DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

FUEL CELL SYSTEMS : THEORY AND APPLICATIONS

by

Mehmet ÖLMEZ

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FUEL CELL SYSTEMS : THEORY AND APPLICATIONS

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by

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"FUEL CELL SYSTEMS : THEORY AND APPLICATIONS"** completed by **MEHMET ÖLMEZ** under supervision of **PROF. DR. CÜNEYT GÜZELİŞ** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Prof. Dr. Cüneyt GÜZELİŞ

(Jury Member)

(Jury Member)

Prof.Dr. Cahit HELVACI
Director
Graduate School of Natural and Applied Sciences

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FUEL CELL SYSTEMS : THEORY AND APPLICATIONS

ABSTRACT

Fuel cells uses electrochemical reactions to produce energy. Because of very useful application areas, proton exchange membrane (PEM) fuel cells are the most promising fuel cell among the other types of fuel cells. PEM fuel cell uses hydrogen as a fuel and as a result of chemical reaction between oxygen and hydrogen, water and electric current is produced. In this thesis, hydrogen energy, other fuel cell types running on hydrogen energy, and challenges on commercialization of fuel cells are presented. Modelling and performance of fuel cells are presented, and also with Matlab simulation program, gross power, polarization curve and the requirement of fuel cell for oxygen, hydrogen and dry air for different current densities are simulated for a PEM fuel cell. The fuel cell system is identified for two different cases, firstly the system is identified for air and hydrogen inputs and voltage output, then for the second case the system is identified for the input is current density and the output is voltage of the cell. Identified systems are tested for different inputs and for the first case when hydrogen and air are inputs, starvation of the fuel cell is shown for different air inputs. The thesis with the presented model give a basis for the control of fuel cell systems.

Keywords : fuel cells, hydrogen energy, renewable energy, modelling, starvation

YAKIT HÜCRESİ SİSTEMLERİ : TEORİ VE UYGULAMALARI

ÖZ

Yakıt hücreleri elektrokimyasal tepkimeler ile enerji üretirler. Kullanım alanlarından dolayı yakıt hücreleri içinde proton değişim zarlı (PEM) yakıt hücreleri ön plana çıkmaktadır. Bir (PEM) yakıt hücresi yakıt olarak hidrojeni kullanır; hidrojenin oksijen ile reaksiyonu sonucu su oluşurken bu süreç içinde elektrik akımı da üretilir. Çalışmada hidrojen enerjisi ve hidrojen enerjisi ile çalışan diğer yakıt hücre tipleri ve bu yakıt hücrelerinin günlük yaşamda kullanımını sınırlayan faktörler tanıtılmıştır. Yakıt hücrelerinin modelllenmesi açıklanmış ve bir PEM yakıt hücresinin kutuplanma eğrisi, akım yoğunluğuna karşı brüt güç eğrisi, ve yakıt hücresinin farklı akım yoğunluklarındaki oksijen, hidrojen ve kuru hava ihtiyacı Matlab benzetim programı ile grafikler halinde gösterilmiştir. Tezde ele alınan yakıt hücresi iki ayrı durum için tanılanmıştır. Birinci durumda sistemin girişleri hava ve hidrojen, çıkışı ise yakıt hücre voltajıdır. İkinci durumda ise giriş, yakıt hücre akım yoğunluğu, çıkış ise yakıt hücre voltajıdır. Tanılanan iki sistem farklı girişler için test edilmiş ve hidrojenin ve havanın giriş olarak kullanıldığı tanılanan sistem üzerinde değişik miktarlarda hava girişleri verilerek yakıt hücresinin açlığı gösterilmiştir. Tezde sunulan model ile yakıt hücre sistemlerinin denetimi için bir taban oluşturmuştur.

Anahtar kelimeler : yakıt hücreleri, hidrojen enerjisi, yenilenebilir enerji, modelleme, açlık

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CHAPTER ONE
INTRODUCTION

Every year by new technological inventions on , energy demands of countries increases. Up to now, worlds' energy demand is supplied mostly by fossil fuels like oil, coal, natural gas etc. Fossil fuels have many disadvantages like air pollution, limited life periods etc.. That's why there is a need for other energy resources. Solar energy, wind energy, nuclear energy, fuel cells etc... are examples of alternative energy sources.

A fuel cell consists of anode and cathode terminals and an electrolyte which is placed between these terminals. Oxygen passes over one terminal and hydrogen over the other terminal, as a result of this process water and electricity are generated. Fuel cells generate DC electrical power. Chapter 2, presents information about hydrogen energy and the importance of fuel cells.

The first fuel cell was built in 1839 by Sir William Grove. First usage area of fuel cells is in a space program. The fuel cells were chosen as the fuel of choice for the United States space program, because nuclear power was risky, solar energy was expensive and not efficient. Fuel cells gave power for the Gemini and Apollo spacecrafts, and provide electricity and water for the space shuttle. Today, many types of fuel cells are designed and each have a different operating structure, those fuel cells are mentioned in Chapter 3.

Although a fuel cell produces electricity there are a number of components connected to a fuel cell to achive proper operation for the required applications. Fuel cells basically run on hydrogen but pure hydrogen is not found on earth, so in order to use different hydrogen resources there is a need for a fuel processor part. For the power stage, fuel cells only produces DC power, so in order to use fuel cells for AC power applications a power stage must be connected to the fuel cell. And also in order to increase efficiency of the fuel cells, some water management, thermal management, air management parts are included to the overall system. In Chapter 4, reformers and general fuel cell system are introduced.

There are many uses for fuel cells in practice. In Chapter 5, automotive, portable, residential and stationary applications of fuel cells are presented.

Fuel cells have many advantages over conventional resources. They are clean, efficient, portable, regenerative etc.... But besides those benefits fuel cells have real drawbacks. These drawbacks are the barriers on commercialization of fuel cells in wide application areas. These barriers are listed and discussed in Chapter 6.

Mathematical models are used to describe the static or dynamic behaviour of the system by using some formulas. Mathematical models are used in many disciplines where an analysis or control of a system is required. In Chapter 7, there is information about mathematical model and performance of fuel cell, and a polarization curve for a fuel cell is simulated and its requirement for hydrogen and oxygen gases is given with Matlab figures. The system is identified and on the identified model starvation of the fuel cell is shown for different air inputs.

In the last chapter, Chapter 8, conclusion part takes place.

CHAPTER TWO
IMPORTANCE OF FUEL CELLS AND HYDROGEN ENERGY

2.1 World's Energy Future

Every year by the inventions on technology, energy demands of countries are increasing. Up to now, worlds energy demand is supplied mostly by fossil fuels like oil, coal, natural gas etc. Fossil fuels have many disadvantages like air pollution, limited life periods etc.. That's why there is a need for another energy resources. These are solar energy, wind energy,nuclear enery ,fuel cells etc...

Solar energy uses light photons for generating electricity. But solar panels are so expensive, we can not have sun always for example at nights or rainy, cloudy days and also solar energy panels uses too much space, so their installations to systems are difficult. And also its efficiency is low. Nowadays they are mostly used at the roofs of the buildings to get hot water and also in some countries ,roofs of the buildings are made up of solar panels to generate electricity in order to use for residential issues.

Wind energy is a good and clean energy but it have very critical drawbacks. First of all wind is a random event we can not have the same wind all the time, and also it has a low efficiency. Wind turbines generate low powers so, many wind turbines must be built in the same area to generate high power. So in some countries there are wind farms which operates like power stations. But wind farms can not be applied all countries for example in Turkey there are lots of rough surfaces so we can not get a constant power due to randomness of wind.

Nuclear energy is a critical energy resource, because after a nuclear reaction we can get lots of power and can easily supply the energy demand of a city. But the drawback of nuclear energy is very dangerous, if security rules are not followed for a nuclear energy station there can be a disaster for the place where the station is installed.

When we look at the energy resources above, the most encouraging energy resource is hydrogen energy which is the fuel of fuel cells. Hydrogen is the most abundant element on earth. Fuel cells have efficiencies in the range of 45-65 percent. This is a very big percentage when compared with other energy resources. No carbon monoxide is given from exhaust which is very dangerous for human health and ozone layer. Fuel cells can be used in a variety of applications like power stations, portable devices, residential use, transportation vehicles, space shuttles etc...

2.2 Fuel Cell Importance

Fuel cells are very important for world's energy future because renewable alternative energy resources are becoming more popular. A fuel cell can be thought like a battery, which an electric current is generated between the terminals. The difference is chemical reactions occurs in the fuel cell and also fuel cells always give energy as soon as fuel is supplied to fuel cell, but batteries looses its energy during operation and we throw them away when all of the energy of a battery is used. The chemical reactions inside the fuel cell changes depending on the type of the fuel cell. Fuel cells have a 150 years past. The first fuel cell was developed by William Grove in the mid-19th century. Now fuel cells are being thought for so many different applications like power stations, portable devices, residential use, transportation vehicles, space shuttles etc... because of their high efficiencies, cleanliness, renewable properties.

2.2.1 Cleanliness and Efficiency of Fuel Cells

Fuel cells reduce air pollution in cities, decrease oil imports for countries, reduce the trade deficit and produce clean future for the next generation.

Stationary fuel cells like solid oxide fuel cells, molten carbonate fuel cells are ideal for electrical power generation. We can connect stationary fuel cells to main power lines or we can provide electricity to many areas that do not have a direct access to power lines, so we can power every equipment in everywhere. And also we can power devices in our houses with fuel cells without connection to power lines. Fuel cells operate silently they do not have moving parts, they reduce air pollution and the heat generated during operation of a fuel cell can be used for many purposes to increase efficiency of the total fuel cell system. Fuel cells are also seen a good alternative to batteries used today, when size problem of fuel cell systems is achieved we will be able to replace batteries with fuel cells.

Efficiency of fuel cells are very great when compared with conventional fossil fuels. Fuel cells have an efficiency of about 40-65 percent. For example a bus running on oil has an efficiency of 10-15 percent (Feldman B.J, nd), and also solar energy has again about 15 percent (Kim B.T., 2004).

2.2.2 Advantages of Fuel Cells

Fuel cells have many advantages over other technologies. There is no another energy technology that have lots of benefits like fuel cells (Fuel Cell Basics Benefits, nd):

The benefits of fuel cells are:

- Energy Security
- Physical Security
- High Reliability/High Quality Power
- Fuel Flexibility
- High Efficiency
- Environmental Benefits
- Modularity/Scalability/Flexible Siting

2.2.2.1 Energy Security

In all over the world many countries using oil for their factories, cars, technology developments import oil. This costs very much load for their budget. If they should use fuel cells instead of using fossil fuel energy they could increase their efficiency and also they should be more wealthier.

2.2.2.2 Physical Security

Fuel cell energy stations have a distributed nature. With the advance on fuel cell energy stations there will be no need to long distance high voltage power grids, because fuel cells will be able to mounted at any area where power is needed, but nowadays all power generation stations are near coal mines, dams, or they are dependent to natural gas. This has a great advantage for physical security because high voltage power grids and central energy stations are always terrorist targets to destroy the countries energy infrastructure.

2.2.2.3 High Reliability/High Quality Power

Energy produced by fuel cells are so reliable and have high quality. Because nowadays central power stations may sometimes broke down and also they dont have constant voltage levels, sometimes these levels get critically high, sometimes they are critically low. But fuel cells generate more reliable power than those conventional power stations and also fuel cell power stations are more efficient than the other stations running on thermoelectric or hydroelectric power stations.

2.2.2.4 Fuel Flexibility

As long as we give fuel to a fuel cell, it continues to generate power. Fuel reformers can get the hydrogen from any material that includes hydrogen , so we can give hydrogen to fuel cells from those materials.

Hydrogen can be supplied from any kind of sources. These sources may be renewable or conventional energy resources but all effort is to use pure renewable and clean resources. For example we can get hydrogen from biomass, natural gas, water, ammonia, hydrocarbons, borohydride etc.. Borohydride is very important for our country because if borohyride could be the best choice to get hydrogen Turkey will be very rich, since it has a huge reserve of boron mines, %72 of worlds total reserve (EtiMaden, nd).

Electrolysis uses an electric current to extract hydrogen from water. So solar energy or wind energy can be used for electrolysis process to provide hydrogen to a fuel cell system. By this way it is a totally zero emission system that requires no fossil fuel. Then energy generated with fuel cell can be used at anywhere. Totally zero-emission energy system promises that, since it requires no fossil fuel and it is not limited by variations in sunlight or wind flow. This system can supply energy for power needs of applications and for transportation, where energy demand changes with load, and since there is no fossil fuel used while generation of electricity it is also a clean energy.

2.2.2.5 High Efficiency

Fuel cells generate energy electrochemically and they do not burn fossil fuels. Fuel cells are more efficient than combustion systems. Combustion systems have mechanical parts so they loose some energy for mechanical process.

When fuel cells are mounted near a place where there is a need of heat, the waste heat generated by fuel cell can be captured and used for many purposes. By this way the efficiency got from fuel cell can be increased.

Nowadays internal combustion engines have 10-15 percent efficiency but fuel cell systems used for transportation will be at least twice more efficient than todays internal combustion engines.

Fuel cell efficiencies vary 40-65 percent nowadays but there are many researches continuing to increase the current efficiencies of fuel cells.

2.2.2.6 Environmental Benefits

Air pollution problem becomes very critical for human being health in big cities. Using fossil fuels for energy generation, transportation etc.. increases carbon emissions to air. This threats human health and also it destroys the environment. Air pollution is the reason of many diseases including cancer, heart disease etc...

Another destroy of fossil fuels to environment is with ozone layer surrounding atmosphere. Carbon emissions destroy ozone layer so ultraviolet lights are not filtered while coming to earth. So today we live some signs of global warming. Summer days are longer when compared with 100 years ago, glaciers started to melt in the poles of earth.

By the use of fuel cells for energy generation, transportation, residential issues, etc... air pollution will dramatically reduce, human health will be safe and global warming due to carbon emissions will stop. That’s why we can leave a clean and health world to the next generations.

2.2.2.7 Modularity/Scalability/Flexible Siting

Fuel cells are scalable, fuel cells can be stacked in series and in parallel until the desired power output is reached. The voltage from a single cell is about 0.7 volts. When the cells are stacked in a series, the operating voltage increases to 0.7 volts multiplied by the number of cells when they are stacked in parallel current capacity of fuel cell can be increased. We can carry fuel cells to anywhere, by this way we can power many portable devices and also we can configure powering capacity of fuel cells for any equipment.

2.3 Hydrogen Energy

Hydrogen is the simplest element to human being. Each atom of hydrogen has only one proton and one electron. It is also the most abundant gas in the universe.

Stars are made primarily of hydrogen. Our sun's energy comes from hydrogen. The sun is composed of hydrogen and helium gases. Inside the sun, hydrogen atoms combine to form helium atoms. This process is called fusion. By this process radient energy is given off. This radiant energy is very important for earth it sustains life on earth. The biggest problem with hydrogen is, it does not exist on earth. It is always mixed with other elements. When a hydrogen element combines with oxygen water (H_2O) is formed. When it combines with carbon many compounds are formed such as methane (CH_4), coal, and petroleum. And also we can find hydrogen in all living and growing things, it is called biomass. It is the lightest element, and it is a gas at normal temperature and pressure. Most of the energy we use today comes from fossil fuels. People want to use more renewable energy because of fossil fuels disadvantages. Hydrogen is usually clean and we can renew it in a short time. Renewable energy sources like solar and wind can not produce energy all the time. The sun does not always shine. The wind does not always blow and it is not a constant event it is always random. We can use many energy sources to produce hydrogen. Hydrogen can store the energy until it is needed and can be moved to where it is needed.

Everyday, we use energy, mostly coal and a little natural gas to make electricity. Electricity is a secondary source of energy. Secondary sources of energy sources are sometimes called energy carriers which we use those sources to store , move, and deliver energy to needed areas. That's why electricity is a secondary source of energy. We convert energy to electricity because first of all electrical energy is very clean and it is easier to move and use it. Electrical energy gives us light, heat, hot water, drive electric machines. We can use this clean energy for indoor and outdoor applications. It would be very time consuming and difficult for us if we had to burn the coal in every application where heat and light is required, or build our own dams. Energy carriers make life easier for human being. Since fuel cells generate electricity hydrogen is very important energy resource for future. Hydrogen is a very clean and efficient energy resource when compared with conventional energy resources.

