

Palestine Polytechnic University  
College of Engineering



College of Engineering and Technology  
Mechanical engineering Department

Graduation Project

# "Electric Power Generation Using Alkaline Fuel Cell"

Students Work

Raed Tarawa Omar Zhou

Project Supervisor

Dr. Zohdi Salhab

Hebron-Palestine

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PROJECT NAME


Implementation simulation model to estimate traffic emission

Prepared By

Raed Tarawa Omar Zhou

According to the directions of the project supervisor and by the agreement of all examination committee members, this project is presented to the department of Mechanical Engineering at College of Engineering and Technology, for partial fulfillment Bachelor of engineering degree requirements.

Supervisor Signature



Committee Member Signature

  
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Department Head Signature

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## 1.1 Introduction

Production and distribution of energy affects all sectors of the global economy. The increasing urbanization of the world is demanding highly efficient energy production. Utilizing a nuclear technology through energy production will support the energy-related activities and the growth of the world and sustainability [1].

## Chapter one

The fuel cell is the most fundamental of the power sources. It has cell operating as a sort of continuous electrolytic battery produce its electrical energy and energy can be used to drive any work load. If the fuel is the hydrogen, the products are only water, heat and CO<sub>2</sub>. Fuel cell plants can be installed in houses, and the energy production can be adjusted to meet the actual demand, which is a characteristic of a power source in a distributed energy [2].

## Introduction and type of fuel cell

The history of fuel cell technology dates back to the 1830s when Sir William Grove first developed the concept of a fuel cell. The first practical fuel cell was developed in 1939 by Francis B. Post, who used a hydrogen-oxygen fuel cell to power a small aircraft. The first commercial fuel cell was developed in the 1960s by General Electric, which used a hydrogen-oxygen fuel cell to power the Apollo space program. The first commercial fuel cell power plant was developed in the 1990s by Ballard Power Systems, which used a proton exchange membrane (PEM) fuel cell to power a small truck. The first commercial fuel cell power plant was developed in the 2000s by Ballard Power Systems, which used a PEM fuel cell to power a small truck. The first commercial fuel cell power plant was developed in the 2010s by Ballard Power Systems, which used a PEM fuel cell to power a small truck. The first commercial fuel cell power plant was developed in the 2020s by Ballard Power Systems, which used a PEM fuel cell to power a small truck. The first commercial fuel cell power plant was developed in the 2030s by Ballard Power Systems, which used a PEM fuel cell to power a small truck. The first commercial fuel cell power plant was developed in the 2040s by Ballard Power Systems, which used a PEM fuel cell to power a small truck. The first commercial fuel cell power plant was developed in the 2050s by Ballard Power Systems, which used a PEM fuel cell to power a small truck. The first commercial fuel cell power plant was developed in the 2060s by Ballard Power Systems, which used a PEM fuel cell to power a small truck. The first commercial fuel cell power plant was developed in the 2070s by Ballard Power Systems, which used a PEM fuel cell to power a small truck. The first commercial fuel cell power plant was developed in the 2080s by Ballard Power Systems, which used a PEM fuel cell to power a small truck. The first commercial fuel cell power plant was developed in the 2090s by Ballard Power Systems, which used a PEM fuel cell to power a small truck. The first commercial fuel cell power plant was developed in the 2100s by Ballard Power Systems, which used a PEM fuel cell to power a small truck.

## 1.1 Introduction

Production and distribution of energy affects all sectors of the global economy. The increasing industrialization of the world requires sustainable, highly efficient energy production. Without a major technology advance, energy production will impact the quality of life on earth. For this reason, the application of the fuel cell technologies.[6]

May be one of the most important technological advancement of the next decades. A fuel cell operating as a sort of continuously replenished battery provides an alternative, whereby electrical energy can be made available with small losses. If the fuel is clean, the effluents are in principle only water, heat and  $CO_2$ . Fuel cell plants can be modular in design, and the energy production can be adjusted to meet the actual demand, which is a convenient feature for a power source in a technological society[6].

The history of the fuel cell dates back to 1839 when Sir William Grove first described its principle and demonstrated a fuel cell at room temperature using a liquid electrolyte. In 1899, Nernst discovered the solid oxide electrolyte when using stabilised zirconia in making filaments for electric glowers. In the middle of the 20<sup>th</sup> century the development accelerated. Several types of fuel cells were developed in the race for conquering the space. In the eighties focus on pollution and the demand for higher efficiency in the exploitation of fossil resources initiated a new wave of fuel cell developments. At present several types of fuel cells are approaching the consumer market within a limited number of years. The primary challenges are cost and durability, to be solved by materials selection and design engineering[7].

