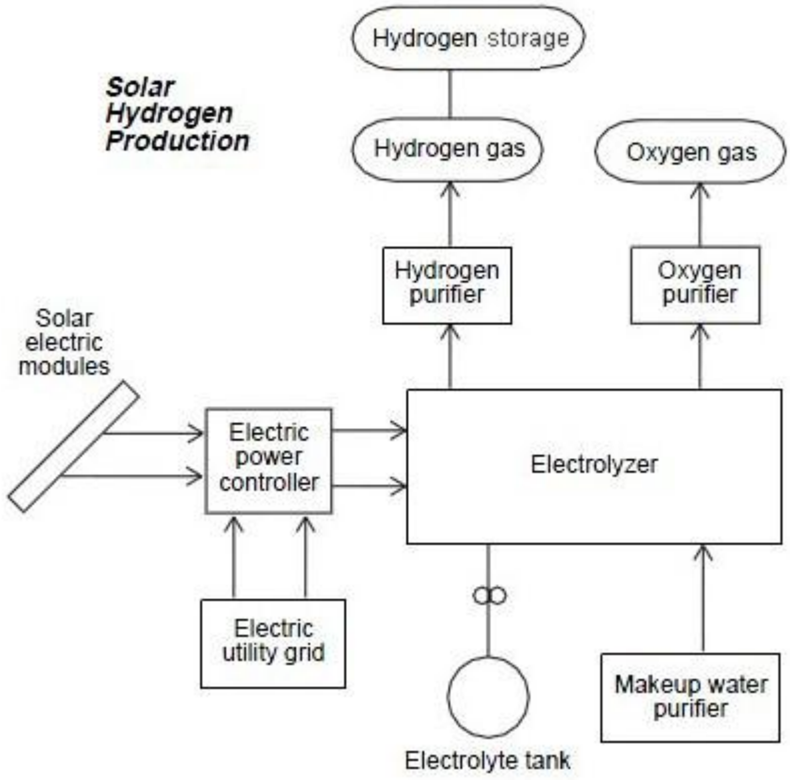


Figure 3.2. The diagram of hydrogen production by electrolysis. [20]

In figure 3.2, solar electric modules are used to transfer solar energy to the electric power, which can be used as electrolyzer. In the electrolyzer, the water is electrolyzed to produce hydrogen and oxygen gas. These two gases will be released to the purifier separately. Then the pure hydrogen will be stored in the hydrogen storage.

Table 3.1. Summary of electrolyte materials, transported irons and operating temperature of common fuel cells.

Fuel cell type	Electrolyte material	Transported ion	Operating temperature
Polymer electrolyte membrane fuel cell (PEMFC)	Cation conducting polymer membrane	H^+	20 - 80 °C
Direct methanol fuel cell (DMFC)	Cation conducting polymer membrane	H^+	20 - 80 °C
Direct formic acid fuel cell (DFAFC)	Cation conducting polymer membrane	H^+	20 - 80 °C
Direct borohydride fuel cell (DBFC)	Aqueous alkaline solution;Anion or cation conducting polymer membrane	H^+	20 - 80 °C
Phosphoric acid fuel cell (PAFC)	Molten phosphoric acid	OH^- or Na^+	150 - 200 °C
Alkaline fuel cell (AFC)	Aqueous alkaline solution	H^+	< 250 °C
Molten carbonate fuel cell (MCFC)	Molten alkaline car-bonate	CO_3^{2-}	600 - 700 °C
Solid oxide fuel cell (SOFC)	Conducting ceramic oxide	O^{2-}	600 - 1000 °C

In table 3.1, the characteristic features of different fuel cell types are discussed. Cation conducting polymer membrane is used as electrolyte material in PEMFC, DMFC, DFAFC and DBFC. The most transported ion of fuel cells is H^+. MCFC and SOFC are classified as high temperature fuel cell, the rest of fuel cells are operating at low temperature. Some of the fuel cells in the table will be analyzed theoretically below.

3.1 Proton exchange membrane fuel cells (PEMFC)

The proton exchange membrane fuel cell (PEMFC) typically operates on pure hydrogen fuel to generate electricity. The PEMFC combines the hydrogen fuel with the oxygen from the atmosphere to produce water, electricity and always heat.

The PEMFC has been recognized as a convenient and efficient power source for portable power applications, such as mobile phones and laptop computers. The PEMFC was developed in the early 1990s. Because of low efficiency and power density, as well as other problems, PEMFCs were not approved in that decade. When the efficiency of PEMFCs was improved to 40 %, the direct methanol fuel cells were widely used in the world. (Zhitong 2004, 45)

The PEMFCs with neither gas compressors nor fuel pumps, offer a simple system and decrease the loss for powering devices. They also work in different temperatures from -20 °C to 40 °C, which gives a great option for use in daily life. (Zhitong 2004, 46)

3.1.1 Properties of PEMFC

Solid polymer membrane is used as an electrolyte in PEMFC. Protons can permeate from this kind of polymer which does not conduct electrons. The chemical reactions and the flow of electrical current are shown in figure 3.3.

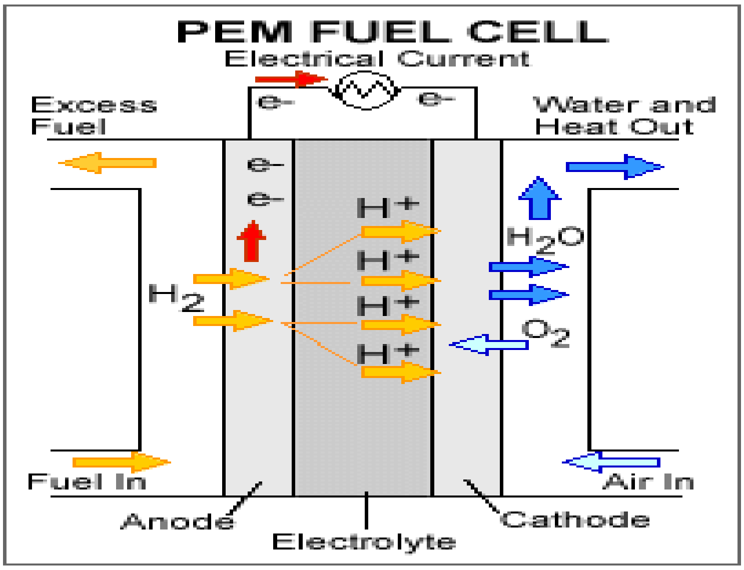


Figure 3.3. The diagram of a proton exchange membrane fuel cell. [12]

The operation of fuel cell can be explained like this: on the anode side, the hydrogen molecule is split into protons and electrons. The protons flow across the electrolyte to the cathode side while the electrons move through an external circuit. On the other side, the ambient air (contains oxygen) is pumped into the fuel cell on the cathode side. At the top of the picture, the anode and cathode sides are connected by an electrical circuit. These electrons move to the cathode side through the electrical circle. The protons and electrons will be combined with oxygen to form water on the side of cathode. The excess water goes out when the action runs regularly. The heat will be formed and will go out at the same time.

The reactions inside the PEMFC are:

Anode $2\ H_2 \longrightarrow 4\ H^+ + 4e^-$

Cathode $O_2 + 4 H^+ + 4e^- \longrightarrow 2 H_2O$

Reaction equation $2 H_2 + O_2 \longrightarrow 2 H_2O$

3.1.2 Advantages and disadvantages of PEMFC

Compared to other types of fuel cells, PEMFCs generate more power for a fixed weight of fuel cell. This high-power density characteristic makes them compact and lightweight. In addition, the operating temperature is less than 100 °C, which allows a rapid start-up. These features and the ability to rapidly change power output are some of the characteristics that make the PEMFC a top candidate for automotive power applications. (Zhitong 2004, 50)

The PEMFCs which are compact and lightweight start up rapidly. Compared to many other fuel cells, the PEMFCs lead to a longer operating life. They are adopted by major auto makers. In addition, the PEMFCs operate at 50% efficiency.

The disadvantage of the PEMFC is that the operating temperature is low. Temperatures near 100 °C are not high enough to perform useful cogeneration. High manufacturing costs are another limitation for the wide use of PEMFCs. Heavy auxiliary equipment and pure hydrogen are needed for PEMFCs. (Zhitong 2004, 51)

3.1.3 Applications of PEMFC

The applications of PEMFCs can be divided into two options. One is a settled power supply, the other one is a portable power supply.

PEMFC is applied in large-scale power plants. However, due to the restrictions of the manufacturing cost and fuel, PEMFC cannot be used in central power stations. PEMFC can be made in any scales which is very flexible as a dispersive power generation. (Zongqiang 2005, 45)

PEMFC used as a portable power supply is suitable for military, communication, computer, geology, microwave station, meteorological observatory, financial market, hospital and other fields. It can be used to propulse a motorcycle, car, train and ship, which will satisfy the environmental requirements for emissions of vehicles and ship. (Zongqiang 2005, 45)

3.2 Direct methanol fuel cells (DMFC)

Direct methanol fuel cells are one of the proton exchange membrane fuel cells in which methanol is used as fuel. Using a liquid rather than a gaseous fuel gives considerable advantages to DMFC developers. As a liquid, methanol can integrate effectively with transmission and distribution systems that already exist.

DMFC technology is still in the early stages of development. However, DMFC technology has been demonstrated in automotive and portable applications. DMFC's operate between temperatures 50 °C and 120 °C with an efficiency of up to 40%. (Zhitong 2004, 65)

3.2.1 Properties of DMFC

DMFCs are similar to the PEMFCs in that the electrolyte is a polymer and the charge carrier is a proton. However, the liquid methanol is oxidized on the anode side where carbon dioxide is generated. The protons react with oxygen to form water. (See figure 3.4)

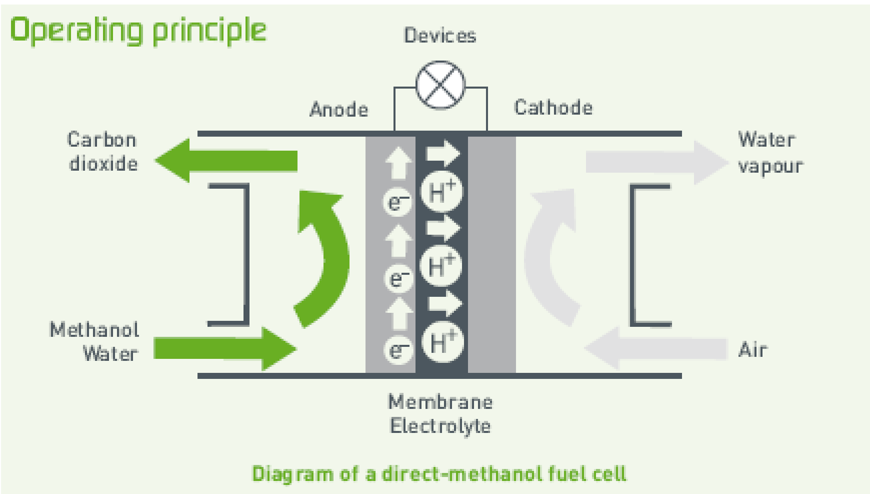


Figure 3.4. Schematics of reactant flow in a DMFC. [7]

Anode $CH_3OH + H_2O \longrightarrow 6\,H^+ + 6e^- + CO_2$

Cathode $3/2\,O_2 + 6\,H^+ + 6e^- \longrightarrow 3\,H_2O$

Reaction equation $CH_3OH + 3/2\,O_2 \longrightarrow 2\,H_2O + CO_2$

On the anode side, a mixture of methanol and water goes into the membrane. The water can be recycled inside the device. On the other side, the ambient air is pumped into the fuel cell on the cathode side. From figure 3.4, the anode and cathode sides are connected by an electrical circuit. When methanol comes into the fuel cell, it is oxidized and releases electrons to the anode. These electrons move to the cathode side by the electrical ciruit. Carbon dioxide is formed on the anode side. Meanwhile, protons are released from the mixture flow over the membrane to the side of cathode. The protons and electrons are combined to form water on the side of the cathode. There is a professional word called stack, which means that the entire reaction takes place in the middle of the fuel cell which heats up 75 °C due to the chemical reaction. There is some water which is not needed and carbon dioxide is released to the atmosphere. This chemical reaction is run inside of the fuel cell continually when there is enough methanol, and the reaction is operated in a safe and quiet condition.

The normal option of membrane is Nafion, which is widely used in the area of fuel cell. The reason is that Nafion has a good thermal resistance, high proton conductivity and chemical stability. The direct methanol fuel cells (a kind of PEMFC) use Nafion as an electrolyte membrane. However, there is a problem called “methanol crossover”, which is a diffusion of methanol through the electrolyte membrane from anode to cathode, that causes a loss of fuel. The cathode voltage and the efficiency of fuel cell are reduced in the cathode side. Furthermore, a considerably high cost of material and a decrease in proton conductivity at an operating temperature above 100 ℃ are also a problem with using Nafion membrane. Therefore, many efforts have been made to develop new electrolyte polymeric membranes which can be used as an alternative membrane for DMFCs.