Today one drawback with hydrogen energy is to store it. Hydrogen is not alone on earth it is always combined with other elements. And also there is an explosion risk for hydrogen. The most promising area for our country with hydrogen technology is storage area. Hydrogen can easily combine with boron to form borohydride and can easily seperate from boron. Turkey has the 72 percent of boron reserves (EtiMaden, nd) in the world, so this technology is very important for our country.

2.3.1 How to Get Hydrogen?

Hydrogen does not exist on earth as a gas, we have to make it. We make hydrogen by separating it from water, biomass, natural gas, ammonia etc..

Today hydrogen is used as a fuel for fuel cells since hydrogen is not found as a pure element. Fuel cell systems have reformers to get pure hydrogen from hydrogen rich resources. For example a simple reforming process is electrolysis, if we are using water as a hydrogen resource with electrolysis fuel cell can get pure hydrogen that it needs. Fuel cells do not care which reforming process is used for getting pure hydrogen any reforming method can be used to seperate hydrogen.

2.3.2 Hydrogen Usage Areas

Hydrogen technology is one of the most promising energy resources for future because we can apply hydrogen technology for any application. It has a very wide use.

First hydrogen energy is used by NASA and it has used for years in the space program. This hydrogen energy is used in alkaline fuel cells to generate electricity for space shuttle and to provide drinking water for astranouts.

Another application area for fuel cells is transportation vehicles. Today almost all big automotive companies completed their prototype fuel cell cars and they are planning to commercialize those cars in 10-15 years time.

Fuel cells promise a great future for residential use. They can be used at homes for home heating, portable devices, providing hot water, running home equipments etc.. Many companies nowadays invest on fuel celled home equipments.

Fuel cells another promising area is n energy production. Fuel cells like solid oxide, and molten carbonate fuel cells can generate much power for an area.

2.3.4 Advantages of Hydrogen Energy

There are lots of advantages of hydrogen energy: (Hydrogen Fuel Technology: a Cleaner and More Secure Energy Future, nd)

- It has the highest energy content per unit of weight of any known fuel.
- When burned in an engine, hydrogen produces effectively zero emissions; when powering a fuel cell, its only waste is water.
- Hydrogen can be produced from abundant domestic resources including natural gas, coal, biomass, and even water.
- Combined with other technologies such as carbon capture and storage, renewable energy and fusion energy, fuel cells could make an emissions-free energy future possible.

CHAPTER THREE
FUEL CELL INTERNAL STRUCTURE AND FUEL CELL TYPES

3.1 Fuel Cell Structure

A fuel cell consists of anode and cathode terminals and an electrolyte is placed between these terminals. Oxygen passes over one terminal and hydrogen over the other terminal, as a result of this process water and electricity is generated. Fuel cells generate electricity as DC. Figure 3.1 (What is a fuel cell, nd) show the basic operation of fuel cell.

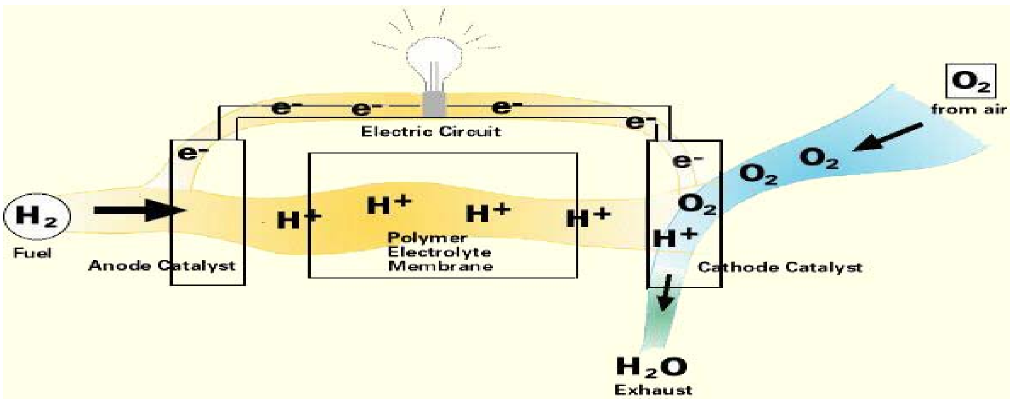

Figure 3. 1 What is a Fuel Cell

While hydrogen passing through the anode terminal hydrogen atom splits into a proton and an electron. Hydrogen proton and electron uses different paths to reach cathode. The proton passes through the electrolyte. The electrons uses an outer path with the load is mounted on. After passing through the load, electrons comes to the cathode. In the cathode terminal, chemical reaction occurs to form water. Reaction process for a fuel cell is shown in Figure 3.2 (What is a Fuel Cell: The HyRoad, nd).

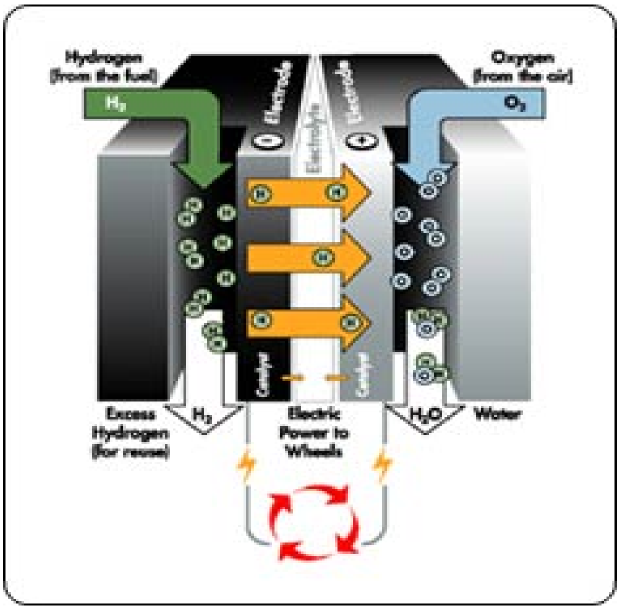

Figure 3. 2 Reaction process

3.1.1 Where did fuel cells originated from?

The first fuel cell was built in 1839 by Sir William Grove. First usage area of fuel cells is , they were chosen as the fuel of choice for the United States space program, because nuclear power was risky, solar energy was expensive and not efficient. Fuel cells gave power for the Gemini and Apollo spacecrafts, and provide electricity and water for the space shuttle.

3.1.2 What sort of fuels can be used in a fuel cell?

Fuel cells work with hydrogen, it is the most abundant element on Earth. The most great thing about fuel cells is that, they do not care about the hydrogen source it can come any source like water, methanol, ethanol, natural gas, gasoline, diesel fuel, ammonia or sodium borohydride. A fuel reformer can extract the hydrogen from any hydrocarbon or alcohol fuel natural gas, ethanol, methanol, propane, and even gasoline or diesel. Hydrogen can also be produced from conventional, nuclear or renewable sources. In Figure 3.3 (Ellis M.W and others, 2001) operation of a fuel cell is shown.

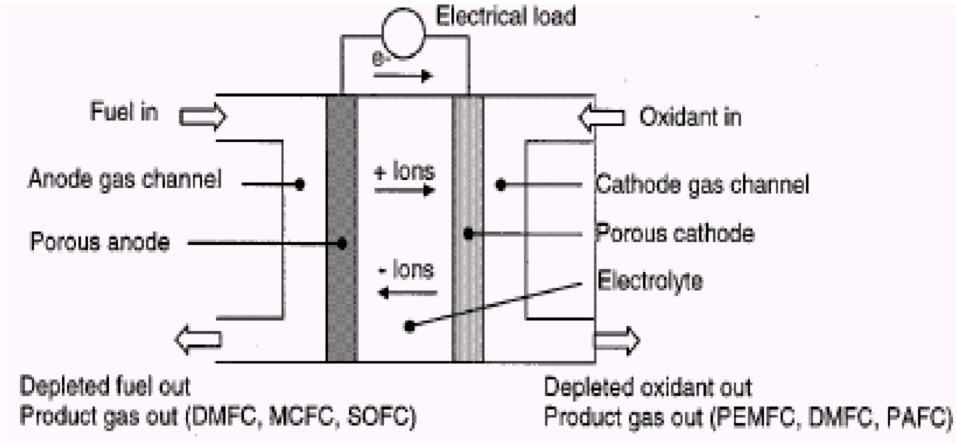

Figure 3. 3 Operation of Fuel Cell

3.2 Types of Fuel Cells

- PEMFC (Proton Exchange Membrane Fuel Cell)
- DMFC (Direct Methanol Fuel Cell)
- AFC (Alkaline Fuel Cell)
- MCFC (Molten Carbonate Fuel Cell)
- SOFC (Solid Oxide Fuel Cell)
- PAFC (Phosphoric Acid Fuel Cell)

Fuel Cell	Anode Reaction	Cathode Reaction
PEMFC	$H_2 \rightarrow 2H^+ + 2e^-$	$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$
DMFC	$CH_3OH + H_2O \rightarrow 6H^+ + 6e^- + CO_2$	$\frac{3}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$
PAFC	$H_2 \rightarrow 2H^+ + 2e^-$	$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$
MCFC	$H_2 + CO_3^{-2} \rightarrow H_2O + CO_2 + 2e^-$	$\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{-2}$
SOFC	$H_2 + O^{-2} \rightarrow H_2O + 2e^-$	$\frac{1}{2}O_2 + 2e^- \rightarrow O^{-2}$
AFC	$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$	$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$

3.2.1 PEM Fuel Cell (PEMFC)

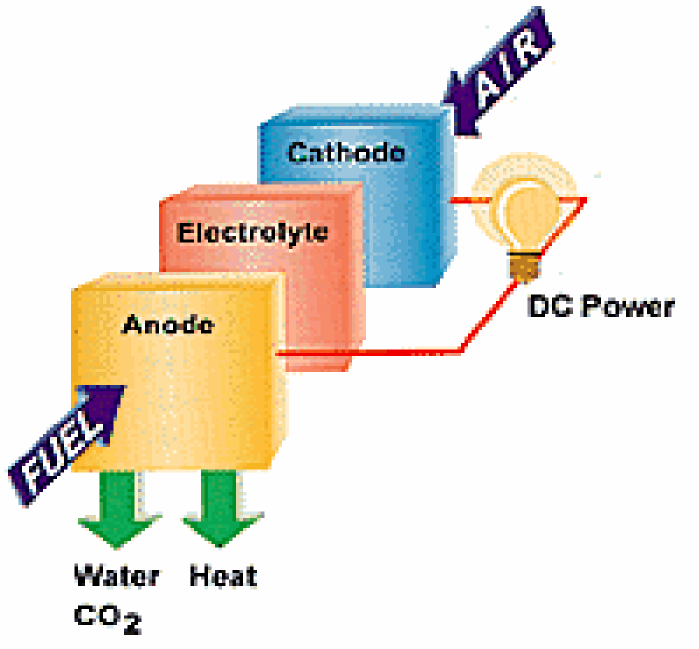

Figure 3. 4 Anode, Electrolyte and Cathode

The Proton Exchange Membrane Fuel Cell (PEMFC) uses a simple reaction. Figure 3.4 (Natural Gas and Technology, nd) shows anode, cathode and electrolyte of the PEMFC.

The electrolyte is the PEM (Proton Exchange Membrane). This membrane only conducts positively charged ions, it blocks negatively charged particles. Figure 3.5 (Nice, nd) shows the internal structure of PEMFC.

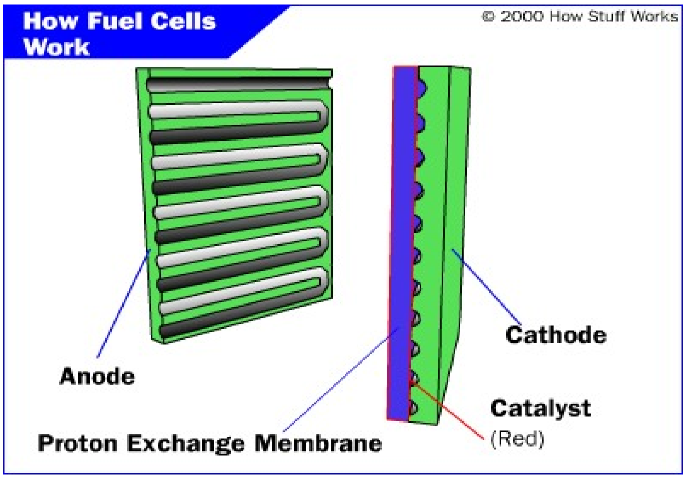

Figure 3. 5 Internal structure of PEMFC

The catalyst is a material where the reaction of oxygen and hydrogen takes place. Rough and porous shape of the catalyst increases the surface area of the platinum.

Proton Exchange Membrane Fuel Cells (PEMFC) are believed to be the best type of fuel cell, since it is thought as a good alternative to gasoline and diesel internal combustion engines.

The fuel for the PEMFC is hydrogen and the charge carrier is the hydrogen ion (proton). At the anode, the hydrogen molecule splits into hydrogen ions (protons) and electrons. The hydrogen ions goes across the electrolyte to the cathode and the electrons flow through an external circuit and produce electric power. Oxygen, usually in the form of air, is supplied to the cathode and combines with the electrons and the hydrogen ions to produce water. The reactions at the electrodes are as below .

Anode Reactions: $2H_2 \Rightarrow 4H^+ + 4e^-$

Cathode Reactions: $O_2 + 4H^+ + 4e^- \Rightarrow 2\,H_2O$

Overall Cell Reactions: $2H_2 + O_2 \Rightarrow 2\,H_2O$

When we compare proton exchange membrane fuel cell with other types of fuel cells PEM fuel cells generate more power per unit wight or volume of any fuel cell type. That's why PEM fuel cell high-power density characteristic makes them relatively compact and lightweight when compared with other types. Also, the operating temperature of PEM fuel cells is 80ºC, which allows rapid start-up. These advantages are very important for automotive applications, so proton exchange membrane fuel cells promise a clean and great future for automotive power applications.

Other advantage of PEM fuel cells is the electrolyte that it uses. It uses a solid electrolyte. Manufacturing of a solid electrolyte compared to liquid electrolyte is less expensive. The solid electrolyte is also more immune to corrosion (PEMFC, nd), compared to many of the other electrolytes, thus less corrosion allows a longer fuel cell system life.

3.2.2 Direct Methanol Fuel Cell (DMFC)

Direct Methanol Fuel Cells (DMFC) technology are thought to be used for portable applications like powering mobile phones and laptop computers.

DMFC has a polymer electrolyte and the charge carrier is the hydrogen ion (proton) like proton exchange membrane fuel cell. But anode and cathode reactions are different. The liquid methanol (CH_3OH) is oxidized with water at the anode generating CO_2, hydrogen ions and the electrons travel through an external circuit which the load is mounted on. The hydrogen ions travel through the electrolyte and react with oxygen from the air and the electrons from the external circuit to form water at the anode completing the circuit.

Anode Reaction: $CH_3OH + H_2O \Rightarrow CO_2 + 6H^+ + 6e^-$

Cathode Reaction: $3/2\ O_2 + 6\ H^+ + 6e^- \Rightarrow 3\ H_2O$

Overall Cell Reaction: $CH_3OH + 3/2\ O_2 \Rightarrow CO_2 + 2\ H_2O$

First developed in the early 1990s, DMFCs were not so good because of their low efficiency and power density (DMFC, nd). But improvements in catalysts and other recent developments have increased power density and the efficiency. But still companies do not invest on direct methanol fuel cells as much as proton exchange membrane fuel cells.

These cells have an operating temperature of about 50ºC-120ºC. This low operating temperature and since direct methanol fuel cells uses methanol directly without any requirement for a fuel reformer, makes the direct methanol fuel cells to use for very small to mid-sized applications, such as cellular phones and other consumer products and also for small sized home equipments.

One disadvantage of the direct methanol fuel cell is that since methanol turns to hydrogen ions and carbondioxide at low temperature this process requires a more active catalyst, which means a larger quantity of expensive platinum catalyst is required than in proton exchange membrane fuel cells (DMFC, nd) .

One other disadvantage with direct methanol fuel cells is, its output is carbondioxide besides water. Since direct methanol fuel cells are thought to be used for small applications, usage of them for indoor applications is not so healthy for human being. Carbondioxide is not toxic as much as carbon monoxide but it is still harmful to human being.