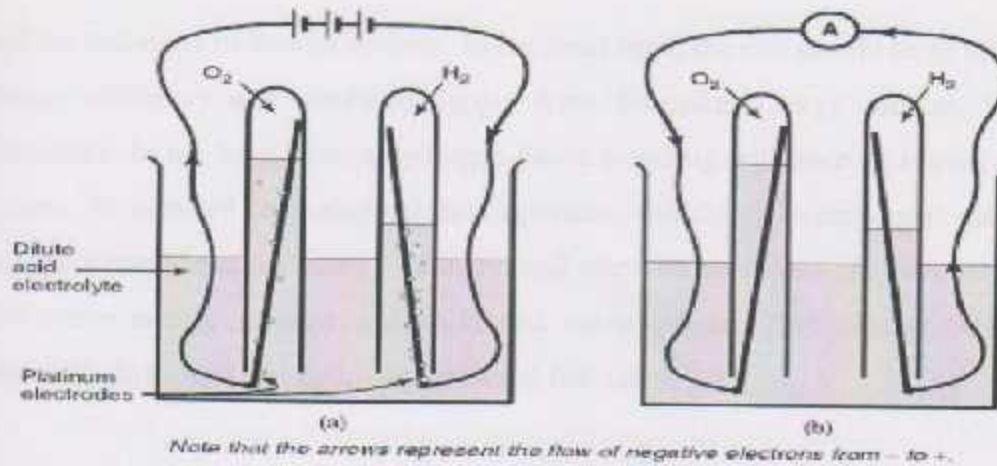


Figure 1.1: (a) The electrolysis of water. The water is separated into hydrogen and oxygen by the passage of an electric current. (b) A small current flows

### 1.1.1 The energy challenge

Worldwide demand for energy is growing at an alarming rate. The European “World Energy Technology and Climate Policy Outlook” (WETO) predicts an average growth rate of 1.8% per annum for the period 2000-2030 for primary energy worldwide. The increased demand is being met largely by reserves of fossil fuel that emit both greenhouse gasses and other pollutants. Those reserves are diminishing and they will become increasingly expensive. Currently, the level of  $CO_2$  emissions per capita for developing nations is 20% of that for the major industrial nations. As developing nations industrialize, this will increase substantially. By 2030,  $CO_2$  emissions from developing nations could account for more than half the world  $CO_2$  emissions. Industrialized countries should lead the development of new energy systems to offset this.

Energy security is a major issue. Fossil fuel, particularly crude oil, is confined to a few areas of the world and continuity of supply is governed by political, economic and ecological factors. These factors conspire to force volatile, often high fuel prices while, at the same time, environmental policy is demanding a reduction in greenhouse gases and toxic emissions.

A coherent energy strategy is required, addressing both energy supply and demand, taking account of the whole energy lifecycle including fuel production, transmission and distribution, and energy conversion, and the impact on energy equipment manufacturers



hydrogen together represent one of the most promising ways to achieve this, complemented by fuel cells which provide very efficient energy conversion.

Hydrogen is not a primary energy source like coal and gas. It is an energy carrier. Initially, it will be produced using existing energy systems based on different conventional primary energy carriers and sources. In the longer term, renewable energy sources will become the most important source for the production of hydrogen. Regenerative hydrogen, and hydrogen produced from nuclear sources and fossil-based energy conversion systems with capture, and safe storage (sequestration) of  $CO_2$  emissions, are almost completely carbon-free energy pathways.

Producing hydrogen in the large quantities necessary for the transport and stationary power markets could become a barrier to progress beyond the initial demonstration phase. If cost and security of supply are dominant considerations, then coal gasification with  $CO_2$  sequestration may be of interest for large parts of Europe. If the political will is to move to renewable energies, then biomass, solar, wind and ocean energy will be more or less viable according to regional geographic and climatic conditions. For example, concentrated solar thermal energy is a potentially affordable and secure option for large-scale hydrogen production, especially for Southern Europe. The wide range of options for sources, converters and applications.

Fuel cells will be used in a wide range of products, ranging from very small fuel cells in portable devices such as mobile phones and laptops, through mobile applications like cars, delivery vehicles, buses and ships, to heat and power generators in stationary applications in the domestic and industrial sector. Future energy systems will also include improved conventional energy converters running on hydrogen (e.g. internal combustion engines, Sterling engines, and turbines) as well as other energy carriers (e.g. direct heat and electricity from renewable energy, and bio-fuels for transport)

and the end-users of energy systems. In the short term, the aim should be to achieve higher energy efficiency and increased supply from European energy sources, in particular renewable. In the long term, a hydrogen-based economy will have an impact on all these sectors. In view of technological developments, vehicle and component manufacturers, transport providers, the energy industry, and even householders are seriously looking at alternative energy sources and fuels and more efficient and cleaner technologies – especially hydrogen and hydrogen-powered fuel cells.

### **1.1.1 Why hydrogen and fuel cells?**

A sustainable high quality of life is the basic driver for providing a clean, safe, reliable and secure energy supply in Europe. To ensure a competitive economic environment, energy systems must meet the following societal needs at affordable prices:

- Mitigate the effects of climate change;
- Reduce toxic pollutants; and
- Plan for diminishing reserves of oil.

#### **Failure to meet these needs will have significant negative**

impacts on:

- The economy,
- The environment, and
- Public health.

#### **Measures should therefore be introduced which promote:**

- More efficient use of energy; and
- Energy supply from a growing proportion of carbon-free sources.

The potential effects of climate change are very serious and most important of all, irreversible. Europe cannot afford to wait before taking remedial action, and it must aim for the ideal—an emissions-free future based on sustainable energy. Electricity and

### 1.2.1 Definition

A fuel cell is an electrochemical device that combines hydrogen and oxygen to produce electricity, with water and heat as its by product[4].