3.2.2 Advantages and disadvantages of DMFC

A DMFC offers plenty of advantages which include four parts:

1. A simpler system design
   The DMFC is a smaller device than any other power generation. There is the potential for low-volume, lightweight packaging. It is convenient for transportation and storage.

2. Classification as a zero-emission power system
   The reaction products from DMFC are carbon dioxide and water. Although carbon dioxide will lead to global warming, it is not a poisonous gas to the environment.

3. Working atmosphere
   Only a small place is needed for the DMFC, because of the small size of DMFC. Besides, when DMFCs are working regularly, it is quiet without any noise.

4. Long membrane lifetime

   The membrane used in DMFCs has a very long lifetime, which is different from other devices.

However, there is also a number of disadvantages of the DMFC, such as:

1. Low cell voltage and low current density

   For this reason, the DMFCs are usually used in small systems in portable applications.

2. Fuel efficiency

   The fuel efficiency of DMFCs is currently 17%, but it is forecast to be 25%.

3. Methanol crossover

   The diffusion of methanol through the electrolyte membrane from anode to cathode is causing a fuel loss of 40%.

3.2.3 Applications of DMFC

The DMFCs can produce power for a long period of time, which makes them unsuitable for powering large vehicles, also adaptive for small vehicles. It is ideal power generation for consumer goods such as mobile phones, digital cameras and laptops. Plenty of digital products' batteries are produced by the DMFCs. Because DMFCs have no noise and no poisonous gas discharged, they are used as emerging applications in military area, such as power for soldier-carried tactical equipment and battery chargers. The DMFCs are also used in autonomous power for test and training instrumentations. (Zongqiang 2005, 65)

According to the different outputs of power, the applications of the DMFCs can be classified into three options.

1. Small systems

   Direct replacement of batteries as power sources for the middle systems of electronic devices. The power is almost 20 watts.

2. Middle systems

   Portable battery charger for secondary batteries, the power is from 150 to 500 watts.

3. Large systems

   They are used in 2 to 5 kW diesel generator replacements

3.3 Molten carbonate fuel cells (MCFC)

Molten carbonate fuel cell (MCFC) is a high temperature fuel cell which operates approximately at 650 °C. This kind of fuel cell uses natural gas directly. High temperature is required to reach enough conductivity of the carbonate electrolyte which enables to use low cost parts.

Molten carbonate fuel cells' appliations are improved in the mid 1960s in anaerobic digestion gas, natural gas and coal-based power plants for infrastructure, industrial, and military applications. Nowadays, Europe, Japan and USA each have at least three developers enhancing the commercialization of MCFCs. For instance, Brandstofel Nederland B.V.(BCN), MTU Friedrichshafen, Ansaldo (Italy), Hitachi, Ishikawajima-Harima Heavy Industries, Mitsubishi Electric Corporation and Toshiba Corporation. (Zhitong 2004, 67)

The efficiency of MCFCs can reach 60 to 80 percent. The output of units can reach 2 megawatts (MW) and designs exist for units up to 100 MW. The high temperature limits the product materials and safe uses of MCFCs which would be too hot for family use. (Zhitong 2004, 68)

3.3.1 Properties of MCFC

MCFCs are high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt mixture. In figure 3.5, when the temperature comes to 650 °C, the electrolyte used as a molten mixture of carbonate salts melts and becomes conductive to carbonate ions. These ions combine with hydrogen to form water on the cathode side. Meanwhile, carbon dioxide and electrons are released during the reaction.

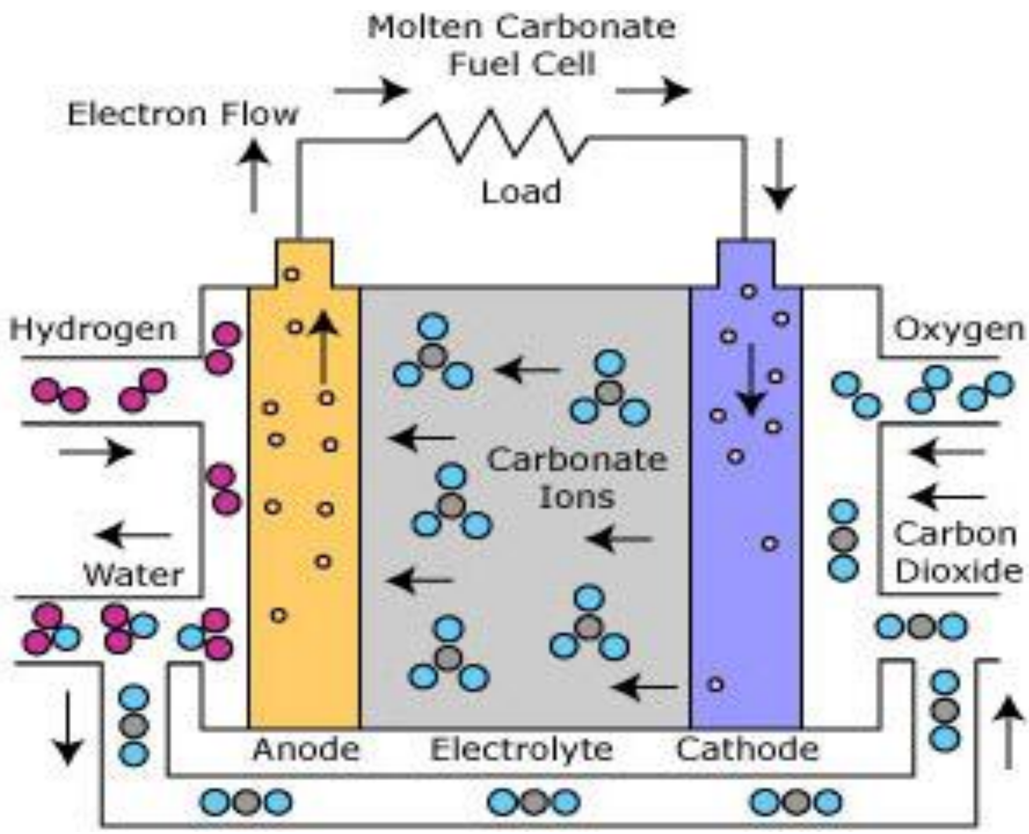


Figure 3.5. Schematics of reactant flow in a MCFC. [10]

The reaction equation of the MCFC is:

Anode $2H_2 + 2CO_3^{2-} \longrightarrow 2CO_2 + 2H_2O + 4e^-$

Cathode $O_2 + 2CO_2 + 4e^- \longrightarrow 2CO_3^{2-}$

Reaction equation $O_2 + 2H_2 \longrightarrow 2H_2O$

On the cathode side, a mixture of oxygen and carbon dioxide is pumped into the device, the carbonate ions will emerge from this reaction, which moves to another side for the next reaction. On the anode side, there is a reaction of hydrogen and carbonate ions, the reaction product is water which will be moved out. In figure 3.5, cathode and anode are connected by an electrical circuit. When hydrogen comes into the device, the carbonate ions will release electrons to the anode. These electrons move to the cathode side by the electrical circuit. Meanwhile, the electrons will be absorbed by carbon dioxide, the carbonate ions come out. In this way, there will be a flow of the electrons; current flow will circulate when there is enough hydrogen and oxygen. Carbon dioxide can be recycled during this reaction, which the figure 3.5 shows in the bottom.

3.3.2 Advantages and disadvantages of MCFC

1) Advantages of MCFC

There is variety of benefits caused by the relatively high operating temperature of MCFC (650 °C). Non-expensive catalysts can be used in conjunction with a number of fuels to provide sufficient activity. Moreover, carbon monoxide and even certain hydrocarbons are the fuels for MCFC. The reason is that they are converted to hydrogen within the stack and enhance the system efficiency to 40% - 50%. In addition, when the reaction works in the device, the high temperature waste heat enables the use of bottom cycle to further boost the system efficiency to 50% - 60%.

2) Disadvantages of MCFC

The main challenge of MCFC developers is how to avoid the electrolyte being corroded. MCFC needs a high temperature of 650 °C, which promotes material problems. There are not so many mechanical devices that can bear such a high temperature. The mechanical stability is a serious test for MCFC. Furthermore, it is dangerous for workers to work nearby MCFC.

3.3.3 Applications of MCFC

MCFCs are developed for natural gas, anaerobic digestion gas and coal based power plants, for electric utility, industrial, and military applications. Besides, MCFCs are an alternative and a cleaner power supply for ships which have been developed by the European-funded MC WAP research project. This will be cleaner and avoid the pollution of the marine diesel engines which currently provide the power in the vast majority of the world’s ships. (Zhitong 2004, 71)

3.4 Solid oxide fuel cells (SOFC)

Solid oxide fuel cells use solid oxide material as electrolyte. In comparison to direct methanol fuel cells (DMFCs), which conduct positive hydrogen ions through a polymer electrolyte from the anode to the cathode, the SOFCs use solid oxide electrolyte to move negative oxygen ions from the cathode to the anode.

SOFC is a high temperature fuel cell, typically between 500 °C and 1000 °C. The expensive platinum catalyst which is necessary for lower temperature fuel cells such as DMFCs is not required for SOFCs. In addition, there will be no poisonous gas like carbon monoxide coming out. (Zhitong 2004, 103)

3.4.1 The properties of SOFC

The figure 3.6 shows how a solid oxide fuel cell works. SOFC is constructed with two porous electrodes and an electrolyte. The gas is impervious to cross-over from one electrode to another.

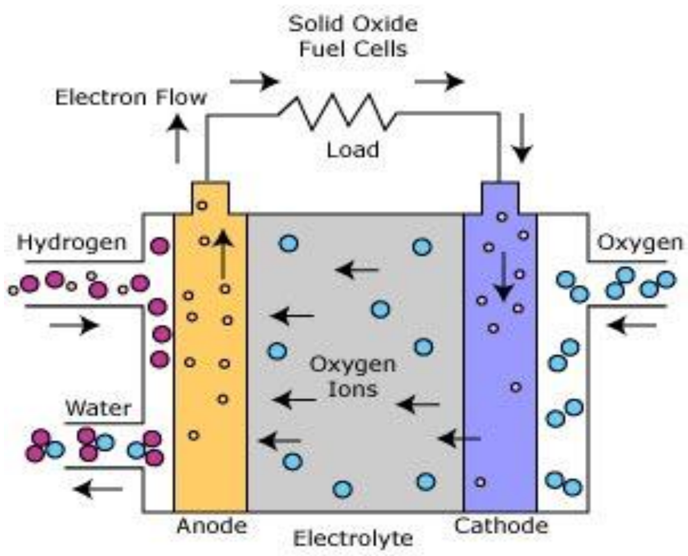


Figure 3.6. Schematics of reactant flow in a SOFC. [20]

The air containing oxygen flows along the cathode from the right part of the picture. An oxygen molecule comes into contact with the cathode and releases two oxygen ions. After that, the oxygen ions move into the electrolyte material and go to the other side of the device. On the anode side, the oxygen ions attach the anode interface and react catalytically. The reaction products are water and carbon dioxide. Heat will be generated at the same time. Meanwhile, the electrons move through the anode to the external circuit and back to cathode, producing useful electrical energy in an external circuit. When there is enough air and hydrogen, the reaction will run continuously.

The reaction equation of SOFC

Anode $H_2 + O^{2-} \rightarrow H_2O + 2e^-$

Cathode $O_2 + 4e^- \rightarrow 2O^{2-}$

Reaction equation $2H_2 + O_2 \rightarrow 2H_2O$

3.4.2 Advantages and disadvantages of SOFC

1) Advantages of SOFC

High efficiency is one of the advantages of the SOFC. It has been demonstrated that the efficiency of the SOFC is between 40 % and 50 %, and the potential for 60 percent plus efficiency exists as it does for MCFC. SOFC uses the natural gas directly. The heat produced by SOFC can be utilized in co-generation. The electrolyte is solid, which avoids the electrolyte movement or flooding in the electrode.

2) Disadvantages of SOFC

One of the advantages of SOFCs is the high operating temperature. The high temperature sets several constraints on materials options and results difficulties in production processes. There are many materials that cannot bear so high temperature. The corrosion of metal stack components is another problem of SOFCs. Therefore, high manufacturing costs is a huge issue for SOFCs.

3.4.3 Applications of SOFC

SOFC has a large numbers of applications from use as an auxiliary power in vehicles to stationary generation with outputs from 100 W to 2 MW. Ceramic Fuel Cell Ltd from Australia successfully achieved an efficiency of a SOFC device up to the previously theoretical mark of 60 percent. (Zongqiang 2005, 79)

Stable installations are primary for some facilities such as homes, industrial sites, offices buildings and military installations. They are suitable for mini-power-grid applications at universities and military bases. (Zongqiang 2005, 79)

A SOFC plant in the Netherlands that has been operational for two years and an earlier prototype installation has been operating for 8 years. The fuel cells have been through over 100 thermal cycles and the voltage degradation during the test time has been minimal, less than 0.1 percent per thousand hours. (Zongqiang 2005, 80)

SOFC is often used in the transportation sector, such as trucks and automobiles. SOFC can probably be used as auxiliary power units to run electrical systems like air conditioning.