3.2.3 Alkaline Fuel Cell (AFC)

Alkaline fuel cells (AFC) have been used since 1960s by NASA in the space shuttle programs. So researchers have more past experince on alkaline fuel cells. These fuel cells are mounted in the space shuttles, they provide electricity for space shuttle and also drinking water for astranouts. Among the other fuel cells alkaline fuel cells has the most efficiency nearly 70 percent in generating electricity. Figure 3.6 (Types of Fuel Cells, 2006) shows the alkaline fuel cell structure.

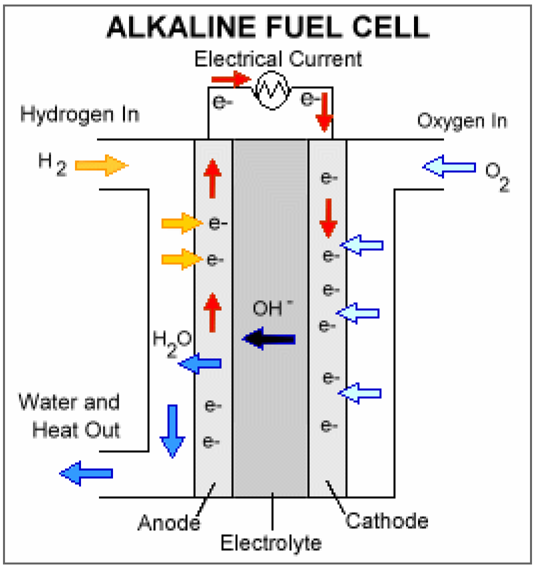

Figure 3. 6 Alkaline Fuel Cell Structure

Alkaline fuel cells use a water-based solution of potassium hydroxide (KOH). The charge carrier for an alkaline fuel cell is the hydroxyl ion (OH-). Hydroxyl ion passes from cathode to anode. In the anode hydroxyl ion meets hydrogen to form water. Formed water then passes to the cathode to produce hydroxyl ions. At the anode side electrons are produced these electrons passes to the cathode by an external way which the load is mounted on. The chemical reactions at the anode and cathode side in an alkaline fuel cell are shown below.

Anode Reaction:	$2\ H_2 + 4\ OH^- \Rightarrow 4\ H_2O + 4\ e^-$
Cathode Reaction:	$O_2 + 2\ H_2O + 4\ e^- \Rightarrow 4\ OH^-$
Overall Net Reaction:	$2\ H_2 + O_2 \Rightarrow 2\ H_2O$

One drawback of alkaline fuel cells is that these fuel cells are very sensitive to carbondioxide. Carbondioxide may be found in the fuel or air if filtering process is not achieved perfectly. When carbondioxide comes into the cell it reacts with the electrolyte and decreases fuel cells performance. That's why alkaline fuel cells input parts must be protected perfectly to prevent carbondioxide coming inside. So nowadays they are used and suitable for space shuttle applications.

Alkaline fuel cells has the big advantage over the other types of fuel cells, manufacturing of alkaline fuel cells is cheap when compared with other types. This is because of the catalyst that is required on the electrodes, they are comparibly inexpensive required for other types of fuel cells.

Although alkaline fuel cells operate at low temperatures compared with others, and has the highest efficiency, they are not suitable for automotive power applications. Because these type of cells sensitive to carbondioxide. They require pure hydrogen and oxygen.

3.2.4 Molten Carbonate Fuel Cell (MCFC)

Molten carbonate fuel cells (MCFC) have high operating temperatures nearly 650ºC. High operating temperatures allow them to use natural gas without using a fuel reformer.

Molten carbonate fuel cells have an electrolyte which is made up of molten mixture of carbonate salts. There are currently two mixtures are in use today. Lithium carbonate and potassium carbonate, or lithium carbonate and sodium carbonate. In order to melt these carbonate salts and have an easy ion crossing through the electrolyte, molten carbonate fuel cells operate at high temperatures. Figure 3.7 (Types of Fuel Cells, 2006) shows the molten carbonate fuel cell structure.

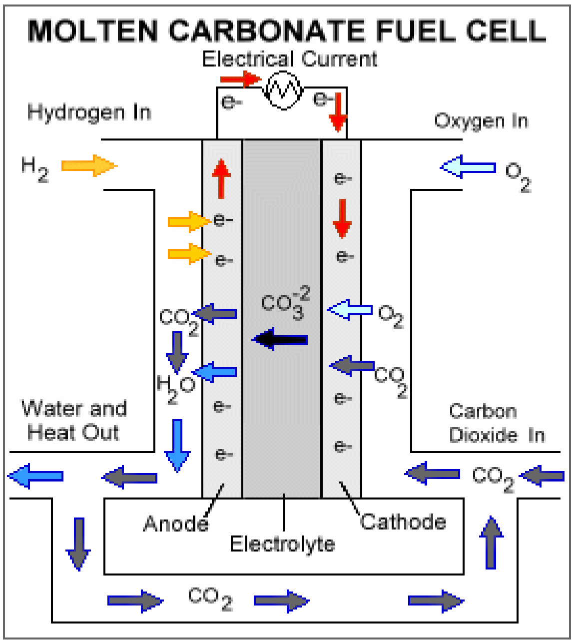

Figure 3. 7 Molten Carbonate Fuel Cell Structure

Carbonate salts melt and allows carbonate ions (CO_3^{2-}) travelling through it at 650ºC. Formed carbonate ions are mobile ions they travel from cathode to the anode. At the anode side carbonate ions combine with hydrogen in order to produce water carbondioxide and electrons. These electrons travel from anode to cathode by an external circuit which the load is mounted on it. Thus electricity and heat is generated. The chemical reactions at the anode and cathode side in a molten carbonate fuel cell are shown below.

Anode Reaction: $CO_3^{2-} + H_2 \Rightarrow H_2O + CO_2 + 2e^-$

Cathode Reaction: $CO_2 + 1/2O_2 + 2e^- \Rightarrow CO_3^{2-}$

Overall Cell Reaction: $H_2(g) + ½O_2(g) + CO_2\ (cathode) \Rightarrow H_2O(g) + CO_2\ (anode)$

Molten carbonate fuel cells have high operating temperatures this property brings advantages and disadvantages when compared with low operating temperature fuel cells. High operating temperature brings fuel cell to use natural gas directly because at high temperatures fuel reforming occurs internally no need for a fuel reformer. Also the heat generated as a result of reaction can be used in many applications in order to increase efficiency of the overall system.

High operating temperature has also disadvantages. High operating temperature requires time to reach operating conditions, so makes the rise time of the system longer. And also it responds slowly to changing power demands. So molten carbonate fuel cells are suitable for applications where constant powers are required.

The 650°C temperature of the MCFC offers several advantages over the lower temperature cells (Hirschenhofer, 1997):

- a major cell component can be made of commonly available sheet metal that can be stamped for less costly fabrication;
- the cell reactions occur with nickel catalysts rather than the more expensive precious metal catalysts;
- reforming can take place within the cell provided a reforming catalyst is added (produces an efficiency gain);
- CO is directly usable in the cell and does not have to be shifted to hydrogen;
- the rejected cell heat is of sufficiently high temperature to drive a gas turbine and/or produce a high pressure steam for use in a turbine as well as for cogeneration.

3.2.5 Solid Oxide Fuel Cell (SOFC)

Solid oxide fuel cell (SOFC) has the highest operating temperature among other fuel cells. They operate in a wide range from 600ºC–1000ºC. In order to operate at such high temperatures solid ceramic is used as an electrolyte. This solid ceramic material allows flowing of oxygen ions (O^{2-}) inside of it.

Oxygen ion (O^{2-}) is the charge carrier in solid oxide fuel cells. Oxygen molecules comes to the cathode side and they split into oxygen ions. These oxygen ions passes through the electrolyte to the anode side. At the anode side these oxygen ions face with hydrogen molecules. At this reaction water and electrons are produced. Formed electrons comes to the cathode by using an outer path at which the load is mounted on. The chemical reactions at the anode and cathode side in a solid oxide fuel cell are shown below. Figure 3.8 (Types of Fuel Cells, 2006) shows the solid oxide fuel cell structure.

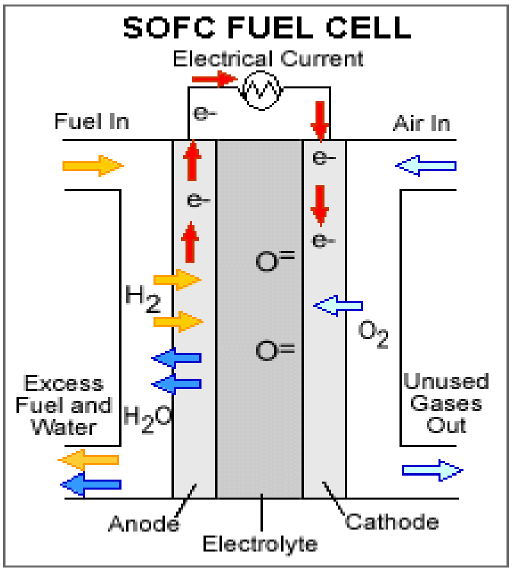

Figure 3. 8 Solid Oxide Fuel Cell Structure

Anode Reaction:	$2\ H_2 + 2\ O^{2-} \Rightarrow 2\ H_2O + 4\ e^-$
Cathode Reaction:	$O_2 + 4\ e^- \Rightarrow 2\ O^{2-}$
Overall Cell Reaction:	$2\ H_2 + O_2 \Rightarrow 2\ H_2O$

The high operating temperature has an advantage because the heat generated after the reaction can be used in any place for heating. Thus efficiency of the fuel cell increases.

High operating temperature has also disadvantages. Like molten carbonate fuel cells, high operating temperature requires time to reach operating conditions, so makes the rise time of the system longer. And also it responds slowly to changing power demands. So solid oxide fuel cells are planned to be used for power station applications.

Another disadvantage of solid oxide fuel cells is, high operating temperatures requires more expensive materials to cover the cell.

Advantage of high operating temperature of solid oxide fuel cell is that there is no need to put a pure fuel inside of it.

3.2.6 Phosphoric Acid Fuel Cell (PAFC)

Phosphoric Acid Fuel Cells (PAFC) are developed in 1960s and after that they have been improved by experts in the case of performance and cost. These developments caused experts to apply these type of fuel cells for early stationary applications.

Phosphoric acid fuel cells uses phosphoric acid (H_3PO_4) as an electrolyte. Since ionic conductivity of phosphoric acid is not sufficient at low temperatures, phosphoric acid fuel cells operate at nearly 200ºC. Figure 3.9 (Types of Fuel Cells, 2006) shows the phosphoric acid fuel cell structure.

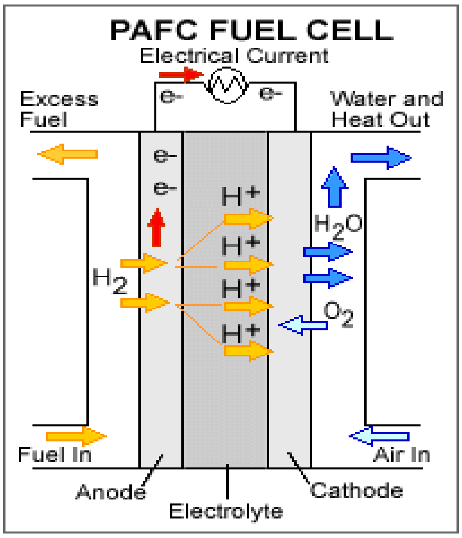

Figure 3. 9 PAFC Structure

The chemical reactions in the phoshoric acid fuel cell is the similar with the reactions in proton exchange membrane fuel cell. The charge carrier is the hydrogen ion (H+). At the anode side hydrogen splits into protons and electrons. The mobile hydrogen ion passes through the electrolyte and comes to cathode side of the fuel cell. The electrons comes to the cathode through an outer way which the load is mounted on. At the cathode side hydrogen ions combine with oxygen to form water and heat. The chemical reactions at the anode and cathode side in a phosphoric acid fuel cell are shown below.

Anode Reaction: $2\ H_2 \Rightarrow 4\ H^+ + 4\ e^-$

Cathode Reaction: $O_2(g) + 4\ H^+ + 4\ e^- \Rightarrow 2\ H_2O$

Overall Cell Reaction: $2\ H_2 + O_2 \Rightarrow 2\ H_2O$

Efficiency of phosphoric acid fuel cell is about 40%. While in operation the operating temperature of phosphoric acid fuel cells can be used for heating applications in order to increase total efficiency.

Another advantage of phosphoric acid fuel cells is, the electrolyte is not affected too much because of poisoning of carbon dioxide so these type of fuel cells can be easily operated with reformed fossil fuel.

Phosphoric acid fuel cells have an electrical power more than 50 kW. So they are applicable to small power station applications.

CHAPTER FOUR
FUEL CELL SYSTEM AND REFORMERS

4.1 Fuel Cell System Schematic

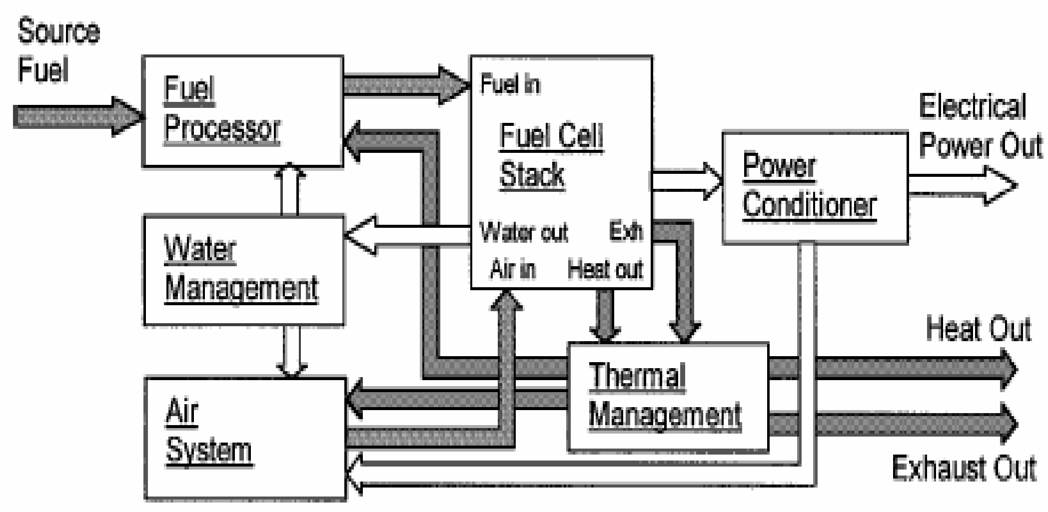

Figure 4. 1 Fuel Cell System Schematic

Although a fuel cell produces electricity there are a number of components connected to a fuel cell to achive proper operation for the required applications. Fuel cells basically run on hydrogen but pure hydrogen is not found on earth so in order to use different hydrogen resources there is a need for a fuel processor part. For the power stage, fuel cells only produces DC power, so in order to use fuel cells for AC power applications a power stage must be connected to the fuel cell. And also in order to increase efficiency of the fuel cell some water management, thermal management, air management parts are included to the overall system.

As seen in the Figure 4.1 (Ellis M.W and others, 2001) the overall fuel cell system consists of a fuel processor (reformer), fuel cell stack, power conditioner unit, air management system, water management system and thermal management systems.

4.2 Reformers

Fuel cells need hydrogen, this needed hydrogen is supplied from different resources. The chemical process while getting hydrogen from different resources is called reforming. Fuels are reformed in different ways. The most used and popular methods are given below.

- steam reforming,
- partial-oxidation reforming,
- autothermal reforming.

Steam reforming has an efficiency advantage over other reforming processes. This process provides the highest concentration of hydrogen when compared with other types. Partial oxidation (POX) reforming is a fast process, it allows rapid starting. But non catalytic partial oxidation reforming process operates at temperatures nearly 1,400°C, but adding a catalyst (catalytic POX or CPOX) can reduce this temperature to as low as 870°C (EG&G Technical Services, 2002). The combination of steam reforming and partial oxidation reforming process is called autothermal reforming.

4.2.1 Steam Reforming

Historically, steam reforming has been the most popular method of converting light hydrocarbons to hydrogen. The fuel is heated and vaporized, then injected with superheated steam into the reaction vessel. The steam-to-carbon molar ratio is usually in the neighborhood of 2.5:1 but developers strive for lower ratios to improve cycle efficiency (EG&G Technical Services, 2002). Excess steam is used to force the reaction to completion and also this excess steam is used to prevent soot.