### 1.2.2 How does a fuel cell work?

A fuel cell consists of two catalyst coated electrodes surrounding an electrolyte one electrode is an anode and the other is a cathode. The process begins when hydrogen molecules enter the anode. The catalyst coating separates hydrogen's negatively charged electrons from the positively charged protons. The electrolyte allows the protons to pass through to the cathode, but not the electrons. Instead the electrons are directed through an external circuit which creates electrical current. While the electrons pass through the external circuit, oxygen molecules pass through the cathode. There the oxygen and the protons combine with the electrons after they have passed through the external circuit. When the oxygen and the protons combine with the electrons it produces water and heat. Individual fuel cells can then be placed in a series to form a fuel cell stack. The stack can be used in a system to power a vehicle or to provide stationary power to a building.

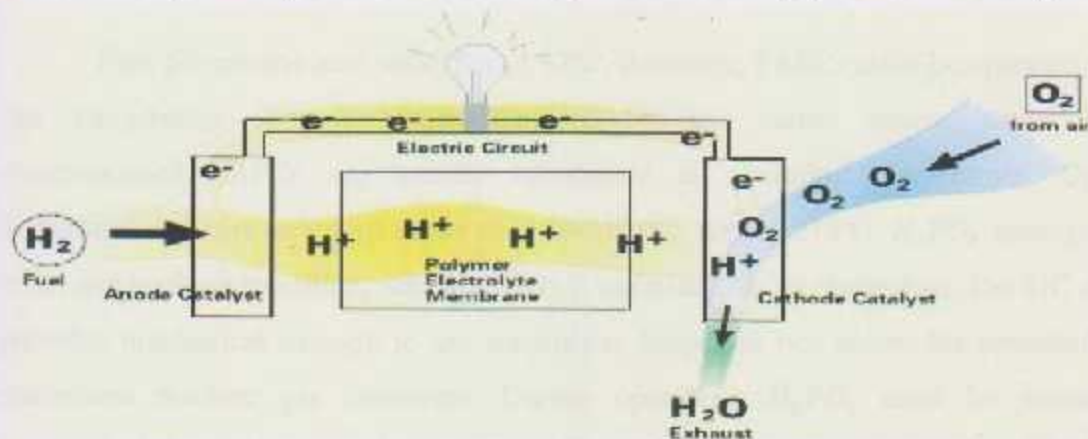


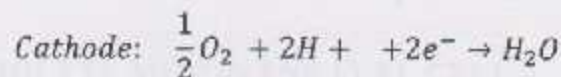
Figure (1.2): Fuel cell work

### 1.3 Major types of fuel cells

In general all fuel cells have the same basic configuration an electrolyte and two electrodes, different types of fuel cells are classified by the kind of electrolyte used, the type of electrolyte used determines the kind of chemical reactions that take place and the temperature range of operation.

#### 1.3.1 PHOSPHORIC ACID FUEL CELL

In the *PAFC*, liquid  $H_3PO_4$  electrolyte (either pure or highly concentrated) is contained in a thin *SiC* matrix between two porous graphite electrodes coated with a platinum catalyst. Hydrogen is used as the fuel and air or oxygen may be used as the oxidant. The anode and cathode reactions are [1].



Pure phosphoric acid solidifies at 42°C. therefore, *PAFCs* must be operated above this temperature. Because freeze-thaw cycles can cause serious stress issues, commissioned *PAFCs* are usually maintained at operating temperature. Optimal performance occurs at temperatures of (180-210)°C. Above 210°C,  $H_3PO_4$  undergoes an unfavorable phase transition, which renders it unsuitable as an electrolyte. The *SiC* matrix provides mechanical strength to the electrolyte, keeps the two electrodes separated, and minimizes reactant gas crossover. During operation,  $H_3PO_4$  must be continually replenished because it gradually evaporates to the environment (especially during higher temperature operation). Electrical efficiencies of *PAFC* units are ~40% with combined heat and power units achieving ~70 %. Because *PAFCs* employ platinum catalyst, they are susceptible to carbon monoxide and sulfur poisoning at the anode. This is not an issue when running on pure hydrogen but can be important when running on reformed or impure feed stocks. Susceptibility depends on temperature; because the *PAFC* operates at higher temperatures than the *PEMFC*, it exhibits somewhat greater tolerance.

Carbon monoxide tolerance at the anode can be as high as (0.5-1.5)%, depending on the exact conditions. Sulfur tolerance in the anode, where it is typically present as  $H_2S$ , is around 50 ppm (parts per million)[1].

#### PAFC Advantages

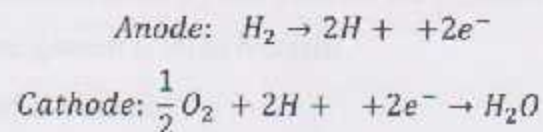
1. Mature technology.
2. Excellent reliability/ Long term performance.
3. Electrolyte is relatively low-cost.

#### PAFC Disadvantages

1. Expensive platinum catalyst.
2. Susceptible to  $CO$  and  $S$  poisoning .
3. Electrolyte is a corrosive liquid that must be replenished during operation.