Those units would be available for saving in diesel fuel expenditure. There will be an important reduction in both diesel exhaust gases and truck noise. Meanwhile, at least 4.5 billion dollars has been invested in the fuel cell research of automobile manufacturers. SOFCs are attractive prospects for the non-polluting cars for the reason that their ability to use readily available and inexpensive fuels. (Zongqiang 2005, 80)

3.5 Phosphoric acid fuel cells (PAFC)

PAFCs were the first fuel cells to be commercialized. They were developed in the middle of 1960s and have been field-tested since the 1970s. The stability, performance and cost have been improved significantly since those times. (Zhitong 2004, 112)

Phosphoric acid fuel cells (PAFC) are one of a type of fuel cell which uses liquid phosphoric acid as an electrolyte. This kind of fuel cell typically operates at 150 to 220 °C. Phosphoric acid is a poor ionic conductor when the temperature is low, and carbon monoxide poisoning of Pt electro-catalyst in the anode becomes severe. The relative stability of concentrated phosphoric acid is highly compared to other common acids. (Zhitong 2004, 112)

3.5.1 Properties of PAFC

In PAFC, the phosphoric acid is an electrolyte that can approach a 100% concentration. The ionic conductivity of phosphoric acid is low.

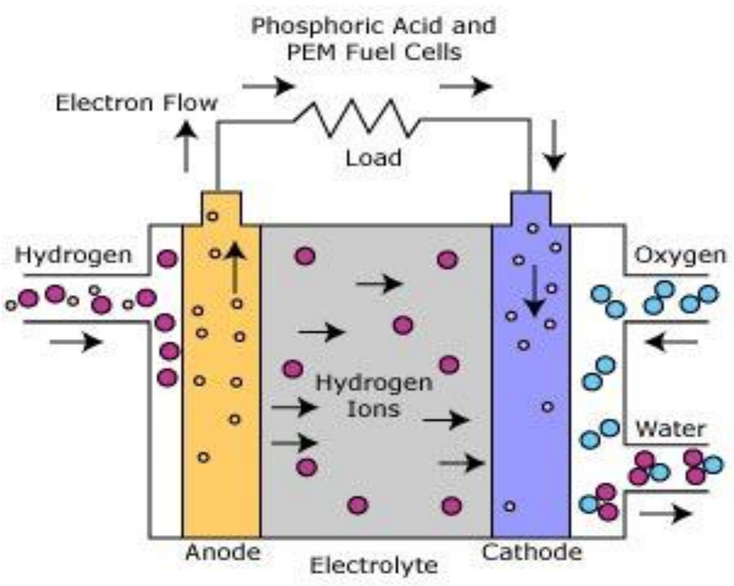


Figure 3.7. Schematics of reactant flow in a PAFC. [14]

The figure 3.7 shows the schematics of a reactant flow in a PAFC. On the anode side, when the hydrogen comes into the fuel cell, it releases hydrogen ions and electrons to the anode. On the cathode side, the air goes into the device. The anode and cathode side are connected by an electrical circle. The electrons move to the cathode side by the electrical circuit. Meanwhile, the hydrogen ions are released from the anode side and flow over the electrolyte to the side of cathode. The hydrogen ions and electrons will be combined to form water on the side of cathode. Besides, heat will come out.

The reaction equation of PAMC is:

Anode reaction: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode reaction: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Overall cell reaction $2H_2 + O_2 \rightarrow 2H_2O$

3.5.2 Advantages and disadvantages of PAFC

1) Advantages of PAFC

PAFCs are sensitive to carbon monoxide and can tolerate about 1.5% of carbon monoxide as diluents. The concentrated phosphoric acid electrolyte can operate above the boiling point of water. The power densities are high and PAFCs can be responsive to changing electrical loads. PAFC provides high quality direct current power and the operating temperature is low to use inexpensive construction materials. Efficiency of PAFC can reach 40% to 50%, but this can rise to about 80% if the waste heat is reused in a co-generation system.

2) Disadvantages of PAFC

The efficiency of PAFC is low because the reduction of oxygen is slow and needs the use of platinum catalyst. The expensive catalyst is needed for operating regularly. PAFCs require extensive fuel processing to achieve perfect performance. Phosphoric acid is highly corrosive material which requires the use of expensive materials in the stack. In addition, it has poor operating reliability in the long term.

3.5.3 Applications of PAFC

PAFCs are mostly used for some facilities as homes, offices buildings, industrial sites and military installations. By the influence of the oil crisis in 1973, Japan decided to develop various types of fuel cells, PAFC as electricity generation technology is developed by NEDO, 200 kW power generation devices are carried out in 1986, in order that it is suitable for remote areas. (Zongqiang 2005, 123)

3.6 Alkaline fuel cells (AFC)

The AFCs were the first modern fuel cells to be developed in the beginning of 1960. This class of fuel cells is used in Apollo-series mission that flew man to the moon. NASA (National Aeronautics and Space Administration) has used alkaline fuel cells since the middle of 1960s. The operating temperature is from 65 °C to 220 °C, and the efficiency can reach 60%.

3.6.1 Properties of AFC

The electrolyte of AFC is an aqueous solution of potassium hydroxide retained in a porous stabilized matrix. The potassium hydroxide can be changed with the operating temperature of AFC.

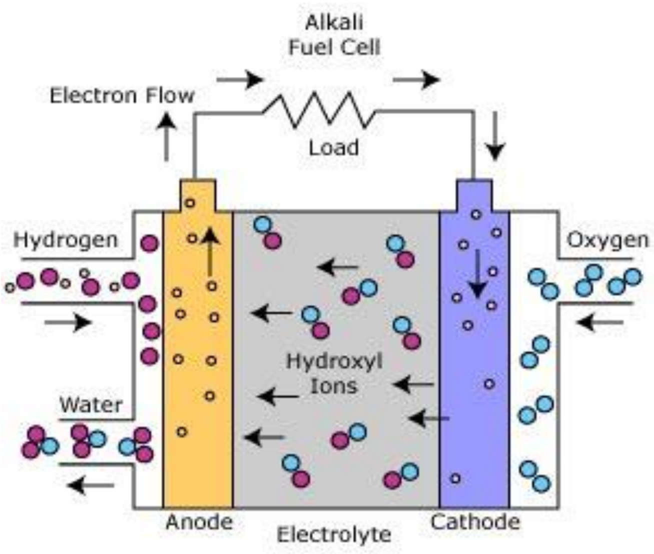


Figure 3.8. Schematics of reactant flow in a AFC. [1]

On the cathode side, when air is pumped into the device, oxygen has a reaction with water to form hydroxyl ions, which will flow over the electrolyte to the anode side. The reaction between hydrogen combines the hydroxyl ions to produce water and the electrons are released on the anode. The anode and cathode side are connected by an electrical circuit. When oxygen comes into cathode, it gains the electrons from the anode side. There will be an electrical circuit formed by the movement of the electrons.

The reaction equation of AFC is:

Anode reaction: $H_2 + 2OH^- \longrightarrow 2H_2O + 2e^-$

Cathode reaction: $O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$

Overall cell reaction: $2H_2 + O_2 \longrightarrow 2H_2O$

3.6.2 Advantages and disadvantages of AFC

1) Advantages of AFC

The AFCs have a quick start-up performance because of the low temperature operation, which is faster than with most other fuel cells. The low manufacturing and operation costs make AFC widely used. AFC does not need a heavy compressor. The active oxygen electrode kinetics and its flexibility to use a wide range of electro-catalysts make the excellent performance of AFCs.

2) Disadvantages of AFC

The highly pure hydrogen should be used as a fuel to have the sensitivity of the electrolyte to carbon dioxide. Therefore, the highly effective carbon monoxide and carbon dioxide removal system is required for the use of a reformer. Pure hydrogen and oxygen are not convenient to get. AFCs always have large-size applications.

3.6.3 Applications of AFC

AFCs were used on Apollo space missions to provide electricity for the on-board needs of the shuttle. During the reaction of AFCs, pure hot water is produced as a product which can be drunk by astronauts. In addition, AFCs can supply heat and cooling that are quite significant in the shuttle. (Zongqiang 2005, 136)

4 FUEL CELL EFFICIENCY

4.1 Efficiency of fuel cell

Efficiency can be defined in many ways, actually it is based on the maximum energy thatcould be gained from a fuel by burning. It is called the heating or calorific value. The efficiency of fuel cells is focused on the amount of power that could be obtained from the fuel. (Fuel cell handbook, 2004)

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

$$\eta = \frac{E_{useful}}{\Delta H} \qquad (4.1)$$

Fuel cells are devices that convert chemical energy directly into electrical energy. ΔG is change of Gibbs energy, which is called by the energy available in the ideal case of fuel. The ideal efficiency of fuel cell is

$$\eta_{ideal} = \frac{\Delta G}{\Delta H} \qquad (4.2)$$

From the basic definition of efficiency:

$$\eta = \frac{W}{Q_{in}} \qquad (4.3)$$

where Q_{in} is the enthalpy of formation of the reaction taking place and W is the output energy. Since two values can often be computed depending on the state of the reactant, the larger one of the two values (Higher Heating Value) is used (HHV). N is the moles of electrons and F is the Faraday constant.

$$\eta = \frac{\Delta G}{HHV} = \frac{NFE}{HHV} \qquad (4.4)$$

The maximum efficiency takes place under open circuit conditions when the highest voltage is gained.

$$\eta_{\max} = \frac{\Delta G}{HHV} = \frac{NFG}{HHV} \qquad (4.5)$$

Take the hydrogen fuel cell reaction for example, at standard conditions of 0°C and 1 atmosphere, the thermal energy in the hydrogen/oxygen reaction is 285.8 kJ/mole, and the Gibbs energy is 237.1 kJ/mole. Thus, the maximum efficiency of the fuel cell at the standard conditions is:

$$\eta_{ideal} = \frac{237.1}{285.8} = 0.83 \quad (4.6)$$

4.2 Classification of losses in fuel cell

When a fuel cell works, the voltage is less than the reversible operational fuel cell voltage. There are some differences to show the performance of a typical single operating in fuel cell low and high temperatures.

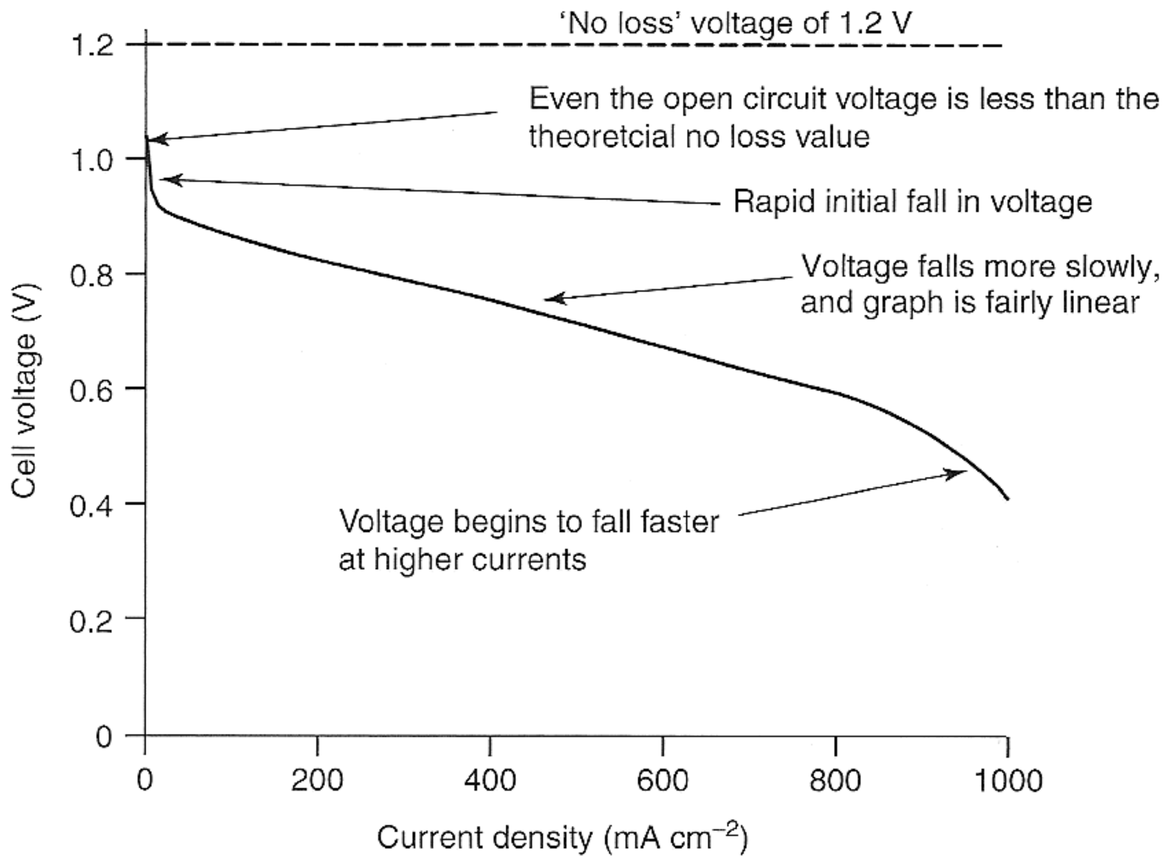


Figure 4.1. Low temperature fuel cell losses. [10]

The figure 4.1 shows the change of cell voltage for a typical temperature at normal air pressure. The open circuit voltage is less than the theoretical no loss value. There is a rapid initial fall in voltage. The voltage falls slowly after the initial fall. The graph is quite linear. The voltage falls rapidly when the current density is high.