Like most light hydrocarbons, heavier fuels can be reformed through high temperature reaction with steam. Steam reforming is usually applied to nickel-based catalysts. It can be applied also to cobalt and noble metals, but these are more expensive. The catalytic activity depends on metal surface area. The steam reformer can operate with or without a catalyst. In many commercial applications while operation of steam reforming a catalyst is used to increase reaction rates at low temperatures. The reforming catalyst also increases the water-gas shift reaction. Steam reforming is endothermic, thus it needs external energy to complete reaction. But it is a slow reaction and requires a large reactor (Gray & Frost, 1998). As a result, rapid start up and transients cannot be achieved by steam reforming due to its inherently slower indirect heating (Flynn & others, 1999).

4.2.2 Partial Oxidation

An amount of air or oxygen is used to partially combust the fuel. Partial oxidation is an exothermic reaction, so the reactants of the reaction takes energy and increase their temperature. Like steam reforming process a catalyst can be used to incease reaction activity at low temperatures.

Partial oxidation reactor temperatures vary widely. Noncatalytic processes for gasoline reforming require temperatures in excess of 1,000°C (EG&G Technical Services, 2002). These temperatures require using special materials. The use of a catalyst can lower the operating temperature, allowing the use of more common construction materials such as steel. Lower temperature conversion will also increase system efficiency.

Advantages of partial oxidation that make this type of fuel conversion suitable for transportation power are:

- Partial oxidation does not need indirect heat transfer (across a wall), so the processor is more compact and lightweight (Ahmed, Kumar and Krumpelt , 1999).
- Contrary to widely-held opinion, partial oxidation and autothermal reforming are capable of higher reforming efficiencies than are steam reformers (Ahmed, Kumar and Krumpelt , 1997).

4.2.3 Autothermal Reforming

The combination of steam reforming with partial oxidation is named autothermal reforming. Since steam reforming reaction is endothermic it absorbs part of the heat generated by the partial oxidation reaction since partial oxidation is exothermic. The net result can be seen as a little exothermic process (EG&G Technical Services, 2002).

CHAPTER FIVE
FUEL CELL APPLICATIONS

5.1 Fuel Cell Applications

There are many uses for fuel cells right now, the most promising area for fuel cells is automotive area. Nowadays almost all of the major automakers are working to commercialize a fuel cell car. Many of them completed their prototype cars and that cars are under test today. Beside powering cars fuel cells can power buses, boats, trains, planes, scooters, even bicycles.

Fuel cells are also thought for residential applications. Fuel cells are planned to use for home heating and powering machines at homes for future.

For portable applications fuel cells serve a great future. Firms are developing miniature fuel cells for cellular phones, laptop computers and portable electronics to market.

Fuel cell generators ranging from subkilowatt portable power units to multimegawatt stationary power plants are emerging to deliver clean and efficient power using a large variety of gaseous and liquid fuels. This new technology is suitable for producing heat and power for residential, commercial, and industrial customers. The fuel cells produce electricity without combustion and use very few moving parts, typically limited to air blowers, and fuel and/or water pumps. Because of high fuel conversion efficiency, combined heat and power generation flexibility, friendly siting characteristics, negligible environmental emissions, and lower carbon dioxide emissions, fuel cells are considered at the top of the desirable technologies for a broad spectrum of power generation applications (Farooque & Maru, 2001).

5.1.1 Stationary Applications

Energy demand of the world is increasing day by day. Most of this demand is used for stationary applications. Conventional energy resources such as coal, natural gas, petroleum, hydroelectric, nuclear, wind and solar has many drawbacks. Some of those energy resources are limited, not efficient and some of them have poisoning effect that causes global warming and danger for human health. That’s why fuel cells promise a great future for stationary applications.

Three types of fuel cells are available for stationary applications. These are molten carbonate fuel cells, solid oxide fuel cells and phosphoric acid fuel cells.

Phosphoric Acid Fuel Cells (PAFC) are developed in 1960s and after that they have been improved by experts in the case of performance and cost. These developments caused experts to apply these type of fuel cells for early stationary applications. These type of fuel cells have an operating temperature of nearly 200ºC. Phosphoric acid fuel cells have an electrical power more than 50 kW. So they are applicable to small power station applications.

Molten carbonate fuel cells (MCFC) have high operating temperatures nearly 650ºC. High operating temperatures allow them to use natural gas without using a fuel reformer. High operating temperature requires time to reach operating conditions, so makes the rise time of the system longer. And also it responds slowly to changing power demands. So molten carbonate fuel cells are suitable for applications where constant powers are required.

Solid oxide fuel cell (SOFC) has the highest operating temperature among other fuel cells. They operate in a wide range from 600ºC–1000ºC. In order to operate at such high temperatures solid ceramic is used as an electrolyte. Like molten carbonate fuel cells high operating temperature requires time to reach operating conditions, so makes the rise time of the system longer. And also it responds slowly to changing power demands. So solid oxide fuel cells are planned to be used for power station applications. Figure 5.1 (Fuel Cell Power Generation, nd) shows the stationary application of a fuel cell.

Figure 5. 1 Stationary Application

For a stationary power station:

- The hours of operation per year
- The efficiency

are very important.

Fuel cells can operate much more hours per year when compared with conventional power stations. And also electrical efficiency is comparatively higher. But nowadays only barrier on fuel cell power stations is installation costs. When installation cost drawbacks have improved, fuel cell power stations will be installed in order to serve electricity to many areas. Now many fuel cell systems have been installed all over the world in hospitals, nursing homes, hotels, office buildings, schools, utility power plants, and an airport terminal, providing primary power or backup.

5.1.2 Residential Applications

Fuel cells are ideal for energy generation, since they operate silently without any noise they can be used for residential applications also their clean operation supports residential use. Fuel cells can be used at homes for hot water, heating and power generation applications.

The most suitable fuel cell type for residential applications is proton exchange membrane fuel cells. These fuel cells have a capacity up to 250 kW so they can serve the energy demand of any home. Figure 5.2 (Household fuel cells cogeneration system, nd) shows the heating fuel cells.

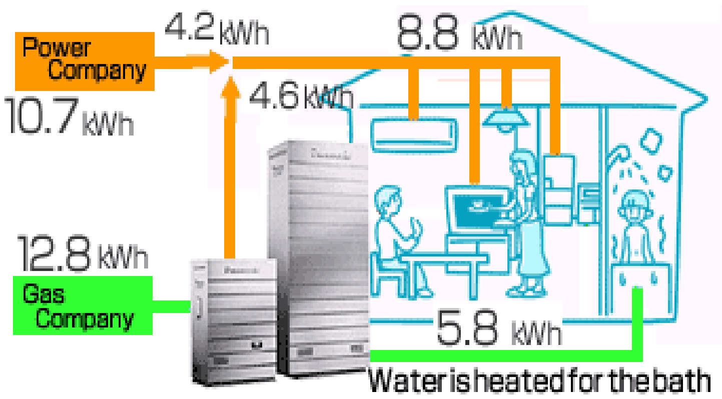

Figure 5. 2 Heating fuel cell

The operating temperature of PEM fuel cells is 80ºC, which allows rapid start-up. The output of the proton exchange membrane fuel cell is water. So from the exhaust 80ºC water and steam is produced. This produced steam energy can be used in heating systems for hot water and home heating. Also the generated electrical energy can power all equipment at home.

For residential applications, fueling the fuel cell system using natural gas is often preferred because of its wide availability and extended distribution system (Dicks, 1996).

5.1.3 Automotive Applications

Nowadays automobiles run on petroleum. Automobiles use internal combustion engines that uses petroleum as a fuel. Burning of oil in an internal combustion engine is very dangerous for environment and also the efficiency of those engines are so low.

Fuel cells produce DC electric power and uses electric motors for mechanical movement of vehicles. That’s why when we compare the efficiency of vehicles run on oil and vehicles run on hydrogen, fuel cell vehicles are much more efficient. And also fuel cell vehicles do not harm to environment. Figure 5.3 (DOE R&D Activities, nd) shows an automotive application of a fuel cell.

Figure 5. 3 Automotive Application of Fuel Cell

Automotive applications require rapid start up, excellent load characteristic, low operating temperature, and long life.

The best type of fuel cells is the proton exchange membrane fuel cells for automotive applications. These fuel cells are believed to be the best type of fuel cell as the alternative to gasoline and diesel internal combustion engines. When we compare proton exchange membrane fuel cell with other types of fuel cells PEM fuel cells generate more power per unit wight or volume of any fuel cell type. That's why PEM fuel cell high-power density characteristic which makes them relatively compact and lightweight when compared with other types. Also, the operating temperature of PEM fuel cells is 80ºC, which allows rapid start-up. These advantages are very important for automotive applications, so proton exchange membrane fuel cells promise a clean and great future for automotive power applications. Other advantage of PEM fuel cells is the electrolyte that it uses. It uses a solid electrolyte. Manufacturing of a solid electrolyte compared to liquid electrolyte is less expensive. The solid electrolyte is also more immune to corrosion, compared to many of the other electrolytes, thus less corrosion allows a longer fuel cell system life.

Nowadays many companies completed the fuel cell powered vehicle prototypes these cars are being tested. Companies planning to commercialize these cars within 10-12 years.

5.1.4 Portable Applications

Today fuel cells are thought to be used in a very wide range area. One of them is the use in portable devices. They are thought to compete with batteries. Because batteries have many disadvantages. They die after a usage period so we throw them away. Batteries contain chemical materials so they are harmful to earth environment. Since they die after a usage period we can not power the same device so long, we have to change the batteries after a period this causes to cut the work done by the device which run on batteries. But fuel cells can operate as long as we give fuel to them. Figure 5.4 (Portable fuel cell powered by water and aluminum, nd) shows the portable application of a fuel cell.

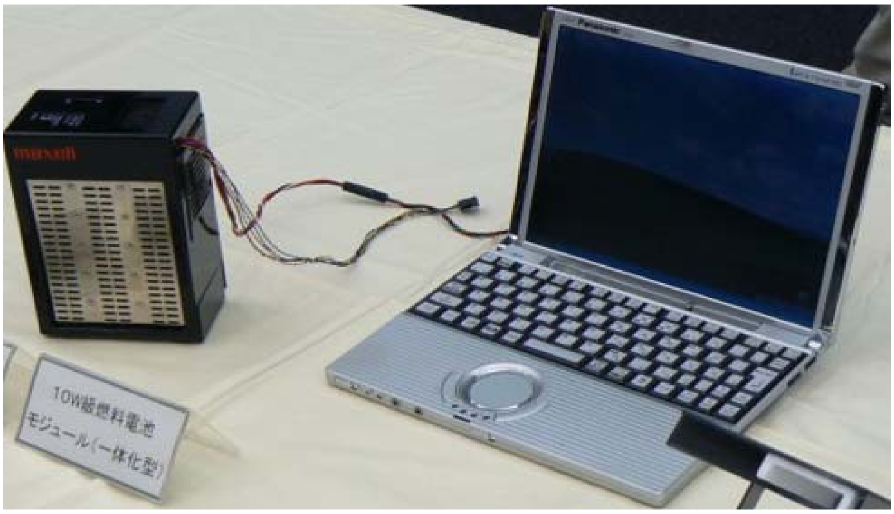

Figure 5. 4 Portable Application of Fuel Cell

As a fuel cell type direct methanol fuel cells are suitable for portable applications. These cells are used in a temperature range from about 50ºC-120ºC. This low operating temperature and since direct methanol fuel cells uses methanol directly without any requirement for a fuel reformer, makes the direct methanol fuel cells to use for very small to mid-sized applications, such as cellular phones and other consumer products and also for small sized home equipments..

CHAPTER SIX
PROBLEMS OF FUEL CELLS

6.1 Drawbacks of Fuel Cell System

Fuel cells have many advantages over conventional resources. They are clean, efficient, portable, regenerative etc.... But besides those benefits fuel cells have real drawbacks. These drawbacks are the barriers on commercialization of fuel cells in wide application areas. These barriers are listed below.

- Management Problems
- High lifetime
- Low Cost
- Hydrogen Storage
- Size, Weight

6.1.1 Management Problems

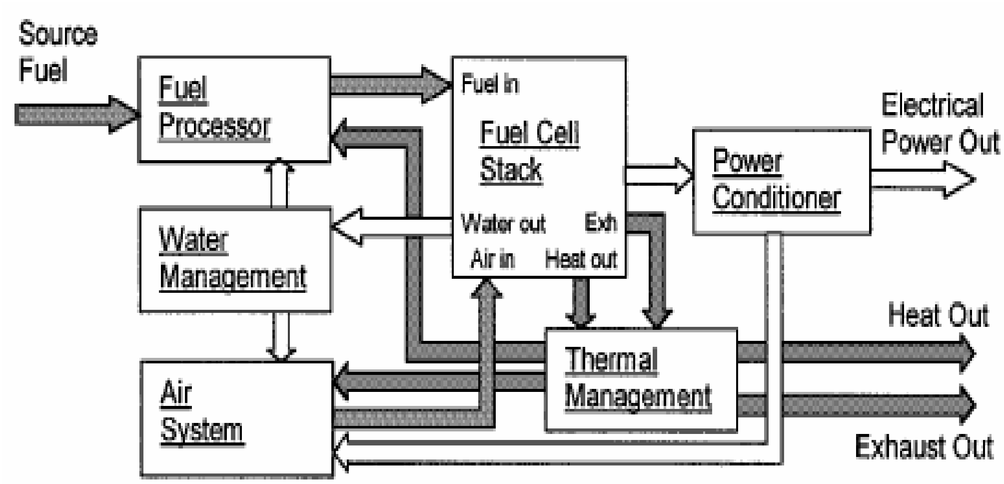

Figure 6. 1 Fuel Cell System

As seen from the Figure 6.1 (Ellis M.W and others, 2001) a fuel cell system is not composed of only fuel cell stack itself. Also there are many subsystems are combined to the fuel cell system. In a fuel cell system;

- Water management,
- Air management,
- Thermal management,
- Power management

subsystems are connected to the stack. These subsystems are designed to increase efficiency of the total system and also they are designed for the application area of the total system.

6.1.1.1 Water Management

Fuel cell systems produce water as output since its input is hydrogen and oxygen. Water from exhaust can be used again as a fuel to reformer for regenerative fuel cells. Also water from exhaust is given to the air system to humidify inside of the stack for proper operation and high life for the stack.

6.1.1.2 Air Management

Fuel cell stack degradation and starvation are very dangerous for cell and equipments running with fuel cell energy. Starvation is a vivid word to describe the operation condition of a fuel cell in sub stoichiometric reactants feeding. In starvation, a fuel cell could not present its best performance, the stack voltage decreases rapidly (Liu & others, 2005)

Fuel cell system must supply oxygen and hydrogen when there is a current demand at load. And also fuel cell humidifier must run properly in order to avoid degradation. So in order to prevent stack degradation and stack starvation compressors that supply air to the stack are very important. Nowadays most compressors have long response times. These transient problem of compressors must be solved by adding additional equipments on it to decrease the response times of compressors. In order to prevent oxygen starvation for a fuel cell, load governer approach is proposed in the literature (Sun & Kolmanovsky, 2005).

6.1.1.3 Thermal Management

Fuel Cell operation is an exothermic reaction. Depending on the type of the fuel cell used the operating temperature changes 40ºC to 1000ºC. So beside electrical energy, thermal energy is produced. The excess heat energy can be used in any area. For example the excess heat energy can be used again for fuel cell operation, residential applications and also for an automotive application the excess heat energy can be used for warming inside of the car in cold days. And also in power generation stations the excess heat can be used to generate steam and this steam can help to turn the turbines, by this way in a fuel cell power station also thermal electrical energy production can be achieved. That's why thermal management for a fuel cell is very important and also this management increases the fuel cell efficiency when the excess heat is used for another application.

6.1.1.4 Power Management

Fuel cells produce DC power but most equipments run with AC power. Then in order to increase total efficiency DC voltage must be converted most efficiently to AC voltage by using power electronic devices such as inverters.

Fuel cells must be used for suitable applications according to their powering degrees. For example there is a device always consuming the same power, e.g. 10 kW, if a fuel cell having 100 kW power generation is used for this application. It will be an expensive construction. So the needs of the application must be understood well, then the fuel cell sytem which will be used for powering an equipment must be installed.