### 1.3.2 POLYMER ELECTROLYTE MEMBRANE FUEL CELL

The *PEMFC* is constructed from a proton-conducting polymer electrolyte membrane, usually a perfluorinated sulfonic acid polymer. Because the polymer membrane is a proton conductor, the anode and cathode reactions in the *PEMFC* (like the *PAFC*) are [1]



The polymer membrane employed in *PEMFCs* is thin (20-200 $\mu$ m), flexible, and transparent. It is coated on either side with a thin layer of platinum-based catalyst and porous carbon electrode support material. This electrode-catalyst-membrane-catalyst-electrode sandwich structure is referred to as a membrane electrode assembly (*MEA*). The entire *MEA* is less than 1 mm thick. Because the polymer membrane must be

hydrated with liquid water to maintain adequate conductivity, the operating temperature of the *PEMFC* is limited to 90°C or lower. [1]

Because of the low operating temperature, platinum-based materials are the only practical catalyst currently available. While  $H_2$  is the fuel of choice, for low-power (<1-KW) portable applications, liquid fuels such as methanol and formic acid are also being considered. One such liquid fuel solution, the direct methanol fuel cell (*DMFC*), is a *PEMFC* that directly oxidizes methanol ( $CH_3OH$ ) to provide electricity. The *DMFC* is under extensive investigation at this time (2005). Some researchers assign these alternative-fuel *PEMFCs* their own fuel cell class. The *PEMFC* currently exhibits the highest power density of all the fuel cell types (300-100  $mw/cm^2$ ). It also provides the best fast-start and on-off cycling characteristics. For these reasons, it is well suited for portable power and transport applications. Fuel cell development at most of the major car companies is almost exclusively focused on the *PEMFC*. [1]

#### **PEMFC Advantages.**

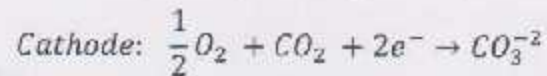
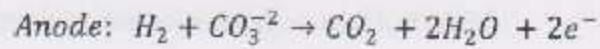
1. Highest power density of all the fuel cell classes.
2. Good start stop capabilities.
3. Low temperature operation makes it suitable for portable applications.

#### **PEMFC Disadvantages.**

1. Uses expensive platinum catalyst.
2. Polymer membrane and ancillary components are expensive.
3. Active water management is often required.
4. Very poor *CO* and *S* tolerance.

### 1.3.3 Molten Carbonate Fuel Cell

The electrolyte in the *MCFC* is a molten mixture of alkali carbonates,  $Li_2CO_3$  and  $K_2CO_3$ , immobilized in a  $LiOAlO_2$  matrix. The carbonate ion,  $CO_3^{2-}$ , acts as the mobile charge carrier in the *MCFC*. The anode and cathode reactions are, therefore,



In the *MCFC*,  $CO_2$  is produced at the anode and consumed at the cathode. Therefore, *MCFC* systems must extract the  $CO_2$  from the anode and recirculate it to the cathode. (This situation contrasts with the *AFC*, where  $CO_2$  must be excluded from the cathode.) The  $CO_2$  recycling process is actually less complicated than one might suppose. Typically, the waste stream from the anode is fed to a burner, where the excess fuel combusts. The resulting mixture of steam and  $CO_2$  is then mixed with fresh air and supplied to the cathode. The heat released at the combustor preheats the reactant air, thus improving the efficiency and maintaining the operating temperature of the *MCFC*. The electrodes in a typical *MCFC* are nickel based; the anode usually consists of a nickel/chromium alloy while the cathode consists of a lithiated nickel oxide. At both electrodes, the nickel provides catalytic activity and conductivity. At the anode, the chromium additions maintain the high porosity and surface area of the electrode structure. At the cathode, the lithiated nickel oxide minimizes nickel dissolution, which could otherwise adversely affect fuel cell performance. [1]

The relatively high operating temperature (650°C) of the *MCFC* provides fuel flexibility. The *MCFC* can run on hydrogen, simple hydrocarbons (like methane) and simple alcohols. Carbon monoxide tolerance is not an issue for *MCFCs*; rather than acting as a poison,  $CO$  acts as a fuel! [1]

Due to stresses created by the freeze-thaw cycle of the electrolyte during startup/shutdown cycle, the *MCFC* is best suited for stationary, continuous power applications.

The electrical efficiency of a typical *MCFC* unit is near 50%. In combined heat and power applications efficiencies could reach close to 90%. [1]

#### **MCFC Advantages.**

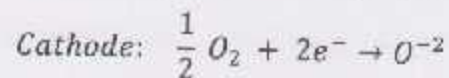
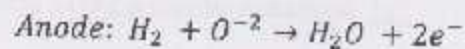
1. Fuel flexibility.
2. Non precious metal catalyst.
3. High- quality waste heat for cogeneration applications.

#### **MCFC Disadvantages.**

1. Must implement  $CO_2$  recycling .
2. Corrosive, molten electrolyte.
3. Degradation/ lifetime issues .
4. Relatively expensive materials.

### **1.3.4. Solid Oxide Fuel Cell**

The *SOFC* employs a solid ceramic electrolyte. The most popular *SOFC* electrolyte material is yttria stabilized zirconia (*YSZ*), which is an oxygen ion (oxygen vacancy) conductor. Since  $O^{-2}$  is the mobile conductor in this case, the anode and cathode reactions are



In a *SOFC*, water is produced at the anode, rather than at the cathode, as in a *PEMFC*. The anode and cathode materials in a *SOFC* are different. The fuel electrolyte must be able to withstand the highly reducing high temperature environment of the anode, while the air electrode must be able to withstand the highly oxidizing high temperature environment of the cathode. The most common material for the anode electrode in the *SOFC* is a nickel\_YSZ cermet (a cermet is a mixture of ceramic and metal). Nickel provides conductivity and catalytic activity. The *YSZ* adds ion conductivity, thermal expansion compatibility, and mechanical stability and maintains the high porosity and surface area of the anode structure. The cathode electrode is usually a mixed ion\_



conducting and electronically conducting (*MIEC*) ceramic material. Typical cathode materials include strontium\_doped lanthanum manganite (*LSM*), lanthanum\_strontium ferrite (*LSF*), lanthanum\_strontium cobaltite (*LSC*), and lanthanum strontium cobaltite ferrite (*LSCF*). These materials show good oxidation resistance and high catalytic activity in the cathode environment. [1]