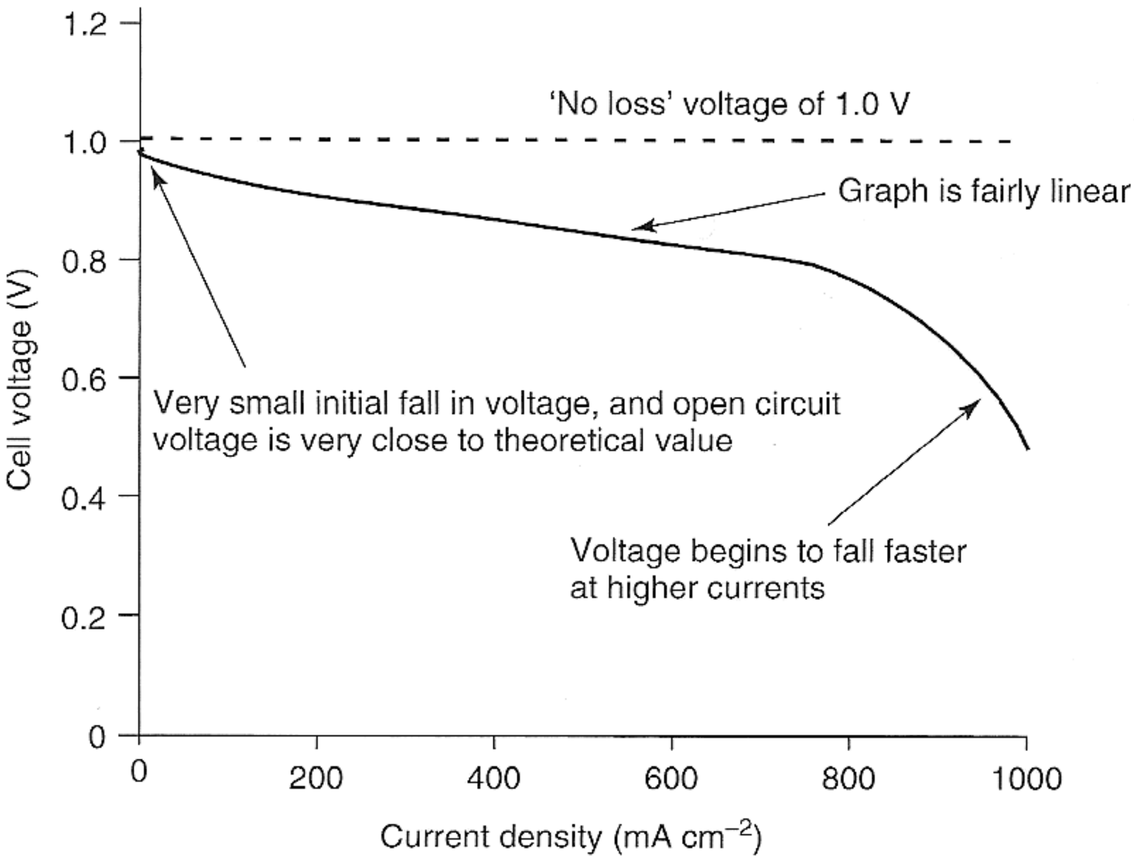


Figure 4.2. High temperature fuel cell losses. [10]

In figure 4.2, there is a small initial fall in voltage, and the open circuit voltage is very close to the theoretical value. The graph is fairly linear and the voltage falls fast at high current, as with lower temperature fuel cells.

The losses that were evident in figure 4.1and figure 4.2 can be divided to five different types of losses. They are listed in the following:

1) Activation losses

Activations losses are usually caused by the slowness of the reaction occurring on the surface of the electrodes. The effect of these losses is most pronounced at low current densities. A proportion of the voltage generated is lost in driving the chemical reaction that transfers the electrons. These losses are basically representatives of a loss of overall voltage at the expense of forcing the reaction to completion. The loss is often termed over potential, and is essentially the voltage difference between the two terminals.

2) Ohmic losses

Ohmic losses are prevalent in every electronic device, and fuel cells are not exception to this rule. Ohmic losses arise due to the resistive losses in the electrolyte and in the electrodes. These losses vary linearly with current density.

3) Concentration losses

Concentration losses are due to the change in concentration of the reactants at the surface the electrodes as the fuel is used. The effect of these losses is showed at low efficiency of fuel cell. If hydrogen is used at a high rate at the anode then the pressure of hydrogen drops, thus the reaction rate is slow. This is also the same case that happens at the cathode with oxygen.

4) Fuel crossover losses

Fuel crossover losses are due to the waste of the fuel passing through the electrolyte and electron conduction through the electrolyte. The electrode is necessary to allow proton transfer, and is also slightly conductive. It is possible for un-reacted fuel and electrons to crossover to the cathode. These losses are typically small, but can be more important in low temperature cells.

5) Mass transport losses

Mass transport losses are due to no reacting diffusion in the gas-diffusion layer and to reacting diffusion in the electrode layers. The decrease in reactant concentration at the surface of the electrodes as fuel is used. The effects of these losses are most pronounced at high current densities.

5 EXPERIMENTS OF FUEL CELL

5.1 EFOY fuel cell

5.1.1 What is EFOY fuel cell?

Figure 5.1. The main equipment of an EFOY 1600 fuel cell.

The EFOY 1600 fuel cell is a safety and convenience generator to have power wherever and whenever you want. The EFOY 1600 is 7 kg in weight and 435 mm*200 mm*276 mm in dimension. The constant voltage is around 12 V. The built-in Automatic Charge Control regulator constantly monitors voltage and recharges the battery completely automatically. If the voltage dips below 12.3 volts and above 14 V, the EFOY fuel cell will cut in automatically to recharge the battery. Once you switch it on, it is the EFOY fuel cell that will communicate with you via the display on the remote control. Besides, the fuel cartridge needs to be changed fortnightly. Changing cartridges takes a few seconds, even if the EFOY fuel cell is running. This equipment can be used in every place where you need power temporarily. The EFOY fuel cells work so quietly that it won't disturb you. Therefore, EFOY is the new kind of battery nowadays in your normal life.

Table 5.1. Key product data of EFOY fuel cell. [3]

Property	EFOY 1600
Rated output	65 W
Charging capacity\ day	1600 Wh/day
Normal voltage	12 V
Charging current (12V)	5.4 A
Standby current consumption	15 mA
Methanol consumption	1.1 L/kWh
Sound pressure level at 7 meters	23 dB(A)
Weight	7.3 kg
Compatible batteries	12V lead rechargeable
Operating temperature	-20 to +40 °C
Dimensions (L*W*H)	43.5*20.0*27.6 cm
Space requirements	51*35*30 cm (minimum)

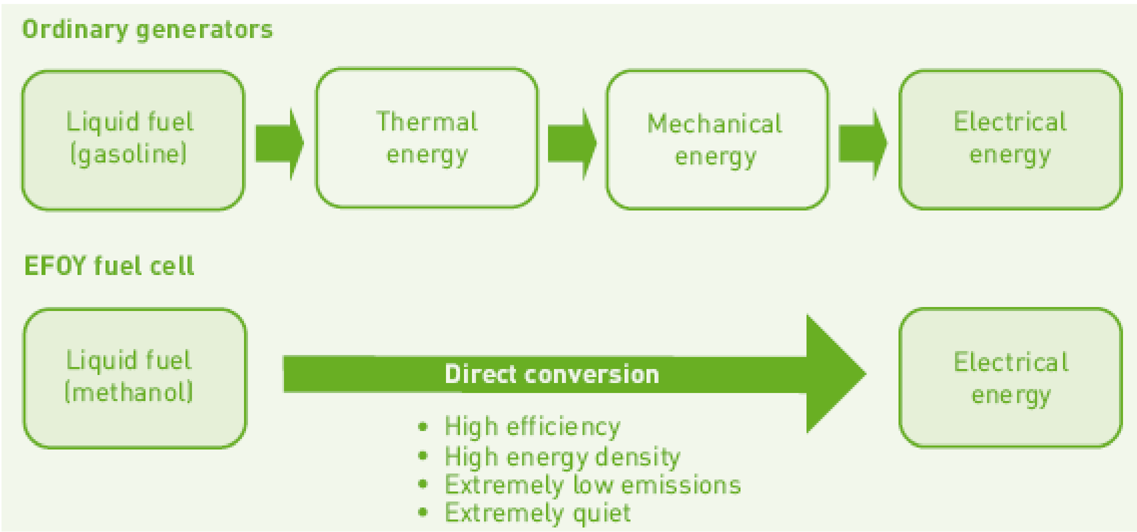


Figure 5.2. Energy transaction of EFOY fuel cell. [3]

In comparison to the ordinary generators, EFOY fuel cells convert liquid fuel directly into electrical energy, leaving out two steps in the conversion of thermal to mechanical energy. Apparently, EFOY fuel cells serve much higher efficiency than the ordinary generators. Besides, there are other advantages of EFOY fuel cells, such as high energy density, extremely low emissions and low noise.

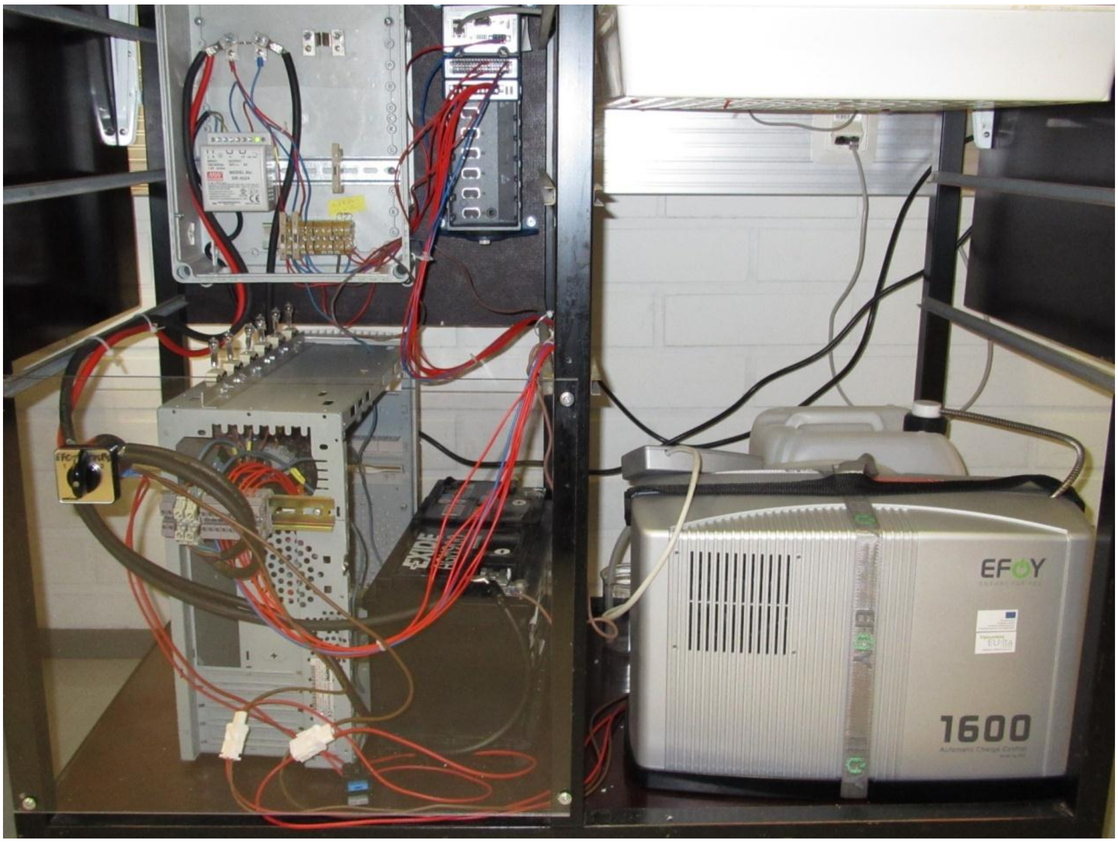


Figure 5.3. EFOY 1600 fuel cell.

Figure 5.3 shows the main parts of EFOY 1600. The device on the right is the EFOY fuel cell. On the left side, there is the power generation equipment and measurement equipment. There is a remote control on the EFOY 1600 fuel cell. On the remote control, there is an information and language selection button, an on/off button, an automatic operation button, a reset button and a warning light.