Automotive applications require great instantaneous powers. While fuel cell driving the vehicle can not supply much power, some rechargable batteries can take place to overcome the instantaneous power demand. Then these batteries are recharged for further use, while there is less power demand from load.

6.1.2 Cost

Fuel cells use catalysts in order to increase the reaction inside the stack. There are many catalysts used in fuel cells but mostly platinium is used because of its stable operation. But nowadays platinium is very expensive and usage of this material increases cost. Especially for automotive applications this is a real problem. Automotive applications use proton exchange membrane fuel cells so platinium usage in these cells increases production costs of fuel cell powered vehicles. Instead of platinium using an alternative material will decrease the cost. The cost of fuel cell power systems must be reduced before they can be competitive with conventional technologies.

6.1.3 Durability and Reliability

Fuel cell power systems require more life to meet the demands of current systems. Nowadays corrosion problems in fuel cell stack is a real problem. To achieve more durable systems scientists are working on corrosion problems inside the stack. They are researching more composite materials that can be used inside the fuel cell stack.

6.1.4 System Size

System size and weight are very important for portable applications and automobile applications.

For portable applications fuel cells are thought to replace batteries which are not friendly to environment and have serious drawbacks. Such as short life time, powering capacity decreases with usage and batteries cause to stop our equipments while replacing new batteries with old ones. Fuel cells offer a clean energy and unlimited usage without interrupting the application. But they are still big when compared with batteries. When this problem is overcome by scientists fuel cell will be a good alternative to batteries for portable applications.

Like portable applications, fuel cells offer a good future for automobile applications. But the same problem for portable applications is valid for automobile applications. Size and weight of current fuel cell systems must be further reduced to meet the packaging requirements for automobiles. This requirement is not only for the stack and also this must be achieved for fuel reformer, compressors, sensors, management systems etc.. Today almost all big automobile companies completed their prototype fuel cell powered vehicles but the similar part of all produced fuel cell powered vehicles is they are all big cars. Companies installed fuel cell systems to all big cars for packaging problems. When packaging problems are achieved fuel cells will be able to installed in every car.

6.1.5 Hydrogen Storage

Hydrogen is not alone on earth it is always combined with other elements. And also there is an explosion risk for hydrogen. The most promising area for our country with hydrogen technology is storage area. Hydrogen can easily combine with boron to form borohydride and can easily seperate from boron. Turkey has the 72 percent of boron reserves (EtiMaden, nd) in the world, so this technology is very important for our country.

CHAPTER SEVEN
MODELLING AND PERFORMANCE OF FUEL CELLS

7.1 Mathematical Models

Mathematical models are used to describe the static or dynamic behaviour of the system by using some formulas. Mathematical models are used in many disciplines where an analysis or control of a system is required.

Mathematical models can be classified in several ways, some of which are described below. (Wikipedia, nd)

1. *Linear vs. nonlinear*: In mathematical models variables are used. And these variables are used with operators. If all operators used in a mathematical model are linear we can say that mathematical model is linear model. Otherwise if at least one of the operators are nonlinear we say that mathematical model is nonlinear.

2. *Deterministic vs. probabilistic (stochastic):* In a deterministic model variables are described by unique values or they are determined by parameters in the model. But in a stochastic model variables are not described by unique values. They are described by probability distributions.

3. *Static vs. dynamic:* A static model is independent of time, but a dynamic model does. Discrete dynamic models are represented by difference equations and analog dynamic models are represented by differential equations.

4. *Lumped parameters vs. distributed parameters*: If the model is a homogeneous model then the parameters are lumped, if the model is a heterogeneous model then the parameters are distributed. Distributed parameters are represented by partial differential equations.

Mathematical modelling problems are often classified into black box or white box models, according to how much information is available of the system. A black-box model is a system of which there is no information available. We only give the inputs to the system and get outputs from it then try to find the internal dynamics of the system. A white-box model is a system where all necessary information is available.

Practically all systems are somewhere between the black-box and white-box models, that type of models are grey-box models.

At the last part it is important to find an answer to this question "Does the developed model represent the system well?" At that point verification data is used to evaluate model performance.

7.2 Analytical and Emprical Models

The steady state performance of the fuel cell stack is expressed by the polarisation curve, which is composed of voltage versus the current density for a fuel cell. The steady state model can be use to predict the polarisation curve and hence the steady state performance of the fuel cell stack (Balkin, Holland, & Zhu, 2002).

In the literature there are analytical and emprical models of proton exchange membrane fuel cells. Analytical models have a theoretical background but emprical models are based on experimental measurement datas. Proton exchange membrane fuel cells are complex systems and driving complete analytical models for these systems are difficult. That's why analytical models have a theoretical background and also emprical models assist analytical models.

Thirumalai and White (Thirumalai & White, 1997) completed a good sensitivity analysis on an earlier model (Nguyen & Whitee 1993) to find the most important operating conditions of the proton exchange membrane fuel cell stack. They found that the below factors are important:

- Gas mass flows (pressure and stochiometry of the inlet gases)
- Operating temperature of the fuel cell stack
- Relative humidity of the reactant gases, primarily of the anode gas.

Simple analytical models attempt to classify the operation of the fuel cell into short equations that reflect the reversible voltage and any voltage losses, but complex analytical models that address the overall operation of PEM fuel cells require years of expertise in fuel cell modelling (Balkin, Holland, & Zhu, 2002).

Because of the complexity and interdependence of variables on performance of the fuel cell stack an emprical equation can be used to predict the polarization curve. A landmark emprical equation was presented by (Kim, Lee, & Srinivasan, 1995) that gives the prediction of the polarization curve without dealing with electrochemistry.

7.3 Gibbs Free Energy

Total energy is composed of two types of energy:

- free energy, G
- unavailable energy,TS.

1. Free energy is the energy that is available for use. The unavailable energy is lost in the system. The maximum electrical work (W_{el}) obtainable in a fuel cell operating at constant temperature and pressure is given by the change in (Gibbs) free energy (ΔG) of the electrochemical reaction (EG&G Technical Services, 2002).

$$W_{el} = \Delta G = -nFE$$

where n is the number of electrons participating in the reaction, F is Faraday's constant (96,487 coulombs/g-mole electron), and E is the ideal potential of the cell. For reactants and products in their standard states, then

$$\Delta G^o = -nFE^o$$

where the superscript represents standard state conditions (25°C or 298°K and 1 atm).

For a fuel cell, the maximum work available is related to the free energy of reaction, whereas the enthalpy (heat) of reaction is the pertinent quantity in the case of thermal conversion (such as a heat engine). For the state function

$$\Delta G = \Delta H - T\Delta S$$

the difference between ΔG and ΔH is proportional to the change in entropy (ΔS). The maximum amount of electrical energy available is ΔG, as mentioned above, and the total thermal energy available is ΔH. The amount of heat that is produced by a fuel cell operating reversibly is $T\Delta S$. Reactions in fuel cells that have negative entropy change generate heat, while those with positive entropy change may extract heat from their surroundings if the irreversible generation of heat is smaller than the reversible absorption of heat.

7.4 Ideal Performance

The ideal performance of a fuel cell is defined by its Nernst potential, E, which is the ideal cell voltage.

The Nernst equation provides a relationship between the ideal standard potential (E°) for the cell reaction and the ideal equilibrium potential (E) at other temperatures and partial pressures of reactants and products.

Cell Reactions:

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

Nernst Equation:

$$E = E^o + \left(\frac{RT}{2F}\right)\ln\left[\frac{P_{H_2}}{P_{H_2O}}\right] + \left(\frac{RT}{2F}\right)\ln\left[P_{O_2}^{1/2}\right]$$

E = Equilibrium Potential

F = Faraday's Constant

P = Partial gas pressure

R = Universal gas constant

T = Temperature (Kelvin)

The ideal standard potential (E^{o}) for a fuel cell in which H_2 and O_2 react is 1.229 Volts with liquid water product, or 1.18 Volts with gaseous water product (EG&G Technical Services, 2002). The difference between 1.229 volts and 1.18 volts represents the heat of vaporization of water at standard conditions.

The Figure 7.1 (EG&G Technical Services, 2002) shows the relation of E to cell temperature. Because the figure shows the potential of higher temperature cells, the ideal potential corresponds to a reaction where the water product is in a gaseous state. E is 1.18 volts at standard conditions when considering gaseous water product.

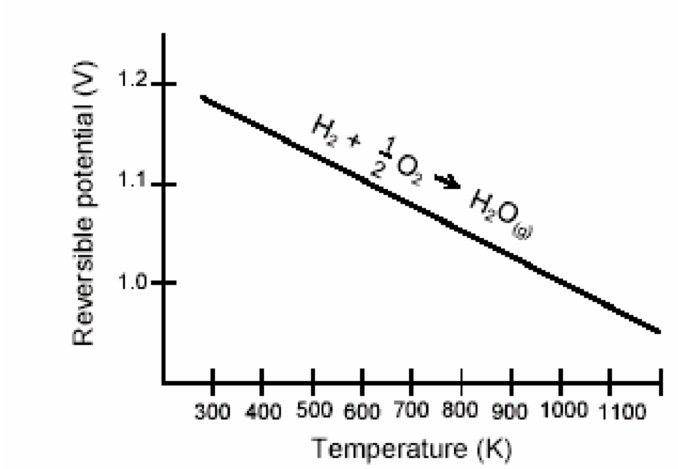

Figure 7. 1 Relation of voltage with cell temperature

The ideal performance of a fuel cell depends on the electrochemical reactions. Low-temperature fuel cells like proton exchange fuel cell, alkaline fuel cell, and phosphoric acid fuel cell require good catalysts to achieve practical reaction rates at the anode and cathode, and H_2 is the only acceptable fuel. With high-temperature fuel cells like molten carbonate fuel cells and solid oxide fuel cells, the requirements for catalyts are relaxed, and the number of potential fuels expands. We have so much alternative for fuel while using these type of fuel cells.

7.5 Unit Operations and Calculations with Fuel Cells

This section includes sample problems to understand better what is going on behind a fuel cell power system. Below, there are two examples given by (EG&G Technical Services, 2002).

The following examples are presented for individual unit operations found within a fuel cell system. Unit operations are the individual building blocks found within a complex chemical process. For example, the desired power output from the fuel cell unit will determine the fuel flow requirement from the fuel processor.

Example 7.5.1 Fuel Flow Rate for 1 Ampere of Current (Conversion Factor Derivation)
What hydrogen flow rate is required to generate 1.0 ampere of current in a fuel cell?

Solution:

For every molecule of hydrogen (H_2) that reacts within a fuel cell, two electrons are liberated at the fuel cell anode. This is most easily seen in the phosphoric acid fuel cells and proton exchange membrane fuel cells because of the simplicity of the anode (fuel) reaction, although the rule of two electrons per diatomic hydrogen molecule (H_2) holds true for all fuel cell types. The solution requires knowledge of the definition of an ampere (A) and an equivalence of electrons.

One equivalence of electrons is 1 g mol of electrons or 6.022 x1023 electrons (Avagadro's number). This quantity of electrons has the charge of 96,487 coulombs (C) (Faraday's constant). Thus, the charge of a single electron is 1.602 x10-19 C. One (1) ampere of current is defined as 1 C/sec.

$$H_2 \rightarrow 2H^+ + 2e^-$$

The moles of hydrogen liberated to generate one amp can be calculated directly:

$$n_{H_2} = (1 \quad A)\left(\frac{1 \quad coulomb/\sec}{1 \quad A}\right)\left(\frac{1 \quad equivalence \quad of \quad e^-}{96487 \quad coulombs}\right)\left(\frac{1 \quad g \quad mol \quad H_2}{2 \quad equiv. \quad of \quad e^-}\right)\left(\frac{3600 \quad \sec}{1 \quad hr}\right) =$$

$$= 0.018655 \ \frac{g \quad mol}{hr - A} H_2$$

$$m_{H_2} = \left(0.018655 \frac{g \quad mol}{hr - A} H_2\right)\left(\frac{2.0158 g}{1 \quad g \quad mol \quad H_2}\right)\left(\frac{1 \quad kg}{1000 \quad g}\right) = 0.037605 \frac{kg \quad H_2}{hr - kA}$$

The result of this calculation, 0.037605 kg H_2 per hour per kA (0.08291 lb H_2 per hour per kA), is a convenient factor that is often used to determine how much fuel must be provided to supply a desired fuel cell power output.

Example 7.5.2 Required Fuel Flow Rate for 1 MW Fuel Cell

A 1.0 MW DC fuel cell stack is operated with a cell voltage of 700 mV on pure hydrogen with a fuel utilization, Uf of 80%.

(a) How much hydrogen will be consumed in lb/hr?

(b) What is the required fuel flow rate?

(c) What is the required air flow rate for a 25% oxidant utilization, Uox?

Solution:

(a) The solution of this problem will be simplified by assuming that the individual fuel cells are arranged in parallel. That is, the fuel cell stack voltage is the same as each individual cell voltage, and the fuel cell stack current is equal to the current of an individual cell times the number of cells.

Recalling that power (P) is the product of voltage (V) and current (I),

P = I x V

Therefore, the current through the fuel cell stack can be calculated as

$$I = \frac{P}{V} = \left(\frac{1 \quad MW}{0.7 \quad V}\right)\left(\frac{10^6 \quad W}{1 \quad MW}\right)\left(\frac{1 \quad VA}{1 \quad W}\right)\left(\frac{1 \quad kA}{1000 \quad A}\right) = 1429 \quad kA$$

The quantity of hydrogen consumed within the fuel cell stack is

$$m_{H_2,consumed} = (1429 \quad kA)\left(\frac{0.08291 \quad lb \quad H_2}{hr - kA}\right) = 118.4\frac{lb \quad H_2}{hr}$$

(b) The utilization of fuel in a fuel cell is defined as

$$U_f = \frac{H_{2,consumed}}{H_{2,in}}$$

Therefore the fuel flow rate required to generate1 MW DC can be calculated as

$$H_{2,in} = \frac{H_{2,consumed}}{U_f} = \frac{118.4\frac{lb \quad H_2}{hr}}{80\%} = 148\frac{lb \quad H_2}{hr}$$

(c) To determine the air requirement, first observe that the stoichiometric ratio (the ratio of atoms in a given molecule) of hydrogen to oxygen is 2 to 1 for H_2O. Thus, the moles of oxygen required for the fuel cell reaction are determined by

$$n_{O_2,consumed} = \left(118.4\frac{lb \quad H_2}{hr}\right)\left(\frac{1 \quad lb \quad mol \quad H_2}{2.0158 \quad lb \quad H_2}\right)\left(\frac{1 \quad lb \quad mol \quad O_2}{2 \quad lb \quad mol \quad H_2}\right) = 29.38\frac{lb \quad mol \quad O_2}{hr}$$

If 25 % utilization is required, then the air feed must contain four times the oxygen that is consumed

$$n_{O_2,\sup plied} = \left(29.38\frac{lb \quad mol \quad O_2 \quad consumed}{hr}\right)\left(\frac{1 \quad lb \quad mol \quad O_2 \quad \sup plied}{0.25 \quad lb \quad mol \quad O_2 \quad consumed}\right) =$$

$$= 117.5 \frac{lb \quad mol \quad O_2}{hr}$$

Because dry air contains 21 % O_2 by volume, or by mole percent, the required mass flow rate of dry air is,

$$m_{air,\sup plied} = \left(117.5 \frac{lb \quad mol \quad O_2 \quad \text{supplied}}{\text{hr}} \right) \left(\frac{1 \quad lb \quad mol \quad air}{0.21 \quad lb \quad mol \quad O_2} \right) \left(\frac{28.85 \quad lb \quad dry \quad air}{1 \quad lb \quad mol \quad of \quad air} \right) =$$

$$= 16142 \frac{lb \quad dry \quad air}{hr}$$

7.6 Fuel Cell Stack Voltage

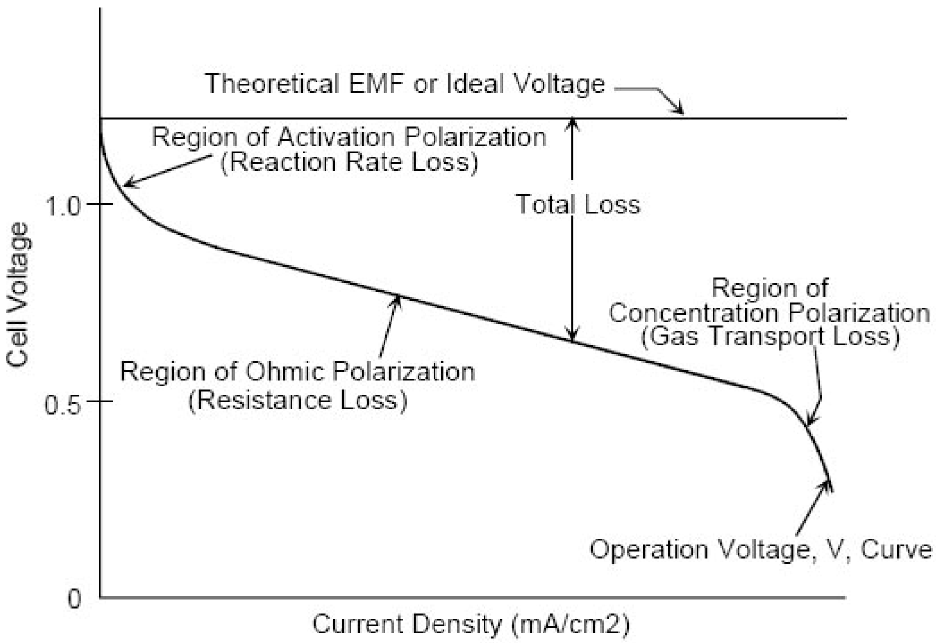

Figure 7. 2 Fuel Cell Voltage

The stack voltage is the function of stack current, cathode pressure, reactant partial pressures, fuel cell temperature and membrane humidity. The current density versus voltage graph is called polarization curve for a fuel cell. Figure 7.2 (Fuel Cell Performances, nd) shows the polarization curve of a fuel cell. Polarization curve is an important feature for performance of any fuel cell. Figure 7.3 (Fuel Cells, nd) shows the construction of the stack from cells.