The operating temperature of the *SOFC* is currently between 600 and 1000°C. The high operating temperature provides both challenges and advantages. The challenges include stack hardware, sealing, and cell interconnect issues. High temperature makes the materials requirement, mechanical issues, reliability concerns, and thermal expansion matching takes more difficult. Advantages include fuel flexibility, high efficiency, and the ability to employ cogeneration schemes using the high- quality waste heat that is generated. The electrical efficiency of the *SOFC* is about (50-60)%; in combined heat and power applications, efficiencies could reach 90%. [1]

An intermediate- temperature (400-700)°C *SOFC* design could remove most of the disadvantages associated with high\_ temperature operation while maintaining the most significant *SOFC* benefits. Such *SOFCs* could employ much cheaper scaling technologies and robust, inexpensive metal (rather than ceramic ) stack components. At the same time, these *SOFCs* could still provide reasonably high efficiency and fuel flexibility. However, there are still many fundamental problems that need to be solved before the routine operation of lower- temperature *SOFCs* can be achieved. [1]

#### **SOFC Advantages.**

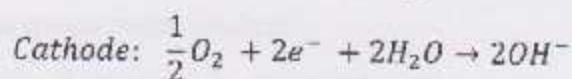
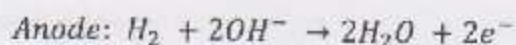
1. Fuel flexibility.
2. Non precious metal catalyst.
3. High\_ quality waste heat for cogeneration applications.
4. Solid electrolyte .
5. Relatively high power density.

### SOFC Disadvantages.

1. Significant high temperature materials issues.
2. Sealing issues.
3. Relatively expensive components/ fabrication.

### 1.3.5 Alkaline fuel cell

The *AFC* employs an aqueous potassium hydroxide electrolyte. In contrast to acidic fuel cells where  $H^+$  is transmitted from the anode to the cathode, in an alkaline fuel cell  $OH^-$  is conducted from the cathode to the anode. The anode and cathode reactions are therefore, [1]



Thus, water is consumed at the cathode of an *AFC* while it is produced (twice as fast) at the anode. If the excess water is not removed from the system, it can dilute the *KOH* electrolyte, leading to performance degradation. For reasons that are still poorly understood, the cathode activation overvoltage in an *AFC* is significantly less than in an acidic fuel cell of similar temperature. Under some conditions, nickel (rather than platinum) catalysts can even be used at the cathode. Because the *ORR* kinetics proceed much more rapidly in an alkaline medium than in an acidic medium, *AFCs* can achieve operating voltages as high as 0.875 V. Remember that a high operating voltage leads to high efficiency\_ an important point if fuel is at a premium. Depending upon the concentration of *KOH* in the electrolyte, the *AFC* can operate at temperature between 60 and 250°C. Alkaline fuel cells require pure hydrogen and pure oxygen as fuel and oxidant because they cannot tolerate even atmospheric levels of carbon dioxide. The presence of  $CO_2$  in an *AFC* degrades the *KOH* electrolyte as follows:



Over time, the concentration of  $OH^-$  in the electrolyte declines. Additionally,  $K_2CO_3$  can begin to precipitate out of the electrolyte (due to its lower solubility), leading to significant problems. These issues can be partially mitigated by the use of  $CO_2$  scrubbers and the continual resupply of fresh  $KOH$  electrolyte. However, both solutions entail significant additional cost and equipment. [1]

Due to these limitations, the *AFC* is not economically viable for most terrestrial power applications. However, the *AFC* demonstrates impressively high efficiencies and power densities, leading to an established application in the aerospace industry. Alkaline fuel cells were employed on the Apollo missions as well as on the Space Shuttle Orbiters. [1]

#### **AFC Advantages**

1. Improved cathode performance.
2. Potential for nonprecious metal catalyst.
3. Low materials costs, extremely low cost electrolyte.

#### **AFC Disadvantages**

1. Must use pure  $H_2 - O_2$
2.  $KOH$  electrolyte may need occasional replenishment.
3. Must remove water from anode.

In this project the alkaline fuel cell is designed because the components of this cell are available and cheap especially in catalyst that coated the electrode where the Raney nickel is used instead of platinum. And the electrolyte is available like  $KOH$ , and this cell is used for low temperature about (70-150) $^{\circ}C$ .