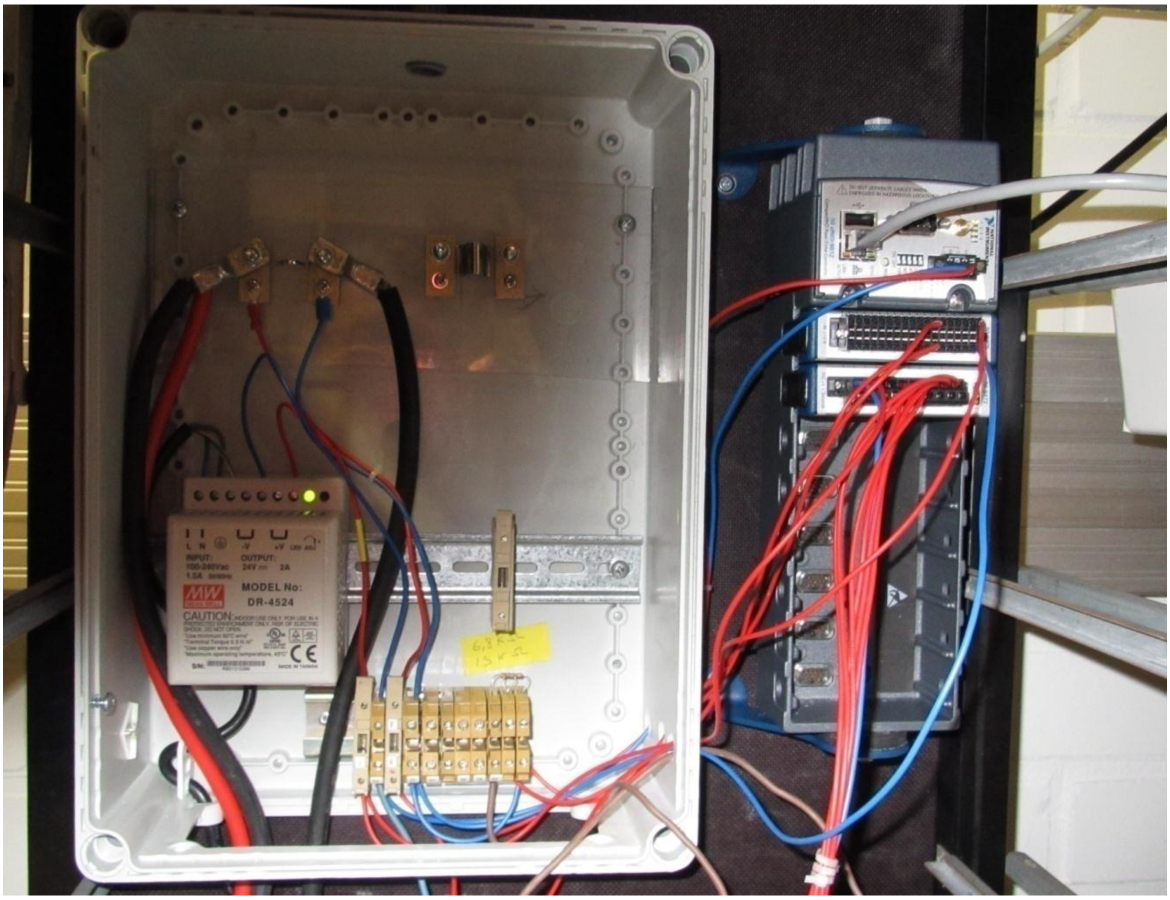


Figure 5.4. Data connected equipment of the experiment.

Figure 5.4 shows the wires and power generation which are used for the computer work for collecting data of the EFOY fuel cell. A shunt resistor is at the top of the box and a voltage divider is at the bottom. Current is obtained from the equation $I = \frac{U}{R}$. On the right side, there is a CompactRIO module that is used for data acquisition. CompactRIO is a real time industrial controller made by National Instruments.

Figure 5.5. Battery of the experiment.

At the bottom, the Exide AGM 900 battery is used to supply power to the electrical equipment. On the top, there are 55 W light bulbs of a car which are used to discharge the battery. The battery must be discharged after charging.

5.1.2 How do the EFOY fuel cells work

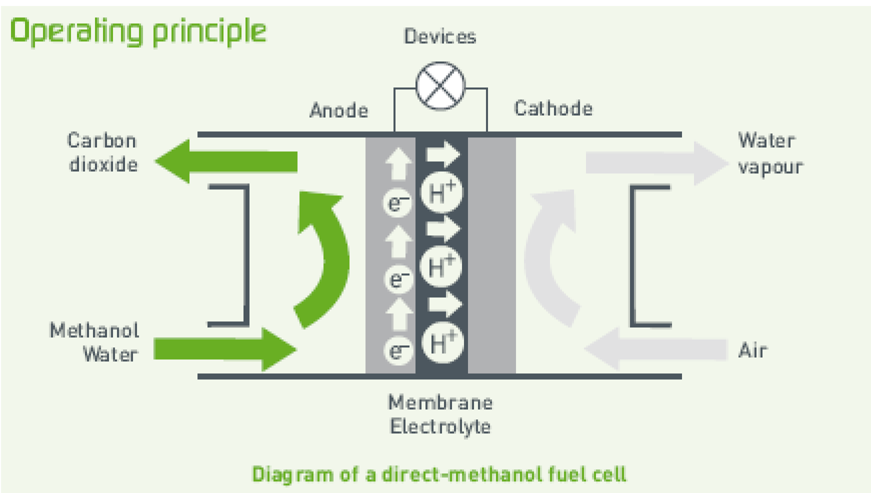


Figure 5.6. The operating principle diagram of EFOY fuel cell. [2]

Figure 5.6 is a diagram of a direct-methanol fuel cell, which shows how it works inside the EFOY fuel cells.

Anode $CH_3OH + H_2O \longrightarrow 6\ H+ + 6e^- + CO_2$

Cathode $3/2\ O_2 + 6\ H^+ + 6e^- \longrightarrow 3\ H_2O$

Reaction equation $CH_3OH + 3/2\ O_2 \longrightarrow 2\ H_2O + CO_2$

5.1.3 Analysis of experiment

Three ranges of temperatures are chosen for testing the EFOY 1600 fuel cell. When we choose a temperature, the weight of EFOY fuel cell should be recorded before the experiment starts. Then computer is used for recording the voltage and current. When we turn the remote control unit on, the fuel cell starts to operate. The fuel cell has to run for more than two hours. After that, the power is cut off. We weigh the fuel cell again and record the data. Then we can calculate how much weight of methanol is used in two hours. The voltage and current data are shown on the computer. The useful energy of methanol is recorded after the experiment. We can use this data to calculate the efficiency. The graph of current, voltage and power versus time can be made by computer.

1. Temperature around 21.7 °C to 22.1 °C

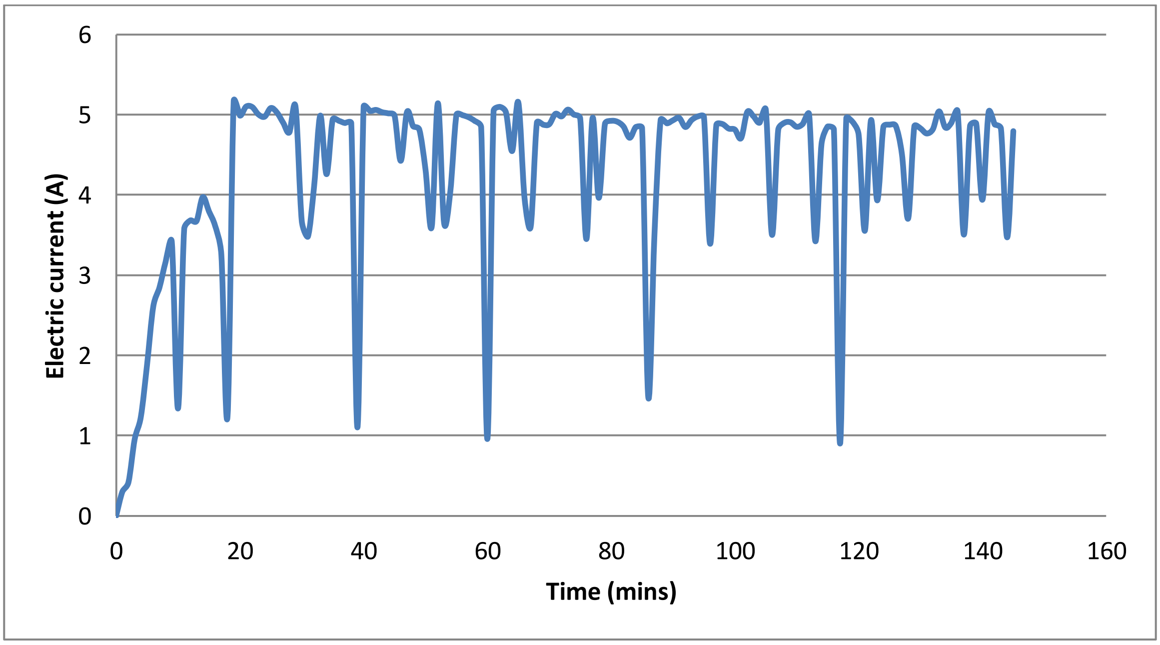


Figure 5.7. Current versus time at 21.7 °C to 22.1 °C.

The graph shows how an electric current change when time goes by. The highest electric current is around 5 A in the graph. In the graph, there are some drops that shows in almost 20 minutes after a start. The workers from development department of EFOY Company said that “load dump” is used for an internal cleaning purpose. The sampling rate did not allow the correct tracking of this “load dump”. The loss of energy was compensated by producing more energy between the “load dump” to ensure nominal energy, for example 1600 Wh per day.

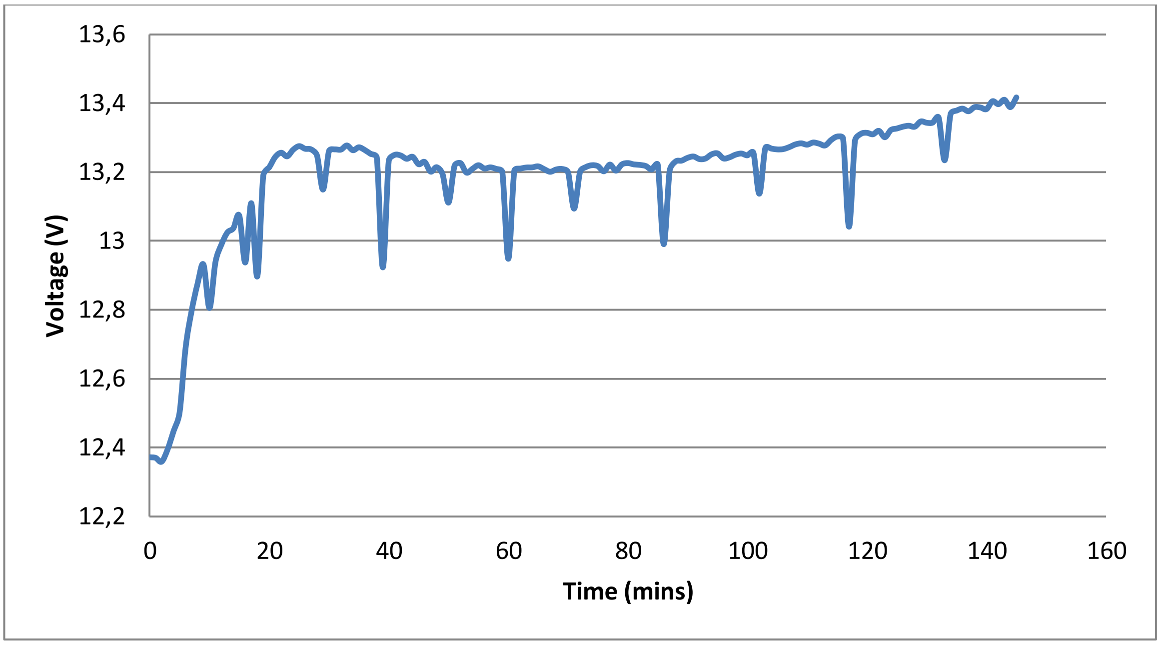


Figure 5.8. Voltage versus time at 21.7 °C to 22.1 °C.

The graph showed the relation between time used in the experiment and voltage. When the EFOY fuel cell operated steadily, the voltage stayed at 13.3V.