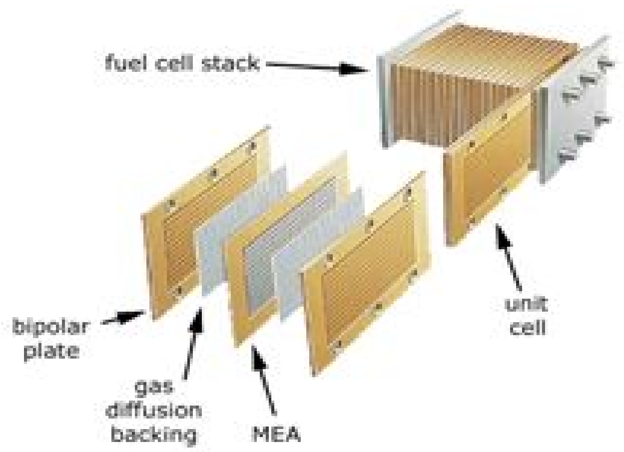

Figure 7. 3 Cell and the Stack

Fuel cell stack consists of multiple fuel cells connected in series, the stack voltage, V_{st}, is obtained as the sum of the individual cell voltages; and the stack current, I_{st}, is equal to the cell current.

7.6.1 Current Density and Stack Voltage

The current density is then defined as stack current per unit of cell active area.

$$I_{fc} = \frac{I_{st}}{A_{fc}}$$

Under the assumption that all cells are identical, the stack voltage can be calculated by multiplying the cell voltage by the number of cells,

$$V_{st} = n \times V_{fc}$$

The fuel cell voltage is calculated using a combination of physical and empirical relationships

$$V_{fc} = E - v_{act} - v_{ohm} - v_{conc}$$

where E is the Nernst thermodynamic potential and v_{act}, v_{ohm} and v_{conc} are activation, ohmic and concentration overvoltages, which represent losses due to various physical or chemical factors.

As developed earlier (Amphlett & others 1994, Baumert ,1993) , the Nernst equation for the hydrogen/oxygen fuel cell, using literature values can be written:

$$E = 1.229 - (8.5 \times 10^{-4})(T - 298.15) + (4.308 \times 10^{-5})T(\ln(p_{H_2}) + \frac{1}{2}\ln(p_{O_2})) \text{ Volts}$$

where T is the cell temperature K , p_{H_2} is the partial pressure of hydrogen at the anode catalyst/gas interface (atm) , and p_{o_2} is the partial pressure of oxygen at the . cathode catalyst/gas interface (atm) .

7.6.2 Activation Overvoltage

The activation overvoltage, V_{act}, becomes because of the need to move electrons and to break and form chemical bonds at the anode and cathode side of the fuel cell (Lee, Lalk, & Appleby, 1998) .

The total activation over voltage is the sum of anode overvoltage and cathode overvoltage.

7.6.2.1 Anode Overvoltage

Anode overvoltage is described by (Amphlett & others, 1995, Berger, 1968) previously with a representation by:

$$n_{act,a} = -\frac{\Delta G_{ec}}{2F} + \frac{RT}{2F}\ln(4FAk_a^0 c_{H_2}) - \frac{RT}{2F}\ln i$$

where ΔG_{ec} is the standard-state free energy of activation for chemisorption (J/mol), F is Faraday's constant (96487 C/equ), A is the active cell area (cm^2), k_a^0 is the intrinsic rate constant (cm/s) for the anode reaction, c_{H_2} is the liquid phase concentration of hydrogen at the anode membrane/gas interface (mol/cm^3), I is the current (amps), and R is the gas constant (J/mol K).,

After substituting known parameters to the equation above equation becomes,

$$n_{act,a} = -(5.18\times10^{-6})\Delta G_{ec} + (4.309\times10^{-5})\times T\left[12.863 + \ln\left(\frac{Ac_{H_2}k_a^0}{i}\right)\right]$$

In the equation above ΔG_{ec} and k_a^0 are chemical parameters of the reaction they are initially unknown, while T , A, c_{H_2} and i can all be quantified (Mann & others, 2000).

7.6.2.2 Cathode Overvoltage

Cathode overvoltage is described by (Amphlett & others, 1995, Berger, 1968) previously with a representation by:

$$n_{act,c} = \frac{RT}{\alpha_c Fn}\left(\ln\left[nFAk_c^0 \exp\left(-\frac{\Delta G_e}{RT}\right)\times\left(c_{O_2}\right)^{(1-\alpha_c)}\left(c_{H^+}\right)^{(1-\alpha_c)}\left(c_{H_2O}\right)^{\alpha_c}\right]-\ln i\right)$$

Both c_{H^+} and c_{H_2O} in above equation should be relatively constant at the membrane/gas interface on the cathode side of the cell (Cisar, 1991). Incorporating these into k_c^0 (to give $k_c^{'}$) and inserting all the known parameter values produces:

$$n_{act,c} = \frac{1}{\alpha_c}\left[-\left(10.36\times10^{-6}\right)\Delta G_e + \left(8.62\times10^{-5}\right)\times T\left(12.863 + \ln A + \ln k_c^{'} + \left(1-\alpha_c\right)\ln c_{O_2} - \ln i\right)\right]$$

where $k_c^{'} = k_c^0\, c_{H^+}\, c_{H_2O}$

Similar to anode overvoltage ΔG_e, α_c and $k_c^{'}$ are chemical properties of thecathode reaction, while T, A, c_{O_2} and i can all be quantified (Mann & others,2000).

7.6.2.3 Total Activation Overvoltage

The total expression giving the total activation overvoltage is the sum of anode overvoltage and the cathode overvoltage (Amphlett & others, 1995)

$$n_{act} = \xi_1 + \xi_2 T + \xi_3 T\left[\ln\left(c_{O_2}\right)\right] + \xi_4 T\left[\ln(i)\right]$$

where;

$$\xi_1 = -\frac{\Delta G_{ec}}{2F} - \frac{\Delta G_e}{\alpha_c nF}$$

$$\xi_2 = \frac{R}{\alpha_c nF}\ln\left[nFAk_c^0\left(c_{H^+}\right)^{(1-\alpha_c)}\left(c_{H_2O}\right)^{\alpha_c}\right] + \frac{R}{2F}\ln\left[4FAk_a^0 c_{H_2}\right]$$

$$\xi_3 = \frac{R(1-\alpha_c)}{\alpha_c nF}$$

$$\xi_4 = -\left(\frac{R}{2F} + \frac{R}{\alpha_c nF}\right)$$

7.6.3 Ohmic Overvoltage

The ohmic voltage drop results from the resistance to the electrons transfer through the collecting plates and carbon electrodes, and the resistance to the protons transfer through the solid membrane. In this model, a general expression for resistance is defined to include all the important parameters of the membrane (Correa & others, 2004).

The equivalent resistance of the membrane is:

$$R_M = \frac{\rho_M . l}{A}$$

where ρ_M is the specific resistivity of the membrane for the electron flow. $(\Omega . cm)$, A is the active cell area, (cm^2) and l is the thickness of the membrane (cm).

The membrane of the Nafion type, is a registered trademark of Dupont and broadly used in PEMFC. Dupont uses the following product designations to denote the thickness of the Nafion membranes: (Correa & others, 2004).

Nafion 117: $l = 178 \mu m$

Nafion 115: $l = 127 \mu m$

Nafion 112: $l = 51 \mu m$

The following numeric expression is used for the resistivity of Nafion membranes (Mann & others, 2000).

$$\rho_M = \frac{181.6\left[1 + 0.03\left(\frac{i_{FC}}{A}\right) + 0.062\left(\frac{T}{303}\right)^2\left(\frac{i_{FC}}{A}\right)^{2.5}\right]}{\left[\varphi - 0.634 - 3\left(\frac{i_{FC}}{A}\right)\right]\exp\left[4.18\left(\frac{T-303}{T}\right)\right]}$$

where the 181.6/(φ-0.634) is the specific resistivity (ohm.cm) at zero current and $30^o C$

The parameter φ has a maximum value of 23 and it is influenced by the membrane preparation procedure, it is a function of the relative humidity and stochiometric ratio of the anode feed gas, and also it is a function of the age of the membrane (Mann & others, 2000).

7.6.4 Concentration Overvoltage

The mass transport affects the concentrations of hydrogen and oxygen. This, in turn, causes a decrease of the partial pressures of these gases. Reduction in the pressures of oxygen and hydrogen depend on the electrical current and on the physical characteristics of the system. To determine an equation for this voltage drop, a maximum current density is defined, J_{max} under which the fuel is being used at the same rate of the maximum supply speed. The current density cannot surpass this limit because the fuel cannot be supplied at a larger rate. Typical values for J_{max} are in the range of 500–1500 mA/cm^2 (Correa & others, 2004).

Thus, the voltage drop due to the mass transport can be determined by:

$$V_{con} = -B \ln\left(1 - \frac{J}{J_{max}}\right)$$

where B(V) is a parametric coefficient, which depends on the cell and its operation state, and J represents the actual current density of the cell $\left(A/cm^2\right)$

7.7 Simulations (Gross Power and Polarization Curves)

PEMFC Stack Model is simulated with the stack parameters (Lin, 1999)

- Number of Cells = 56
- Max. Current Density = 1800 mA/cm^2
- Cell Area = 170 cm^2
- Power = 5.9 kW

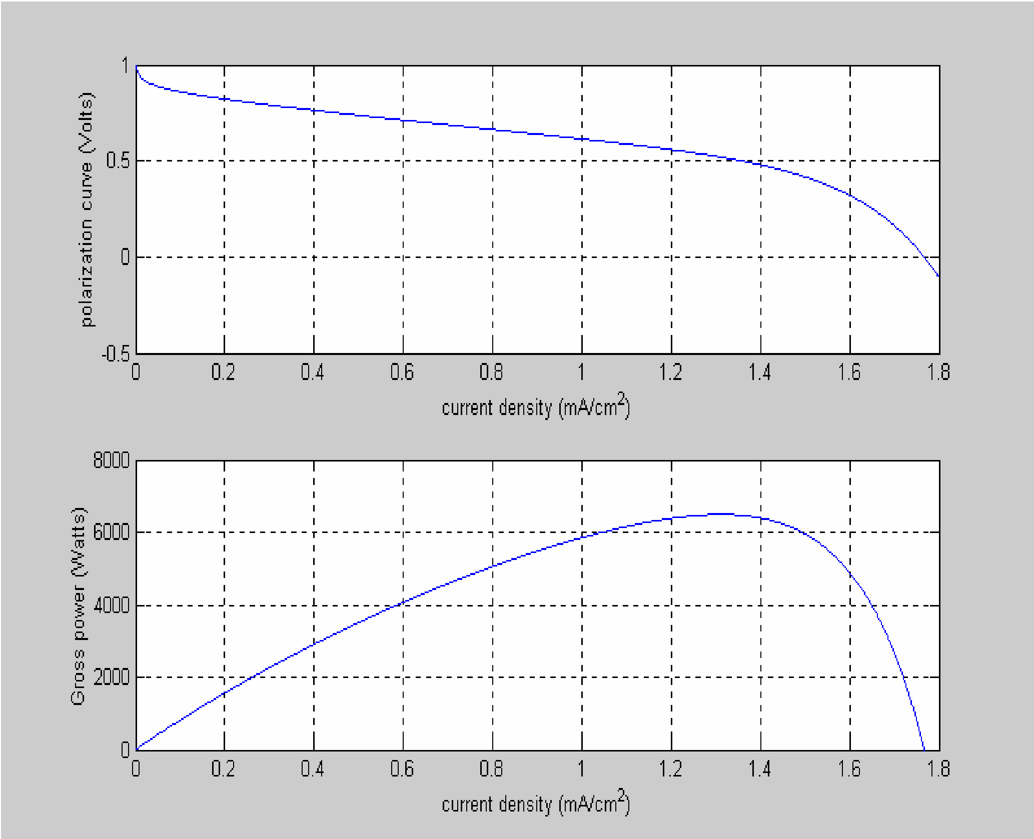

Figure 7. 4 Polarization curve and gross power

Figure 7.4 is plotted in order to show the polarization curve and gross power of the fuel cell. Polarization curve is plotted for a single cell and gross power is plotted for the stack which is composed of 56 cells.

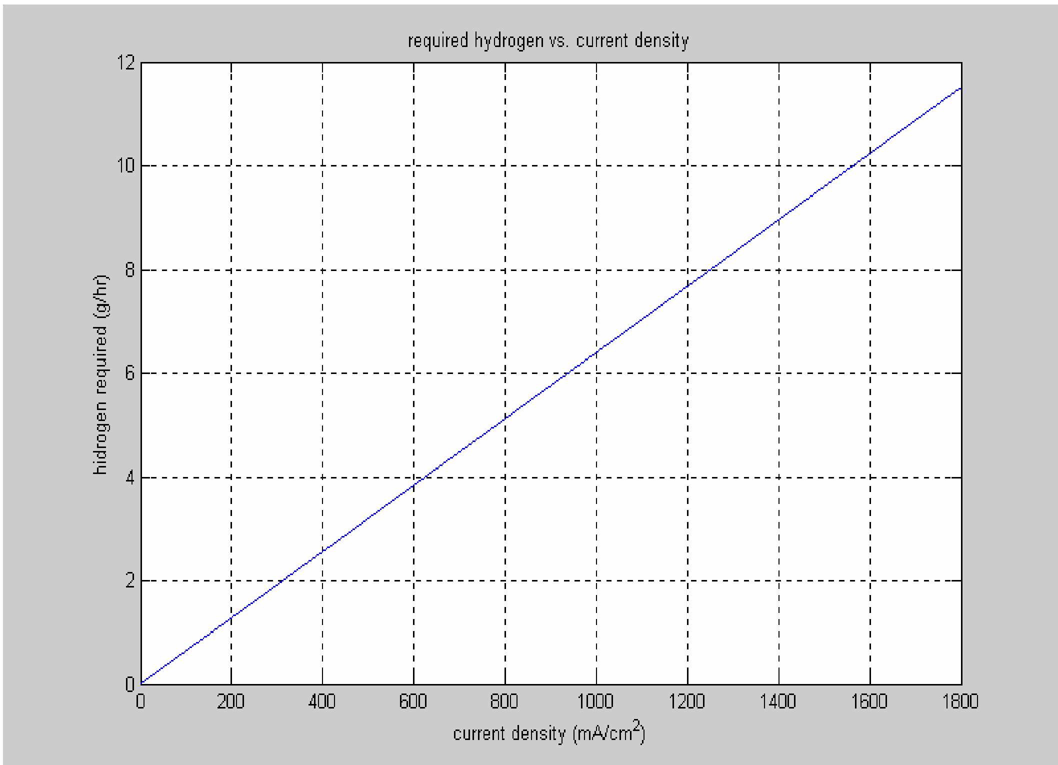

Figure 7. 5 Required hydrogen vs. current density

Figure 7.5 is plotted to show the hydrogen need of the fuel cell. The hydrogen need of fuel cell is computed using unit operation examples in Chapter 7, and then it is plotted using Matlab simulation program.