## **1.4 Literature review**

### **1.4.1 Siemens *SOFC* surpasses 10,000 hours at the *FCTec***

A 5kW Siemens Power Generation Solid Oxide Fuel Cell (*SOFC*) has been operating at the *FCTec* for over 10,000 hours. The system uses the new Siemens tubular *SOFC* design with cells that have been fabricated using an atmospheric plasma spray process. [9]

The system began operation at the Siemens facility in Churchill, PA in December 2004 where it operated successfully and without interruption for 2,304 hours. The system was installed at the *FCTec* and started in May 2005 and operated until February 2006. After Siemens completed modifications to the system, it was restarted in August 2006. While at the *FCTec* the system has operated successfully for over 10,000 hours and produced over 29,000 kWh of electrical energy and 25,000 kWh of thermal energy.[9]

### **1.4.2 The High Technology Development Corporation (*HTDC*) awards contract to Concurrent Technologies Corporation (*CTC*) through the Hawaii Center for Advanced Transportation Technologies (*HCATT*) Program**

The High Technology Development Corporation (*HTDC*) awarded a contract to Concurrent Technologies Corporation (*CTC*) through the Hawaii Center for Advanced Transportation Technologies (*HCATT*) program to convert an electric pickup truck into a fuel cell augmented flight line maintenance support vehicle for demonstration and performance evaluation at Hickam Air Force Base (HAFB) in Honolulu, Hawaii.[9]

To fulfill the obligations of this contract award, *CTC* purchased a 2000 Electric Ford Ranger as the demonstration platform. A proton exchange membrane (*PEM*) fuel

cell will be integrated into this platform to provide auxiliary power and to provide power to the original equipment manufacturer (*OEM*) traction motor and battery pack for range extension. The on-board compressed hydrogen storage will power the fuel cell and will be compatible with the existing hydrogen infrastructure at *HAFB*. Upon completion of system integration, the vehicle will be demonstrated at *HAFB* for a period of 12 months. The demonstration is scheduled to commence in April of 2008. [9]



Figure (1.3): Automotive Fuel Cell

#### 1.4.3 *CTC* Successfully Conducts *SOFC* Testing With Japanese Town Gas

*CTC* has recently completed 2000 hours of testing on a Siemens Power Generation 5kW Solid Oxide Fuel Cell (*SOFC*). Siemens personnel requested *CTC* to supply simulated Japanese town gas to the *SOFC* to validate that Siemens' technology could operate effectively on this fuel. Japanese town gas has higher levels of butane, propane, and ethane than typical US natural gas. Siemens plans to partner with their client, Meidensha, to operate the unit in Japan. [8]

Siemens indicated that *CTC* had exceeded their expectations in preparing for and executing the test. *CTC* successfully adapted to changing customer test needs by modifying the existing *SOFC* test station to enable custom batch mixing and delivery of Japanese town gas. The 2000-hour test was monitored closely by *CTC*, Siemens, and Meidensha. Siemens and Meidensha participated in testing activities at *CTC* during multiple key periods. *CTC* responded quickly to all *SOFC* hardware issues, as well as special customer requests. The test served as a validation that the *SOFC* test station and

*CTC* engineers could perform very effectively to meet diverse and changing client needs.[8]

#### **1.4.4 AFCC Automotive Fuel Cell Cooperation Corp.**

*AFCC* Automotive Fuel Cell Cooperation Corp. (*AFCC*) is a private Vancouver, Canada-based automotive fuel cell technology company founded in 2008 and owned 50.1% by Daimler AG, 30% by Ford Motor Company and 19.9% by Ballard Power Systems. *AFCC* was created to focus on fuel cell research, development and design specifically for automotive applications.[11]

*AFCC* will work closely with Daimler and Ford to evolve automotive fuel cell technology. *AFCC* will continue to be positioned for success in automotive fuel cell technology development over the longer term, with management and program funding provided by Daimler and Ford.[11]

Ballard's relationship with *AFCC*, and our minority ownership position in that company, confer important benefits to us, including

- *AFCC* is an important Ballard customer, to which we provide contract technical services and fuel cell manufacturing services on a profitable basis;
- Ballard is permitted to use automotive fuel cell intellectual property owned and developed at *AFCC*, Daimler and Ford in non-automotive applications.[11]

#### **1.4.5 Toyota and Hino Team Up to Provide Fuel Cell Bus in Tokyo**

Toyota Motor and Hino Motors have announced that they will provide a fuel-cell hybrid bus for a commercial bus route between central Tokyo and Tokyo International Airport.[8]

The bus is a response to a request from the Research Association of Hydrogen Supply/Utilization Technology (*HySUT*), a participant in the Hydrogen Highway Project.

The Hydrogen Highway Project is a part of Japan's Ministry of Economy, Trade and Industry (*METI*)'s Demonstration Program for Establishing a Hydrogen-based Social System. [8]

*TMC* and Hino will modify their jointly developed "FCHV-BUS" fuel-cell hybrid bus to Airport -route specifications and lease it to *HySUT*, and *HySUT* will outsource operation of the bus to Airport Transport Service. Starting on December 16, the bus will make one round trip per day on a route between Shinjuku Station's West Exit and Haneda Airport and on one between Tokyo City Air Terminal and Haneda Airport. [8]

The bus will be fueled with hydrogen at Tokyo Suginami Hydrogen Station in central Tokyo and Haneda Hydrogen Station in Haneda; both facilities are to begin operations on December 15. [8]

#### **1.4.6 Ballard to Supply Fuel Cell Modules for Three New Fuel Cell Buses**

Ballard Power Systems has announced that it has secured an order for three *FC* velocity fuel cell modules to power hydrogen hybrid fuel cell buses in London. [8]

For the London deployment, Ballard is providing modules to a consortium that includes transit bus supplier Wright bus, bus operator First Group, as well as Transport for London. Three additional fuel cell buses will join five existing buses, also powered by Ballard's *FC* velocity fuel cell modules and scheduled for deployment in revenue service in *TfL*'s fleet by the end of 2010. [8]