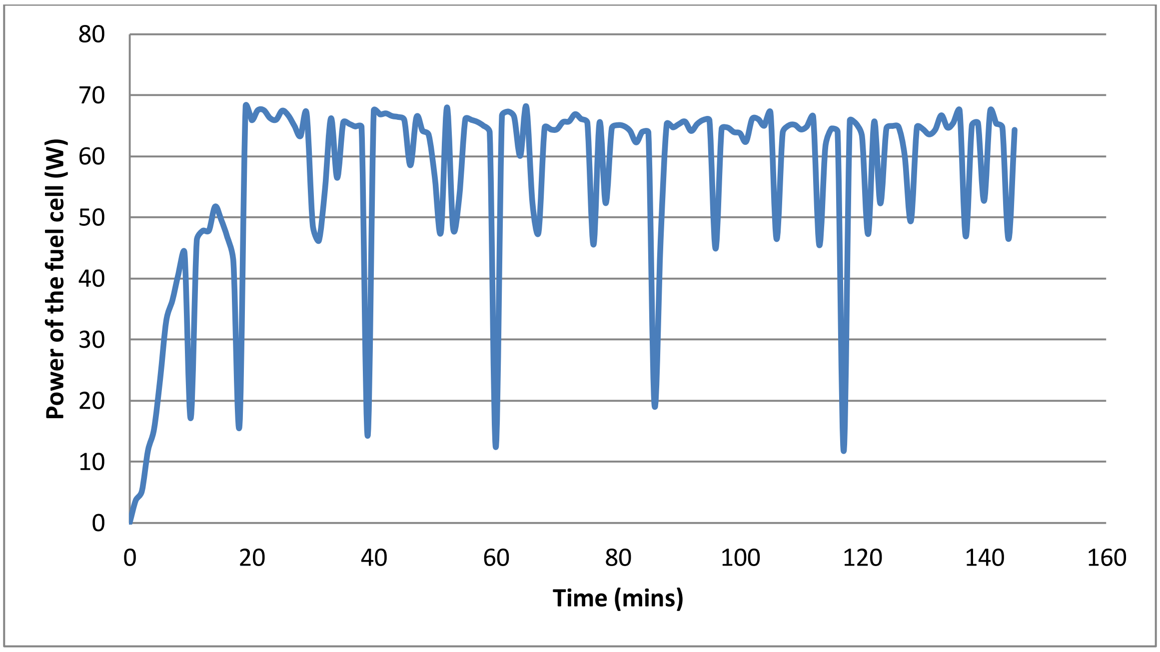


Figure 5.9. Power versus time at 21.7 °C to 22.1 °C.

This graph was similar to the figure 5.9, however, it showed the changes of power when time went by. In the graph, the highest power was close to 70 W, the variation of the power was between 50 W and 70 W regularly.

2. Temperature from -4 °C to 0 °C

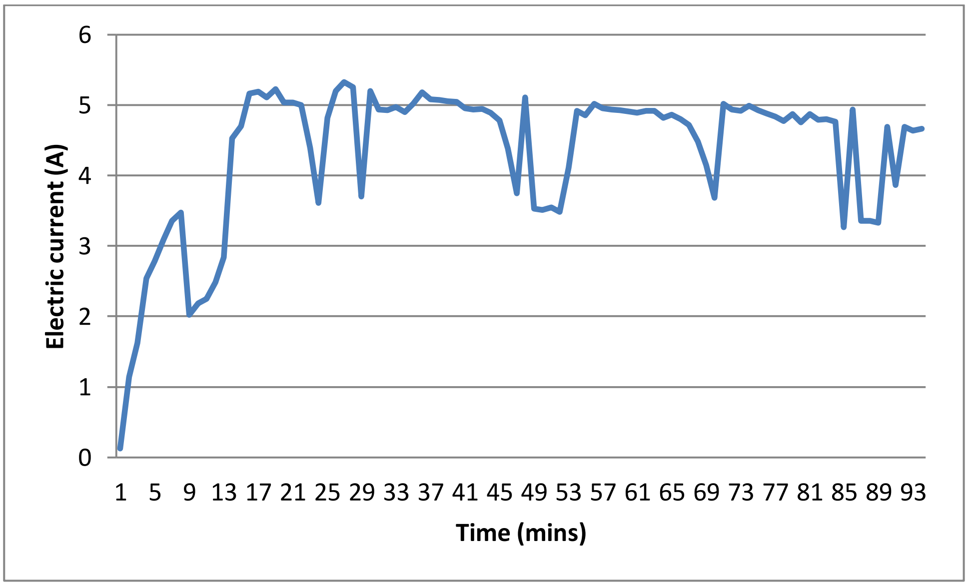


Figure 5.10. Current versus time at -4 °C to 0 °C.

This Time-Electric current graph was not quite regular compared to the graph in the temperature from 21.7°C to 22.1°C. However, the basic changes were almost the same. The highest electric current was around 5A.

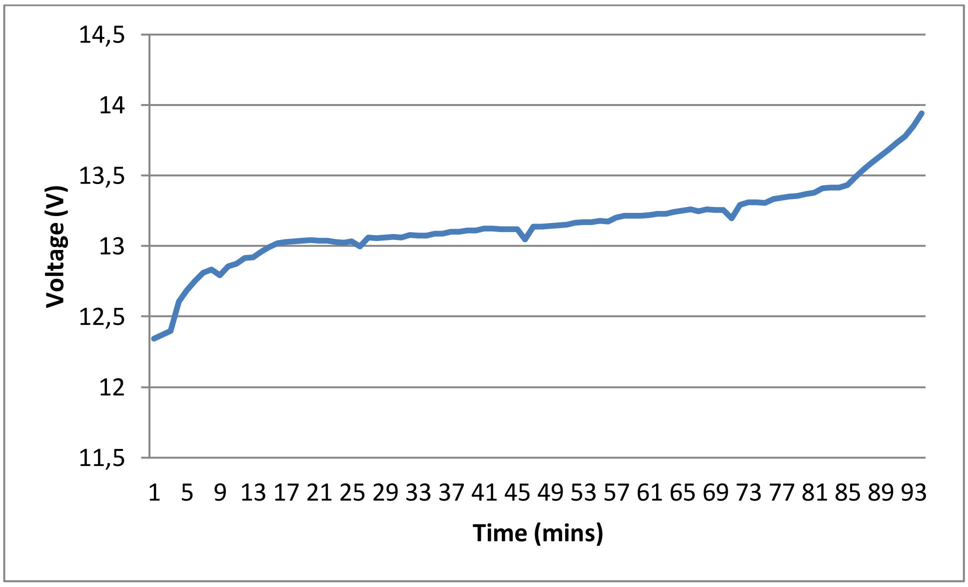


Figure 5.11. Voltage versus time at -4 °C to 0 °C.

The graph showed that the stable voltage was between 13 V to 13.4 V, the drops which showed in every 20 minutes were not obvious in the graph. The minutes between 20 and 80 should be used to analyze the changes of voltage.

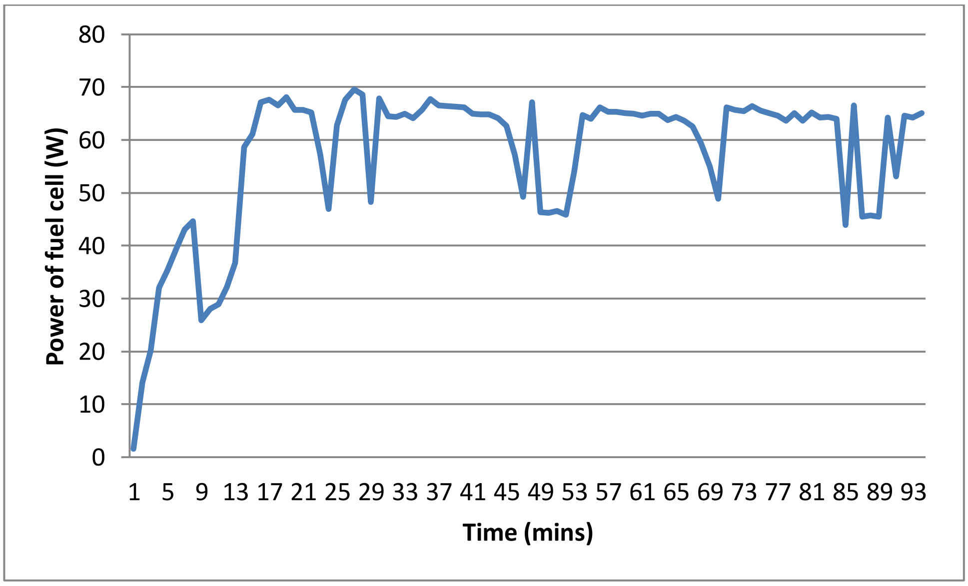


Figure 5.12. Power versus time at -4 °C to 0 °C.

The graph showed the relation between time and power of fuel cell. The highest power of the fuel cell was close to 70 W, and always changed between 50 W and 70 W. There was variation between the time of 20 minutes and 40 minutes, two drops were shown here.

3. Temperature from 6 °C to 8 °C

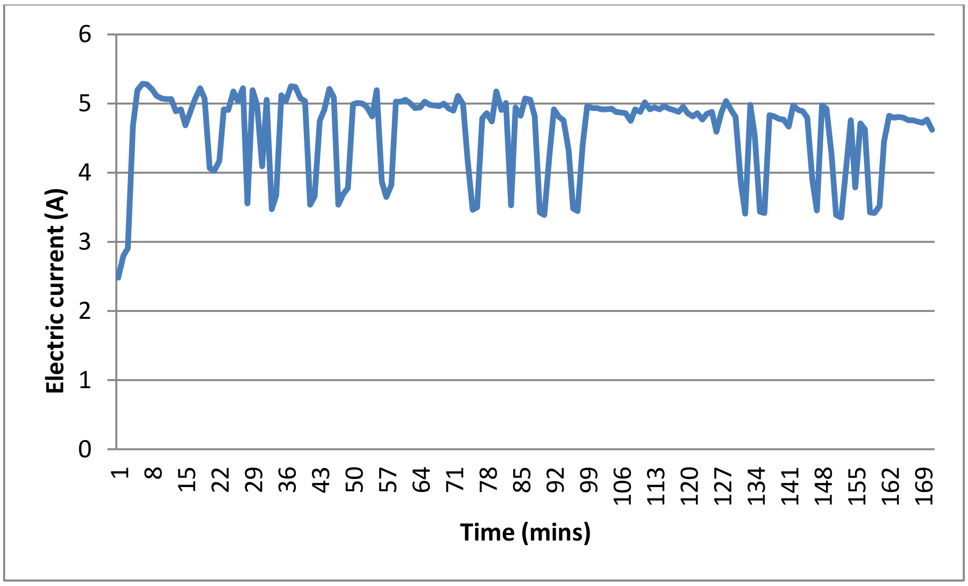


Figure 5.13. Current versus time at 6 °C to 8 °C.

The graph showed that the highest electric current was almost 5 A, besides the changes of electric current were from 3 A to 5 A. There are 5 drops in every 50 minutes.

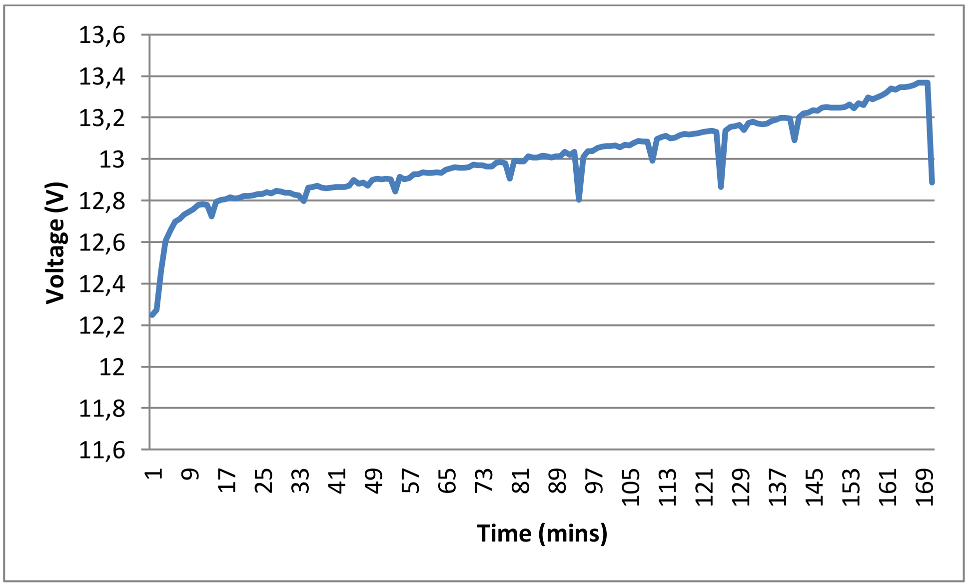


Figure 5.14. Voltage versus time at 6 °C to 8 °C.

The graph showed that the highest voltage in the operating time was 13.4 V. The regular changes of the voltage were between 12.8 V to 13.4 V.

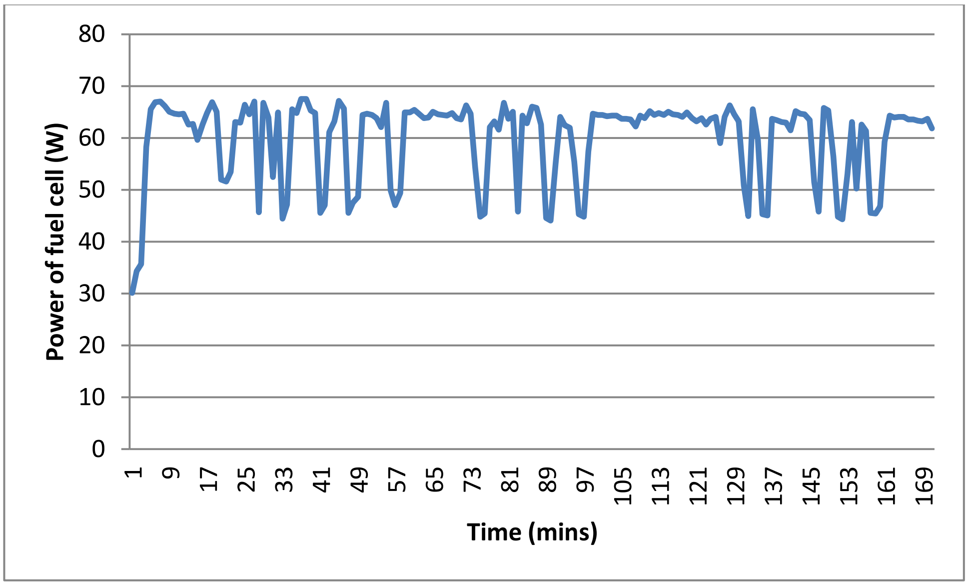


Figure 5.15. Power versus time at 6 °C to 8 °C.