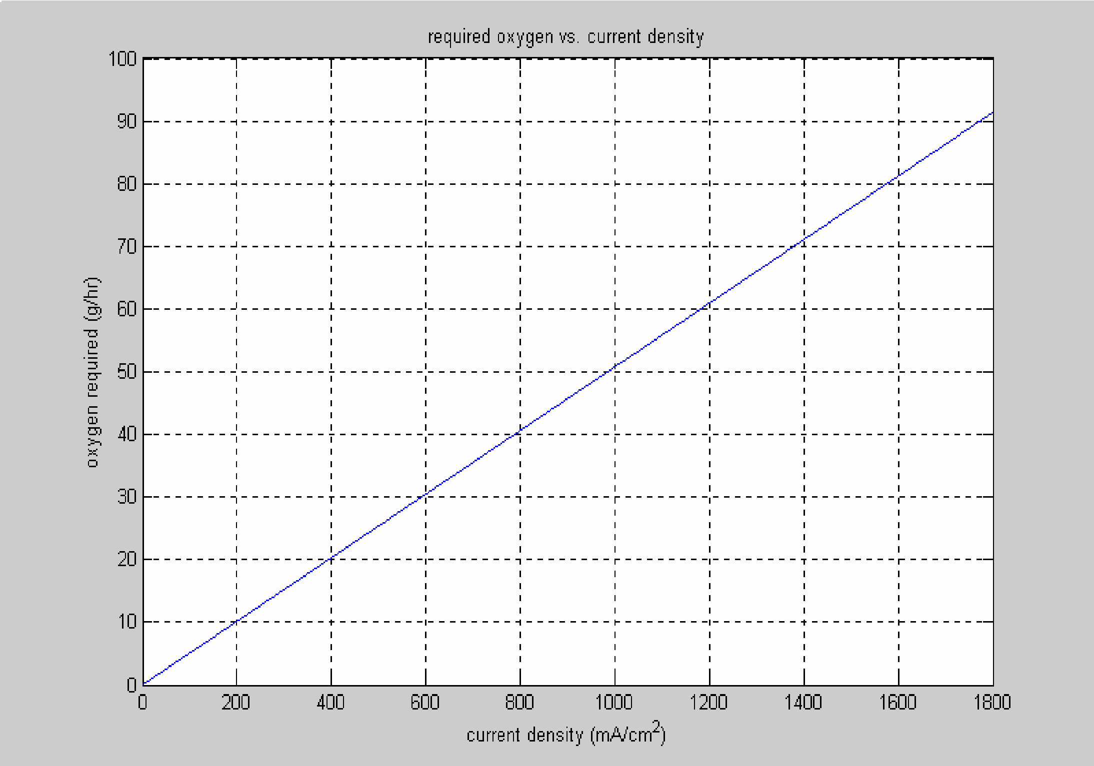

Figure 7. 6 Required oxygen vs. current density

Figure 7.6 is plotted to show the oxygen need of the fuel cell. The oxygen need of fuel cell is computed using unit operation examples in Chapter 7, and then it is plotted using Matlab simulation program.

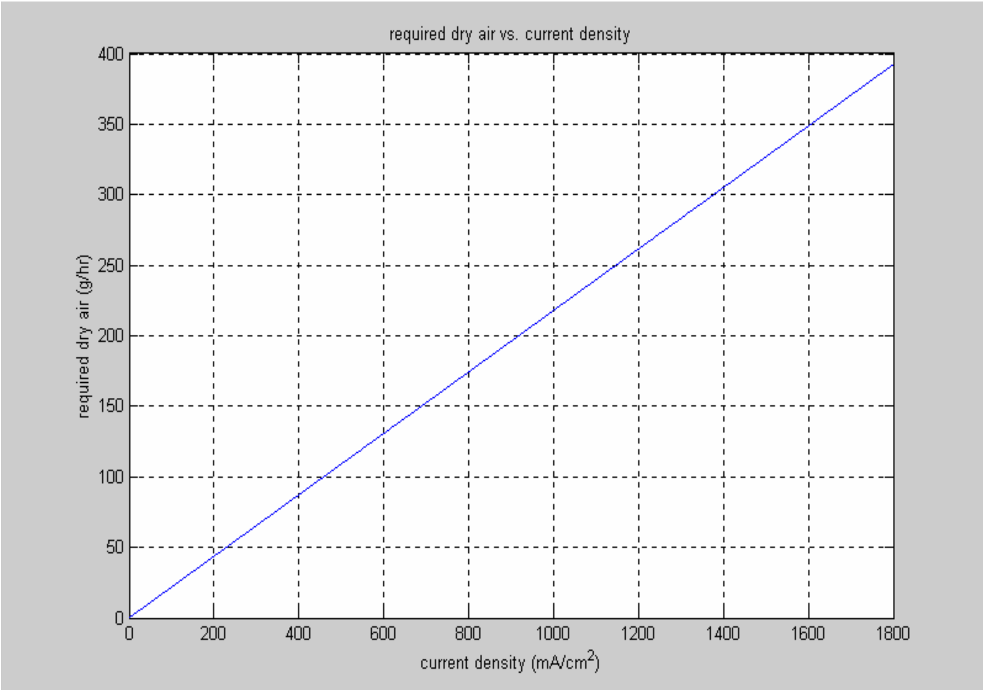

Figure 7. 7 Required dry air vs. current density

Figure 7.7 is plotted to show the dry air need of the fuel cell. The dry air need of fuel cell is computed using unit operation examples in Chapter 7, and then it is plotted using Matlab simulation program.

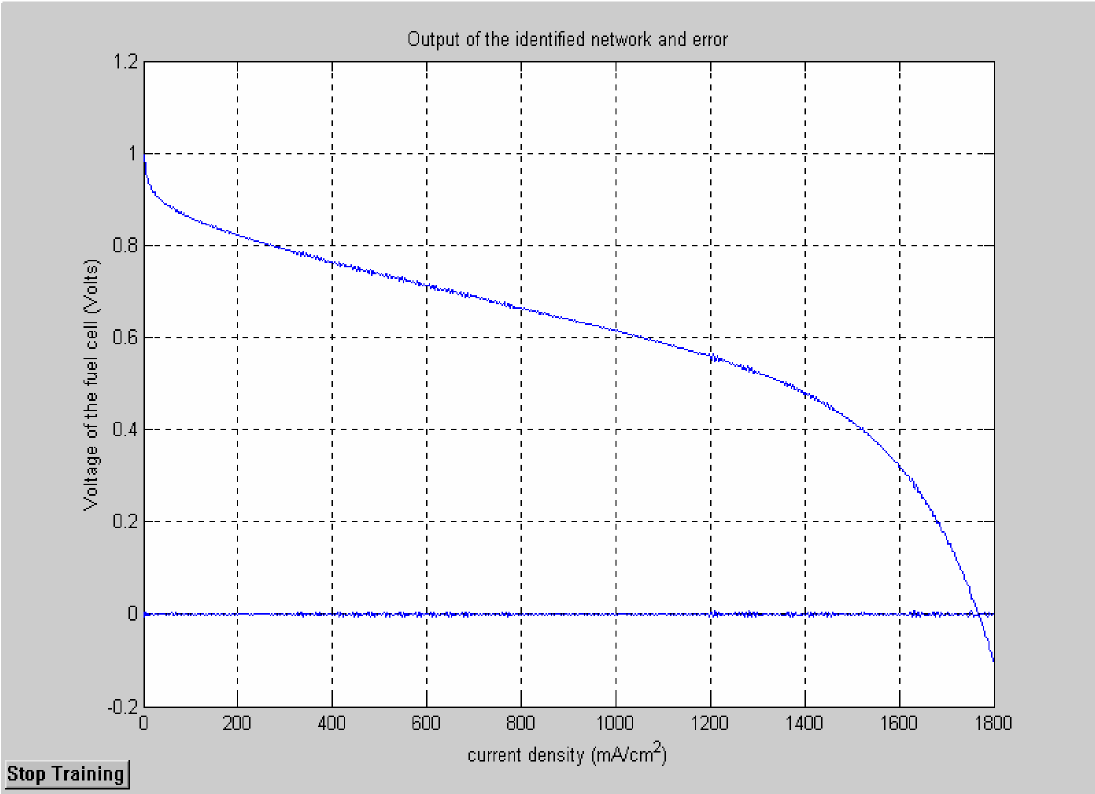

Figure 7.8 Identified system output, when inputs are air and hydrogen

The fuel cell is identified with an RBF network, The system is identified with inputs dry air and hydrogen computed in Figure 7.7 and Figure 7.5, and with an output which is the polarization curve of the fuel cell plotted in Figure 7.4. Figure 7.8 shows the identified system output which is the polarization curve and the error which is very close to zero.

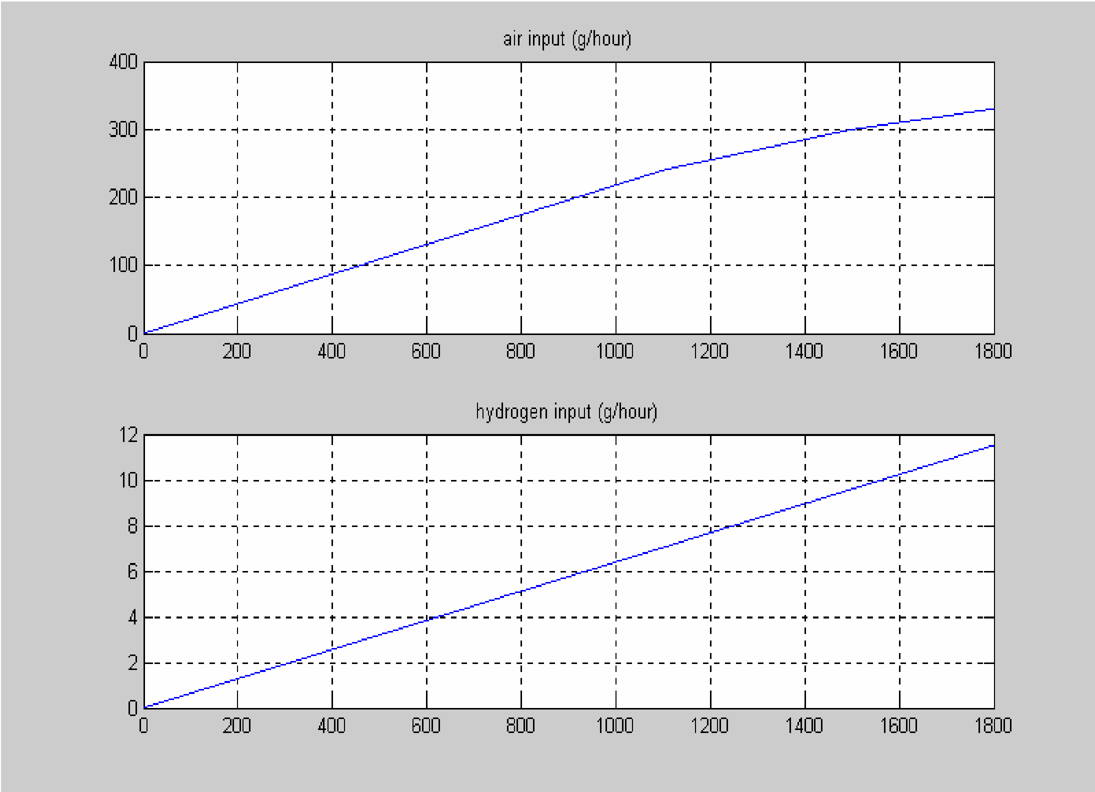

Figure 7.9 Input to the identified system (with less air than required)

The system is identified and then inputs are given to the identified system in order to show starvation problem of the fuel cell. Figure 7.9 shows the inputs (dry air and hydrogen) that is given to the system. To show starvation dry air input is given less than required to the system.

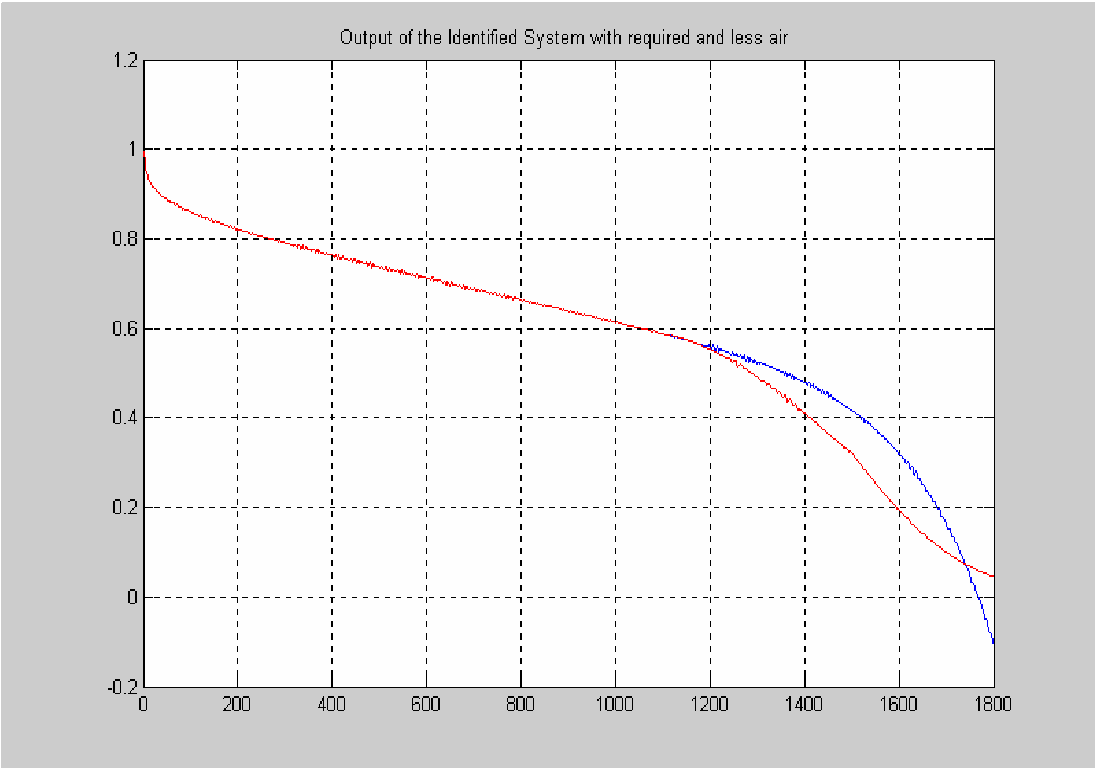

Figure 7.10 Starvation of the cell when less oxygen is given than required

When inputs are dry air and hydrogen in Figure 7.9, output of the system which is the polarization curve is observed. Figure 7.10 shows two polarization curves the above curve is for the system when inputs are like in Figure 7.5 and 7. 7, below curve shows the fall on the voltage of the cell when inputs are like in Figure 7.9.