All eight buses will be deployed by the end of 2011, enabling *TfL* to operate its central Covent Garden-Tower Gateway route entirely by means of hydrogen hybrid fuel cell buses. These buses will be served by a new central hydrogen refueling station, with fuel provided by Air Products. [8]

Project funding is being provided as part of the European Union's Cleaner Hydrogen in Cities (*CHIC*) project. [8]





## 2.1 Introduction

The Alkaline Fuel Cell (AFC) was one of the first modern fuel cells to be developed, beginning in 1960. The application at that time was to provide on-board electric power for the Apollo space vehicle. Desirable attributes of the AFC include excellent performance compared to other candidate fuel cells due to its active  $O_2$  electrode kinetics and flexibility to use a wide range of electro-catalysts. The AFC continues to be used: it now provides on-board power for the Space Shuttle Orbiter with cells manufactured by UTC Fuel Cells.

## 2.2 Fuel cell components

### 2.2.1 Basic Structure

Unit cells form the core of a fuel cell. These devices convert the chemical energy contained in a fuel electrochemically into electrical energy. The basic physical structure, or building block, of a fuel cell consists of an electrolyte layer in contact with an anode and a cathode on either side. A schematic representation of a unit cell with the reactant/product gases and the ion conduction flow directions through the cell[4]



Figure (2.1): Fuel cell Basic Structure

The basic components of fuel cell stack are the electrolyte, the anode, the cathode and the interconnect. The materials for different cell components have been selected based on the following criteria:

- suitable electrical conducting properties required of different cell components to perform their intended cell functions.
- adequate chemical and structural stability at high temperatures during cell operation as well as during cell fabrication.
- minimal reactivity and inter diffusion among different cell components, matching thermal expansion among different cell components.

### 2.3. Electrolyte

A critical portion of most unit cells is often referred to as the three-phase interface. These mostly microscopic regions, in which the actual electrochemical reactions take place, are found where either electrode meets the electrolyte. For a site or area to be active, it must be exposed to the reactant, be in electrical contact with the electrode, be in ionic contact with the electrolyte, and contain sufficient electro-catalyst for the reaction to proceed at the desired rate. The density of these regions and the nature of these interfaces play a critical role in the electrochemical performance of both liquid and solid electrolyte fuel cells.

In liquid electrolyte fuel cells, the reactant gases diffuse through a thin electrolyte film that wets portions of the porous electrode and react electrochemically on their respective electrode surface. If the porous electrode contains an excessive amount of electrolyte, the electrode may "flood" and restrict the transport of gaseous species in the electrolyte phase to the reaction sites. The consequence is a reduction in electrochemical performance of the porous electrode. Thus, a delicate balance must be maintained among the electrode, electrolyte, and gaseous phases in the porous electrode structure.[4]

In solid electrolyte fuel cells, the challenge is to engineer a large number of catalyst sites into the interface that are electrically and ionic ally connected to the electrode and the electrolyte, respectively, and that is efficiently exposed to the reactant gases. In most successful solid electrolyte fuel cells, a high-performance interface requires the use of an electrode which, in the zone near the catalyst, has mixed conductivity (i.e. it conducts both electrons and ions). Over the past twenty years, the unit cell performance of at least some of the fuel cell technologies has been dramatically improved. These developments resulted from improvements in the three-phase boundary, reducing the thickness of the electrolyte, and developing improved electrode and electrolyte materials which broaden the temperature range over which the cells can be operated.[4]

In addition to facilitating electrochemical reactions, each of the unit cell components have other critical functions. The electrolyte not only transports dissolved reactants to the electrode, but also conducts ionic charge between the electrodes[4].

In this project the liquid electrolyte as  $KOH$  is used because it has a higher conductivity than most other alternatives such as sodium hydroxide which is cheaper but less conductive. It is also worth noting that the conductivity of concentrated  $KOH$  rises rapidly with temperature. The main function of the electrolyte is to transport the  $OH$  ions and the water molecules between the two electrodes. The electrolyte also acts as cleaning and temperature control medium and to extract water from the cell. This means that the concentration of the electrolyte diminishes after a period of time and the electrolyte must be replenished with fresh  $7M KOH$ . Thus, the ideal fuel cell electrolyte is not only highly ionically conducting, but also impermeable to gases, electronically resistive and chemically stable under a wide range of conditions. Moreover, the electrolyte must exhibit sufficient mechanical and chemical integrity so as not to develop cracks or pores either during manufacture or in the course of long-term operation.

## 2.4 Types of Alkaline Electrolyte Fuel Cell

### 2.4.1 Mobile electrolyte

The basic structure of the mobile electrolyte fuel cell is shown below in Figure (2.2). The  $KOH$  solution is pumped around the fuel cell. Hydrogen is supplied to the anode, but must be circulated, as it is at the anode where the water is produced. The hydrogen will evaporate the water, which is then condensed out at the cooling unit through which the hydrogen is circulated. The hydrogen comes from a compressed gas cylinder, and the circulation is achieved using an ejector circulator. The majority of alkaline fuel cells are of this type. The main advantage of having the mobile electrolyte is that it permits the electrolyte to be removed and replaced from time to time. This is necessary because, the carbon dioxide in the air will react with the potassium hydroxide electrolyte.[3]