The graph was similar to the graph in the temperature from 21.7 °C to 22.1 °C. In the graph, there were five drops in 50 minutes. The highest power was around 70 W, and the operating power of the fuel cell was between 40 W to 70 W.

According to the analyses above, the numerical value was basically the same in different temperatures, which means that the variation of temperatures had no effect on the EFOY fuel cell. The EFOY fuel cell could operate in the temperatures from -4 °C to 22.1 °C

5.2 Efficiency calculations

In this work, the heating value of methanol is given as a constant value. Mass, voltage and electric current are determined from the measured values. In addition, energy of methanol and useful energy of methanol are calculated by the measurement data.

Heating value of methanol $H = 19.9$ MJ/kg (5.1)

Measured mass of methanol m (kg) (5.2)

Energy of methanol $Q = m \cdot H$ (J) (5.3)

Useful energy of methanol $E = UIt = Pt$ (J) (5.4)

P is the summation power in almost two hours. From 21.7 °C to 22.1 °C,

$E = 8311.767W * 60s = 498706$ J.

So similarly, from -2.5 °C to 0 °C,

$E = 5354.267W * 60s = 321256$ J.

From 6 °C to 8 °C,

$E = 10232.401W * 60s = 613944$ J

Efficiency of methanol $\eta = \frac{E}{Q} \cdot 100\%$ (5.5)

Table 5.11 to shows the data in the experiment:

Table 5.2. The experimental data of EFOY fuel cell.

Temperature(°C)	Measured mass(g)	Energy Q (J)	Useful energy E (w)	Efficiency
21.7 to 22.1	100	489706	136.00	0.246
-2.5 to 0	68	321256	90.85	0.255
6 to 8	118	613944	170.54	0.269

This experiment showed that the efficiency of the EFOY 1600 fuel cell was not affected by the temperatures. The efficiency was always about 25 percent in different temperatures.

5.3 A fuel cell car

A fuel cell car runs on clean hydrogen fuel using PEMFC. Oxygen and hydrogen gases are formed in two transparent containers at the back of the vehicle. The car’s fuel cell unit combines water electrolysis and fuel cell functions into one device.

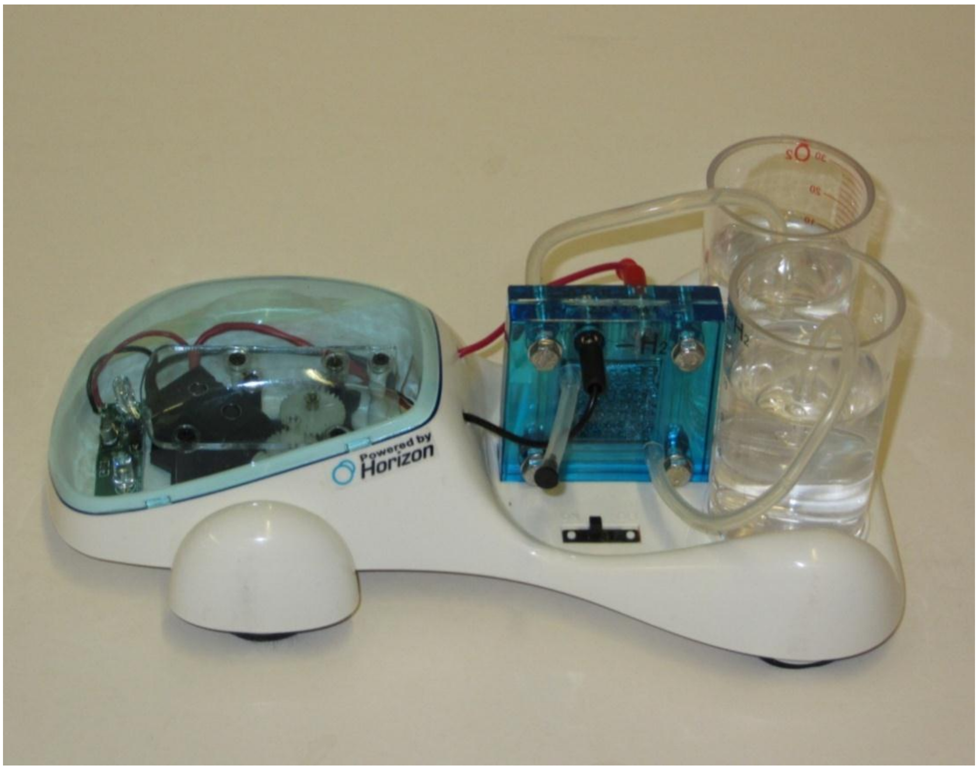


Figure 5.16. A fuel cell car.

The hydro car is a pin-sized vehicle that is powered entirely by a hydrogen fuel cell. It is a next generation power system for electric powered hobby-grade vehicles. In figure 5.16 and 5.17, we can see an LED light and motor, a battery pack with connecting leads, a hydrogen tank, an oxygen tank, inner gas containers, plastic plug pins for fuel cell, transparent silicon tubing. Besides, 0.75 W solar cell and syringe are used for this car.

Figure 5.17. Backside of the hydro car.

This vehicle converts water to hydrogen and oxygen by using energy captured from the sun. 100% clean fuel can be produced by the reversible fuel cell. The fuel cell is a device that can convert hydrogen to usable electric power. Besides, the fuel cell is an assembly of advanced material layers where hydrogen and oxygen react with each other to generate electricity and water, without any combustion. When the car runs on its own hydrogen, two bright blue LED lights will start to flash from the top the car's motor.

In the fuel cell experiment, the voltage, electric current, time, and volume of the water are read during the measurement. The formulas that will be used are:

Useful energy $E = U \cdot I \cdot t$ (5.6)

Energy of hydrogen $Q = n \cdot H$ (5.7)

Amount of substance of hydrogen $n = \frac{V}{V_m}$, (mol) (5.8)

where n equals to the number of mole, V is volume and V_m is mole volume.

The efficiency of the fuel cell $$\eta = \frac{Q}{E} \qquad (5.9)$$

Some data can be used: H = 289.5 kJ / mol, Vm = 22.4 L/ mol. H is the heating value.

In this experiment, electricity is generated by the solar cell. Two tanks are filled with water. The volume of water in hydrogen tank should be recorded before. Then the instrument of measuring voltage and current is collected to the car to operate for a period of time. The voltage, current and time will be recorded. Then we get the volume of hydrogen tank. This experiment has to be done 6 times.

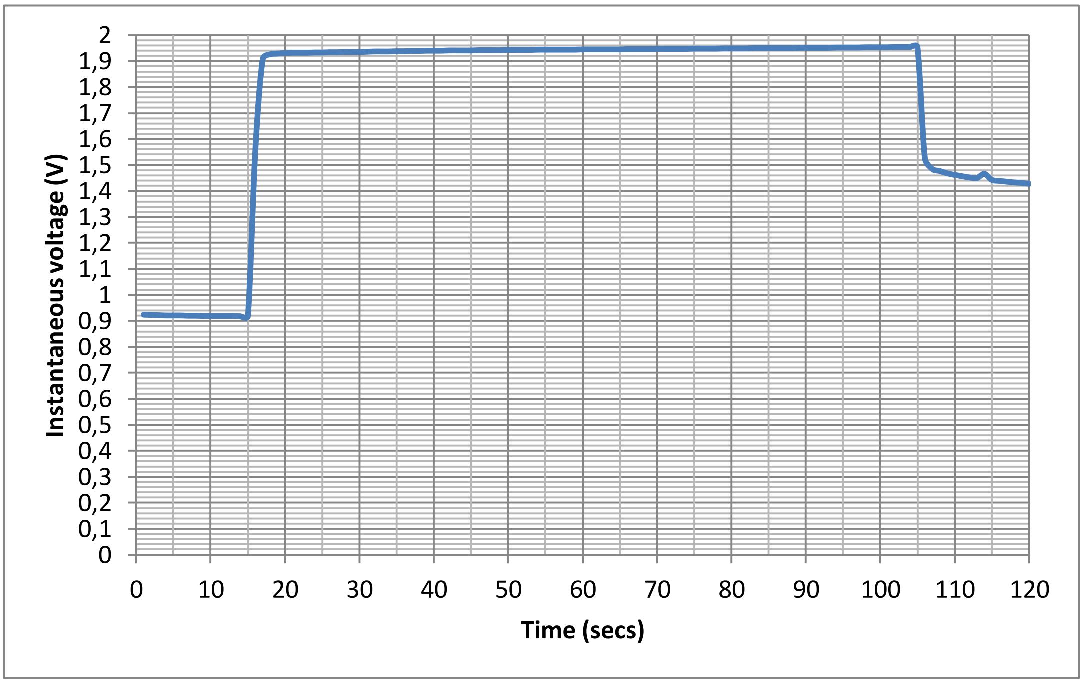


Figure 5.18. Time-instantaneous voltage graph of the Hydrocar experiment.

The graph shows how the instantaneous voltage changes by time in two minutes. The voltage stays at a stable data in the first 15 seconds. It suddenly goes up in 2 seconds. Then, the voltage is stable until it drops in the time of 105 seconds.

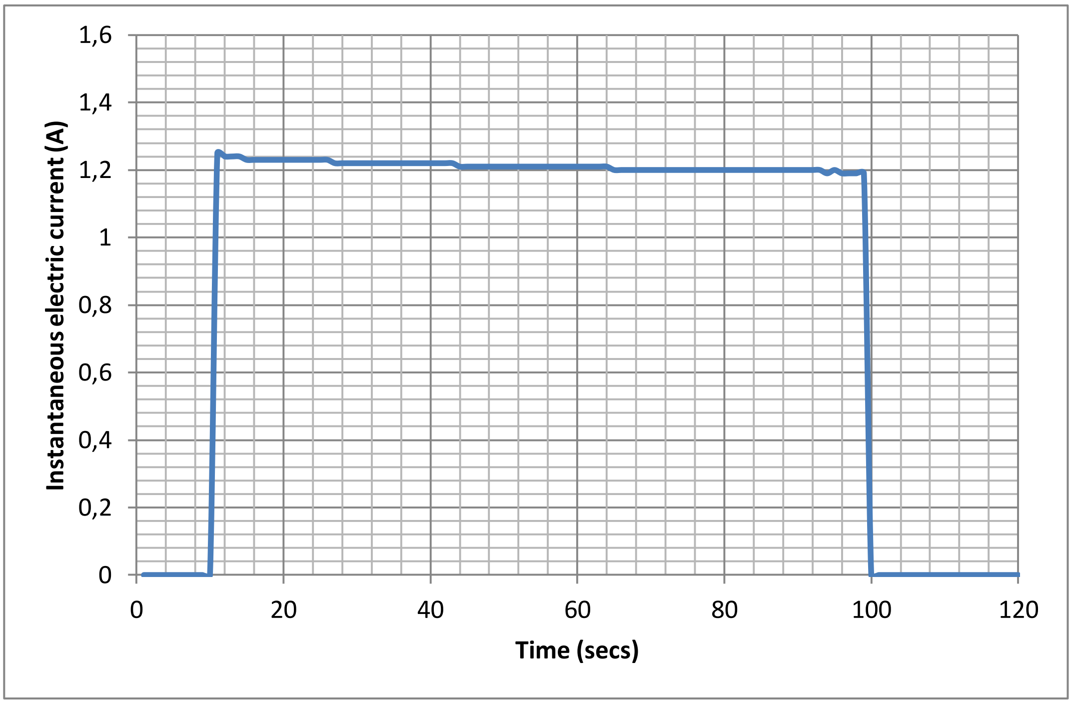


Figure 5.19. Time-instantaneous electric current graph of the Hydrocar experiment.

The graph shows how the instantaneous electric current changes by time in two minutes. There is no electric current in first 10 seconds. The electric current increases after 10 seconds. There is no electric current after 100 seconds. The electric current stays at a stable number from 10 seconds to 100 seconds.

The changes of the instantaneous voltage and instantaneous electric current make the power output to be continuous. When the voltage and the electric current are kept in stable, the power output is produced regularly.

The experimental data is collected in table 5.3.

Table 5.3. The experiment data of solar vehicle.