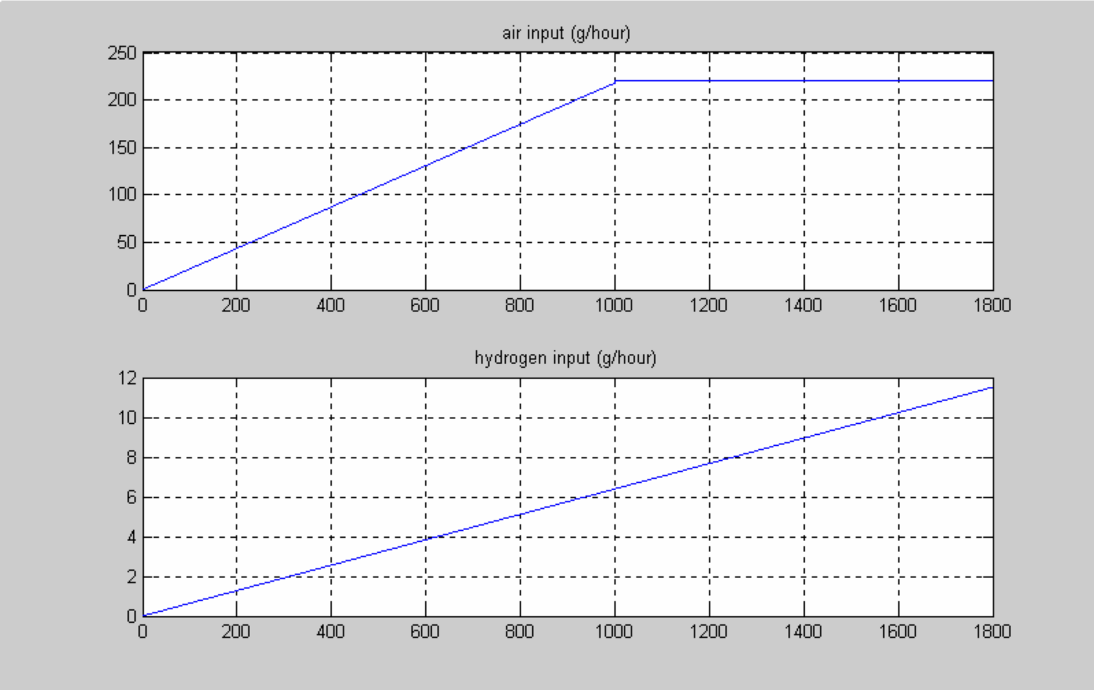

Figure 7.11 Input to the identified system (with an exaggerated air input)

The system is identified and then inputs are given to the identified system in order to show starvation problem of the fuel cell. Figure 7.11 shows the inputs (dry air and hydrogen) that is given to the system. To show starvation dry air input is given very very less than required, to the system.

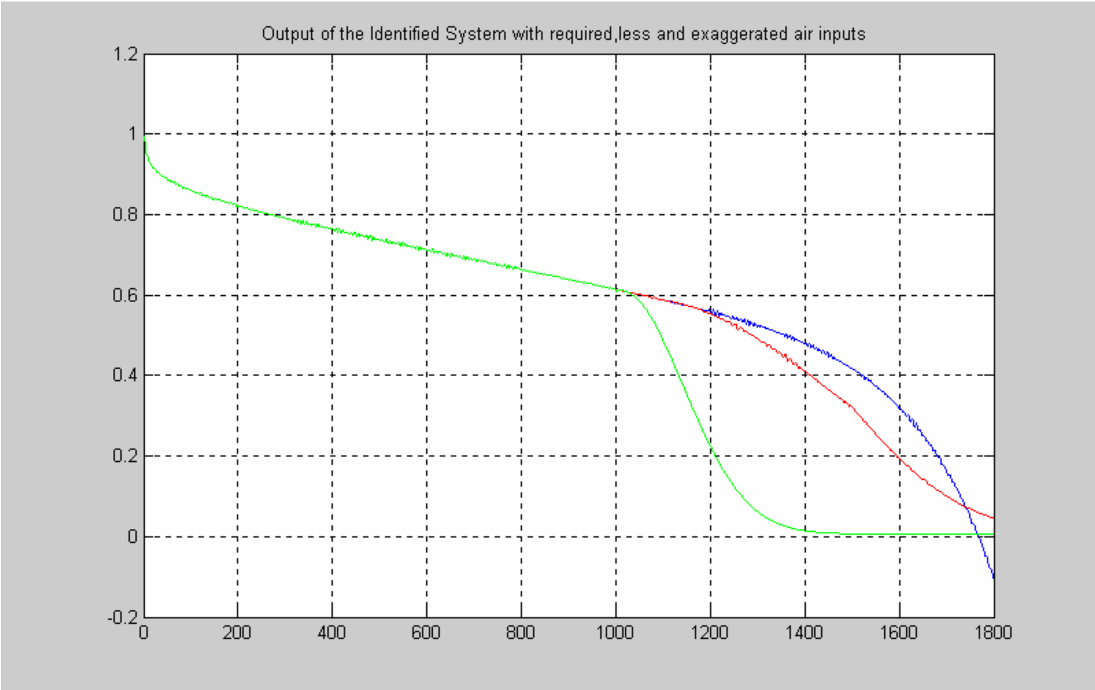

Figure 7.12 Starvation of the cell for different dry air inputs

When inputs are dry air and hydrogen in Figure 7.11, output of the system which is the polarization curve is observed. Figure 7.12 shows three polarization curves, the above curve is for the system when inputs are like in Figure 7.5 and 7. 7, the curve in the middle shows the fall on the voltage of the cell when inputs are like in Figure 7.9, the curve which is placed in the below of the other two curves shows the rapid fall on the voltage of the cell when inputs are like in Figure 7.11

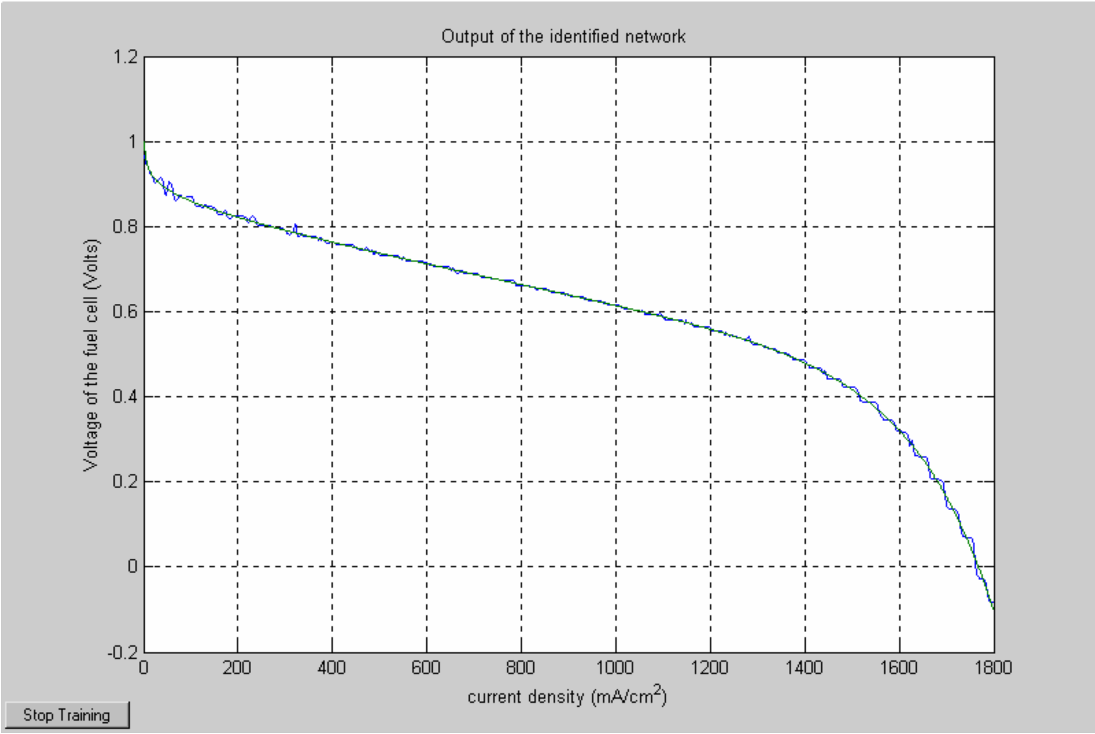

Figure 7.13 Identified system output when input is current density

The fuel cell is identified with a multi layer perceptron network, The system is identified with input current density which changes from $1mA/cm^2$ to $1800mA/cm^2$, and with an output which is the polarization curve of the fuel cell plotted in Figure 7.4. Figure 7.13 shows the identified system output which is the output voltage of the fuel cell.

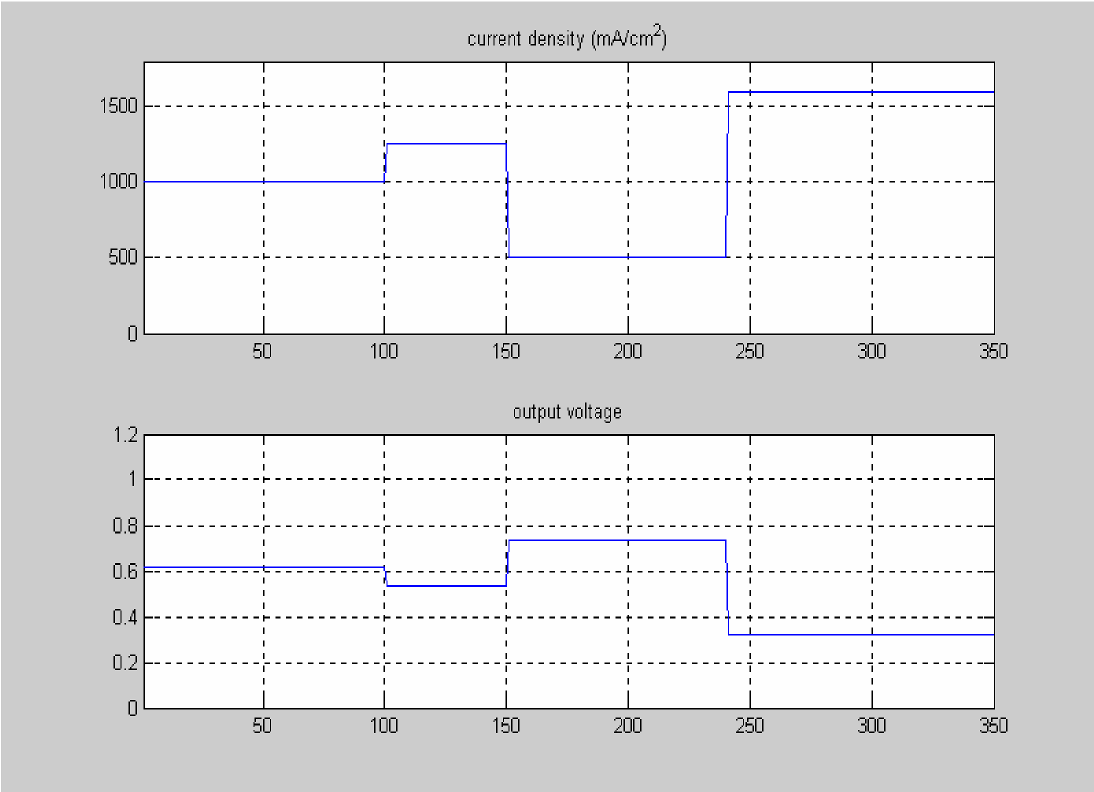

Figure 7.14 Input and output graph of the identified system

In order to observe the identified system output, a current density input shown in Figure 7.14 is applied to the identified system and output is plotted in Figure 7.14. Figure 7.14 tells us that while the current density of the fuel cell increases, the voltage of the cell decreases.

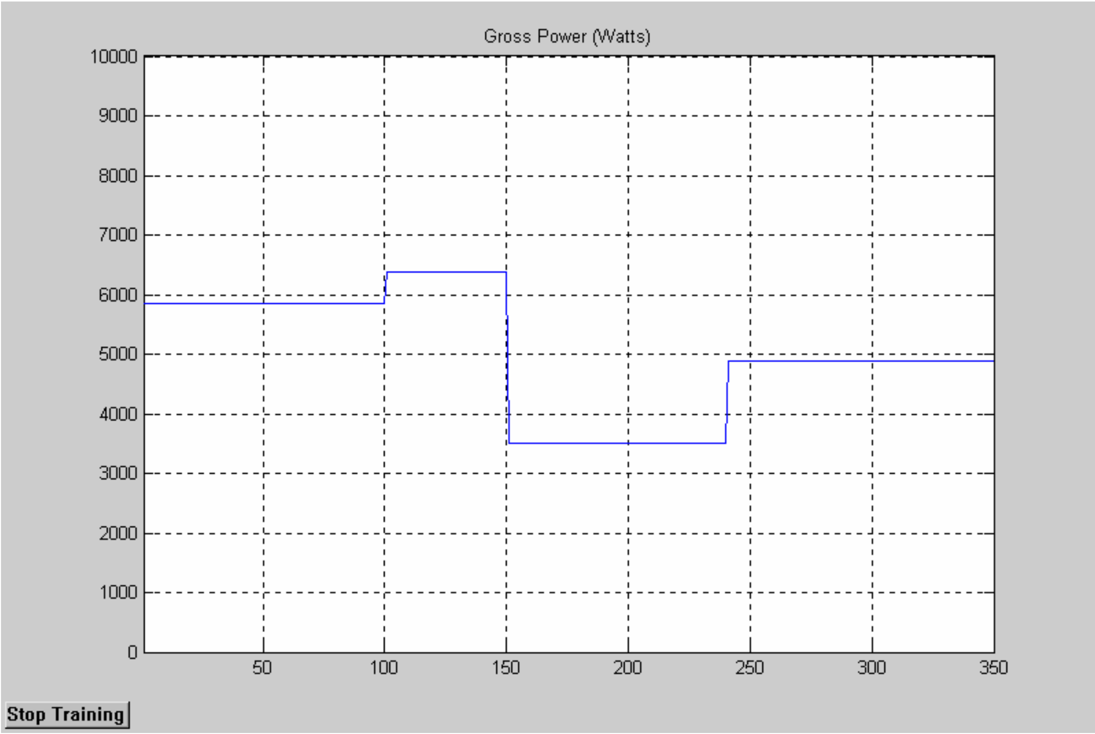

Figure 7.15 Gross power of the identified system

In order to observe the gross power of the identified system, input and output plots in Figure 7.14 are used. The gross power curve is plotted in Figure 7.15 for the system which has 56 cells and $170cm^2$ cell area.

CHAPTER EIGHT
CONCLUSION

Every year with the increase in human being population and advances on technology, energy demand of the countries is increasing up. Nowadays most energy used by countries is generated from coal, petroleum, natural gas etc… Those energy resources are limited, harmful to environment and not efficient, so there is a need to used renewable, clean and efficient energy resources. These energy resources are solar energy, wind energy, fuel cells etc… Fuel cells are the most promising alternative energy resource. There is no another energy technology that have lots of benefits like fuel cells. Fuel cells offer secure energy, physical security, reliable and high quality power, fuel flexibility, high efficiency, clean environment, modularity and scalability.

A fuel cell consists of anode and cathode terminals and an electrolyte is placed between these terminals. Oxygen passes over one terminal and hydrogen over the other terminal, as a result of this process water and electricity is generated. Fuel cells generate electricity as DC. The first fuel cell was built in 1839 by Sir William Grove. Now there are six main types of fuel cells they are proton exchange membrane fuel cells, direct methanol fuel cells, alkaline fuel cells, solid oxide fuel cells, molten carbonate fuel cells and phosphoric acid fuel cells.

The overall fuel cell system consists of a fuel processor (reformer), fuel cell stack, power conditioner unit, air management system, water management system and thermal management systems. Problems with these management systems, high cost, big system size, durability and hydrogen storage are barriers on commercialization of fuel cells.

There are many uses for fuel cells right now, the most promising area for fuel cells is automotive area. Nowadays almost all of the major automakers are working to commercialize a fuel cell car. Many of them completed their prototype cars and that cars are under test today. Beside automotive area fuel cells are also designed for residential, portable and stationary applications.

Mathematical modelling is used to analyze real time processes, once the system is modelled very close to its real life operation, that system is then open to analyze. Fuel cell systems are very complex systems, it has chemical operation beside electrical. Electrochemical equations are used to model fuel cell systems. In the literature there are emprical and analytical models of fuel cells. In this thesis by using the fuel cell properties in the literature, its polarization curve, gross power curve, fuel cells' oxygen and hydrogen demands at changing current densities and also its requirement for dry air is simulated by using Matlab. Then the fuel cell system is identified for two different cases, firstly the system is identified for air and hydrogen inputs and voltage output, then for the second case the system is identified for the input is current density and the output is voltage of the cell. Identified systems are tested for different inputs and for the first case when hydrogen and air are inputs, starvation of the fuel cell is shown for different air inputs. The simulation results agreed with theory since fuel cells' demand on dry air, hydrogen and oxygen increased with increasing current density of the fuel cell. Gross power curve also gave that maximum gross power is nearly 5.9 kW, like in the properties of the system taken for simulation. Fuel cell polarization curve tells us that, when an increase occurs in current density of the cell, fuel cell voltage decreases due to the increase in activation, ohmic and concentration overvoltages explained in Chapter 7.

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