Voltage(V)	Electric current (A)	Time (s)	E (J)	Volume (ml)	n (mol)	Q (J)	Efficiency η
1.847	0.95	126.89	223	13	$5.8*10^{-4}$	167.91	0.7542
1.836	1.00	121.09	222	13	$5.8*10^{-4}$	167.91	0.7553
1.842	1.02	119.24	224	13	$5.8*10^{-4}$	167.91	0.7494
1.843	0.99	122.73	224	13	$5.8*10^{-4}$	167.91	0.7498
1.846	0.93	152.47	262	15	$7.0*10^{-4}$	202.65	0.7728
1.996	1.26	90.92	229	15	$7.0*10^{-4}$	202.65	0.8862

In table 5.3, formula (5.6) is used to calculate E. The efficiency is almost the same in each case. Thus, there are changes in voltage, electric current and time, but the efficiency is stable.

6 CONCLUSIONS

In this thesis, the possible technical benefits of fuel cells are introduced, as well as various scenarios for fuel cell applications. Fuel cells are considered as a significant part of the creation of the possible hydrogen economy. There is a variety of applications used in the area of fuel cells.

Fuel cells can convert chemical energy directly into electrical energy without combustion. Some energy is lost in the form of heat during the process, however, this heat can be utilized for either heating or cooling.

There are five classes of fuel cells: polymer electrolyte fuel cells (PEMC, also called PEMFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), phosphoric acid fuel cells (PAFC) and alkaline fuel cells (AFC). These fuel cells have been developed rapidly and utilized widely all over the world, especially in developed countries.

These five different fuel cells are introduced in the five sections of my thesis. In the introduction part, brief information has been elaborated to make the readers know what the fuel cell is, and the operating temperatures etc. The second part will give the properties of the different kind of fuel cells in detail. There are formulas, chemical reaction and diagram emerged in focus for readers. Besides, the advantages and disadvantages cannot be missed in this section, because readers want to know what kind of fuel cells can be used in a suitable place. People who read this section can compare the advantages and disadvantages with five fuel cells that will help them to understand fuel cells. The target of fuel cells is to put them into use. The last part, applications of fuel cells show how fuel cells are utilized almost everywhere in people's life.

The most important aspect of the fuel cell is that the fuel cells' efficiency is dependent on the amount of power drawn from it. Drawing more power means drawing more current, this increases the losses in the fuel cells. Most losses manifest themselves as a voltage drop in the cell, so the efficiency of a cell is almost proportional to its voltage. For this reason, it is common to show diagrams of voltage versus current for fuel cells. That is the reason I tend to put in the experiment section in a quite important position. Two experiments are used to confirm the effect of the efficiency on the fuel cells.

EFOY 1600 fuel cell is a kind of safety and convenience generator to have power wherever and whenever you want. We used a fuel cell to load a battery. When the voltage drops below 12.3 volts, it will start automatically to recharge the battery and it shuts itself fully automatically at 14 volts. I chose three different kinds of temperatures to test the efficiency of EFOY 1600 fuel cell. The voltage, electric current and power diagrams were showed in this section. With the calculation of the data I collected from the computer and books, the efficiency of EFOY 1600 fuel cell was calculated. The results showed that EFOY fuel cell was not affected by temperature.

The second experiment is the test of fuel cell vehicle toy, which is powered by a hydrogen fuel cell. According to the test, we can easily get almost the same efficiency in different voltages. This experiment is to make the fuel for the car.

Why are fuel cells used so frequently nowadays? The most important reason is the benefits of the fuel cells. Compared to present energy production with an average of about 40 percent electrical efficiency, high temperature fuel cells with their potential of 50 to 60 percent electrical efficiency, offer significantly reduced carbon emissions and importantly lower emission of other pollutants. The possibility of using heat in the centralized district heating infrastructure offers additional benefits. The ability to use a large range of hydrocarbons as fuel provides a strong advantage in the use of renewable fuels. Anaerobic fermentation-produced biogases from landfill, water purification and agriculture, in addition to gasification gases from solid biomass, can be utilized with good efficiency. Fuel cell is also the most efficient way of utilizing third-generation renewable fuels.

7 REFERENCES

[1] Alkaline Fuel Cells (AFC).
http://www.fctec.com/fctec_types_afc.asp. Search date: 07.05.2011

[2] EFOY Fuel Cell Generators.
http://www.orionair.co.uk/EFOY%20Fuel%20Cells.htm. Search date: 05.06.2011

[3] Energy Efficient Products.
http://www.orionairsales.co.uk/efoy-fuel-cells-efoy-1600-generator-1751-p.asp. Search date: 30.10.2011.

[4] Fuel Cell Handbook.
http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/pubs/fchandbook7.pdf. Search date: 15.03.2011.

[5] Geographical Trends in Fuel Cells.
http://www.cleantechinvestor.com/portal/fuel-cells/6421-geographical-trends-in-fuel-cells.html. Search date: 05.10.2011

[6] How does a fuel cell work.
http://manuscriptedit.wordpress.com/category/scientific/. Search date: 22.04.2011.

[7] How does the EFOY fuel cell work?
http://fuelcells.caravanmoversonline.co.uk/efoy/howfuelcellswork.html. Search date: 01.11.2011.

[8] Introduction to Fuel Cell Technology.
http://nd.edu/~msen/Teaching/DirStudies/FuelCells.pdf. Search date: 17.10.2011

[9] Mao Zongqiang. 2005. Fuel cell. Beijing: Chemical industry Publishing Company.

[10] Molten Carbonate Fuel Cells (MCFC).
http://www.fctec.com/fctec_types_mcfc.asp. Search date: 10.04.2011.

[11] Operational Fuel Cell Voltage.
http://ase.kuas.edu.tw/green/info/solar/Operational_Fuel_Cell_Voltage.pdf. Search date: 16.10.2011.

[12] PEMFC – Proton Exchange Membrane (PEM) Fuel Cells Portal Page.
http://www.fuelcellmarkets.com/fuel_cell_markets/proton_exchange_membrane_fuel_cells_pemfc/4,1,1,2502.html. Search date: 05.04.2011

[13] Performance charactization of passive direct methanol fuel cells.
http://www.me.ust.hk/~mezhao/pdf/104.PDF. Search date: 24.03.2011.

[14] Phosphoric Acid Fuel Cells (PAFC).
http://www.fctec.com/fctec_types_pafc.asp. Search date: 01.05.2011.

[15] Proton Exchange Membrane Fuel Cells PEMFC.
http://www.google.com.hk/url?sa=t&source=web&cd=2&ved=0CCcQFjAB&url=http%3A%2F%2Fwww3.hi.is%2F~hj%2Fh-school08%2FLectureNotes%2FJensOlufJensen2.pdf&rct=j&q=advantage%20and%20disadvantage%20of%20PEMFC&ei=Z6CJTrnKDuW_0QWTp4joDw&usg=AFQjCNEiTUfRKLLYrk4EYr6FxUoDxcircA&cad=rja. Search date: 08.04.2011.

[16] Ritva Hirvonen, Seppo viinikainen, Isomo Nousiainen, Kari Edelmann, Jussi Manninen, Sami Tuhkanen, Juhani Laurikko and Antti Lehtila. 2003. Energy visions 2030. Helsinki: Edita Prima Ltd.

[17] Seppo viinikainen, Isomo Nousiainen, Kari Edelmann, Jussi Manninen, Sami Tuhkanen, Juhani Laurikko and Antti Lehtila. 2009. Energy vision 2050. Helsinki: WS Bookwell Oy.

[18] Sui Zhitong. 2004. Fuel cells and applications. Beijing: Ye Jing Industry Punishing Company.

[19] Solid Oxide Fuel Cell (SOFC).
http://www.fctec.com/fctec_types_sofc.asp. Search date: 15.04.2011.

[20] Solar Hydrogen Production by Electrolysis.
www.dangerouslaboratories.org/h2homesystem.pdf. Search date: 15.10.2011.

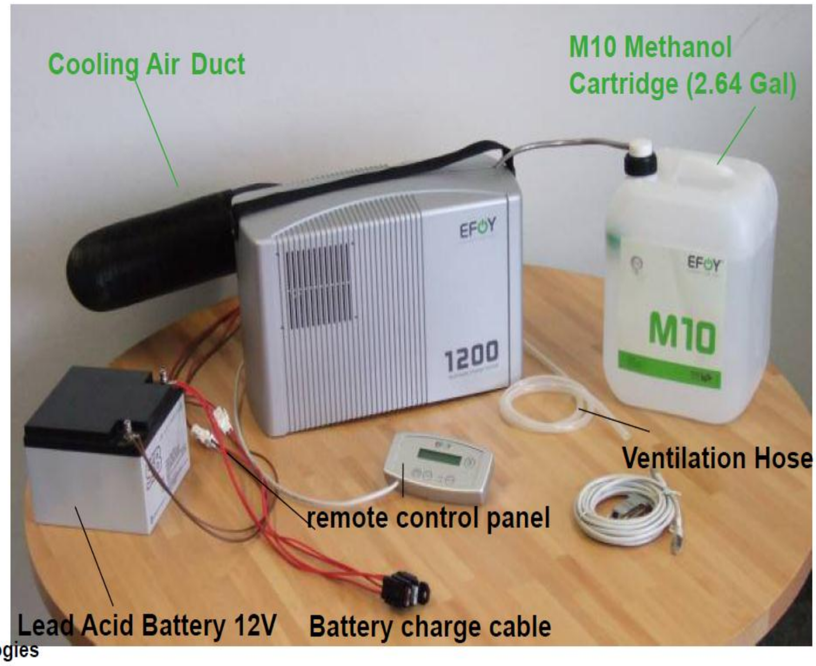
APPENDIX 1 EFOY 1600 Specifications

Application Example EFOY 1200

EFOY
ENERGY FOR YOU

- Continuous output:
  EFOY 600: 2.1 A
  EFOY 1200: 4.2 A
  EFOY 1600: 5.4 A

- Available Cartridge sizes
  M5 (1.3 gal)
  M10 (2.6 gal)
  M28 (7.4 gal)



Sandpiper Technologies
Manteca, California
(209) 239-7460
sales@sandpipertech.com

Remark: Battery is shown for illustration purposes only.
Not Included in delivery.

EFOY Remote Control panel

(included in delivery)

EFOY
ENERGY FOR YOU

data cable to
EFOY main unit

surface mount

frame

Features:

- 16-bit digital display
- "ON / OFF" button to switch device on (manual start) and off
- "AUTO" button to switch device into automatic mode
- "RESET" button
- "SCROLL" button for additional information and language control
- Status LEDS indicating error conditions
- Flush-mounting and on the surface mounting possible

Sandpiper Technologies
Manteca, California
(209) 239-7460
sales@sandpipertech.com

Specifications EFOY 600 / 1200 / 1600

EFOY
ENERGY FOR YOU

Model	600	1200	1600
Charging capacity	600 Wh/day 50 Ah/day	1200 Wh/day 100 Ah/day	1600 Wh/day 130 Ah/day
Nominal voltage	12 V	12 V	12 V
Nominal power	25 W	50 W	65 W
Nominal current	2.1 A	4.2 A	5.4 A
Fuel	1.1 l/kWh	1.1 l/kWh	1.1 l/kWh
consumption	1.3 l/100 Ah	1.3 l/100 Ah	1.3 l/100 Ah
Noise emission	23[1] | 39[2] dB(A)	23[1] | 39[2] dB(A)	23[1] | 39[2] dB(A)
Weight	16.0 lbs	16.5 lbs	16.7 lbs
Operating temperature	-4 °F … +104 °F		
Dimensions	(L x W x H) 17.1“ x 7.9“ x 10.9“		
Recommended batteries	12 V lead batteries (lead-acid or lead-gel).		

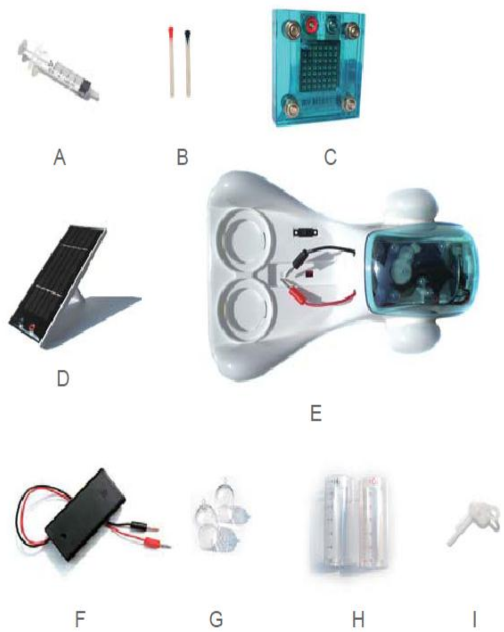
1) 25 ft distance 2) at 3.1 ft distance

Sandpiper Technologies
Manteca, California
(209) 239-7460
sales@sandpipertech.com

APPENDIX 2 Horizon Hydrocar Specification

3. List of Components

A. Syringe
B. Short rubber tubes (see Chapter 4, Step 1)
C. Reversible Fuel Cell
D. Solar panel
E. Car chassis with motor and LED lights
F. Battery pack
G. Inner cylinders
H. Outer cylinders
I. Long rubber tubes (see Chapter 4, Step 1)



You will also need the following 3 items (not included in this kit):
- 2 AA batteries (alkaline batteries highly recommended)
- Scissors
- 100 ml of distilled water*

* Distilled water is highly recommended for optimal use.