The potassium hydroxide is thus gradually changed to potassium carbonate. The effect of this is that the concentration of  $OH^-$  ions reduces as they are replaced with carbonate  $CO_3^{2-}$  ions, which greatly affects the performance of the cell. From the air as much as possible of, and this is done using a  $CO_2$  scrubber in the cathode air supply system. However, it is impossible to remove all the carbon dioxide, so the electrolyte will inevitably deteriorate and require replacing at some point. [3]

This mobile system allows that to be done reasonably easily, and of course potassium hydroxide solution is of very low cost. The disadvantages of the mobile electrolyte centre around the extra equipment needed. A pump is needed, and the fluid to be pumped is corrosive. The extra pipe work means more possibilities for leaks, and the surface tension of  $KOH$  solution makes for a fluid that is prone to find its way through the smallest of gaps. Also, it becomes harder to design a system that will work in any orientation. There is a further very important problem that cannot be deduced from since it only shows one cell. Because the electrolyte is pumped through all the cells in a stack, they are effectively joined together. Ionic conduction between the cells within a stack can

seriously affect the stack performance. This is mitigated by making the circulation system give the longest and narrowest possible current path between the *KOH* solution in each cell. Otherwise the electrolyte of each and every cell will be connected together, and there will be an internal 'short-circuit'.<sup>2</sup> The problem is also reduced in some systems by connecting the cells in series and parallel, to reduce the internal voltages. So, for example, a 24-cell stack may be connected as two systems of 12 cells in parallel. To summaries then, the main advantages of the mobile electrolyte-type alkaline fuel cell are as follows:

- The circulating electrolyte can serve as a cooling system for the fuel cell.
- The electrolyte is continuously stirred and mixed.[3]

Having the electrolyte circulate means that if the product water transfers to the electrolyte, rather than evaporating at the anode, then the electrolyte can be passed through a system for restoring the concentration (i.e. an evaporator).[3]

It is comparatively straightforward to pump out all the electrolyte and replace it with a fresh solution, if it has become too dilute by reaction with carbon dioxide. This mobile electrolyte system was used by Bacon in his historic alkaline fuel cells of the 1950s and in the Apollo mission fuel cells. It is almost universally used in terrestrial systems[3].

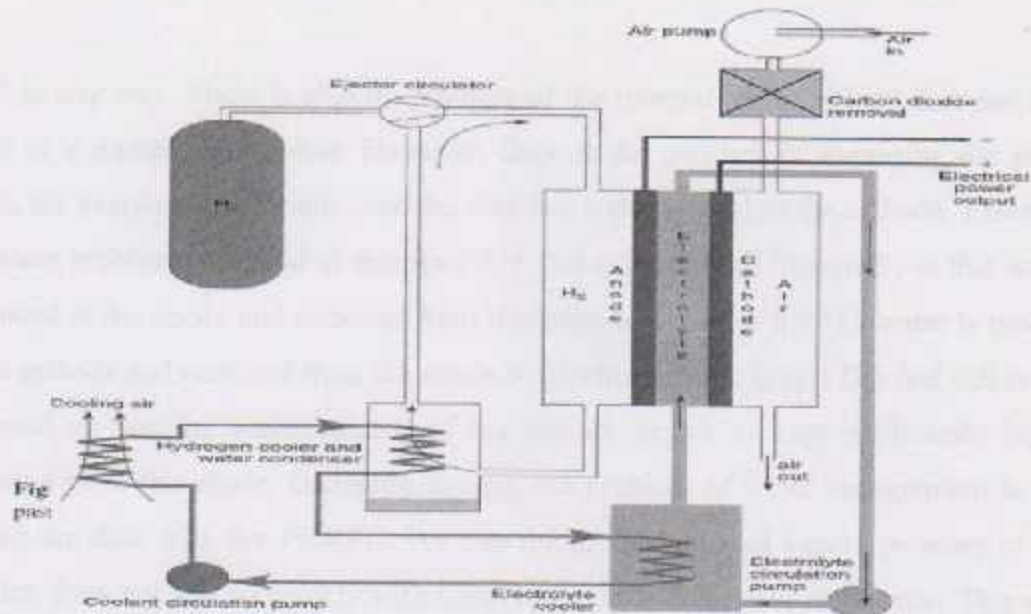


Figure (2.2): Diagram of an alkaline fuel cell with mobile electrolyte. The electrolyte also serves as the fuel cell coolant. Most terrestrial systems are of this type.

#### 2.4.2 Static electrolyte alkaline fuel cells

An alternative to a 'free' electrolyte, is for each cell in the stack to have its own, separate electrolyte that is held in a matrix material between the electrodes. The *KOH* solution is held in a matrix material, which is usually asbestos. This material has excellent porosity, strength, and corrosion resistance, although, of course, its safety problems would be a difficulty for a fuel cell system designed for use by members of the public.[3]

The system uses pure oxygen at the cathode, and this is almost obligatory for a matrix-held electrolyte. The hydrogen is circulated, as with the previous system, in order to remove the product water. In the spacecraft systems, this product water is used for drinking, cooking, and cabin humidification. However, a cooling system will also be needed, and so cooling water, or other fluid, is needed. In the Apollo system it was a glycol/water mixture, as is used in car engines. In the Orbiter systems the cooling fluid is a fluorinated hydrocarbon dielectric liquid (Warshay and Procopius, 1990).[3]

This matrix-held electrolyte system is essentially like the *PEM* fuel cell—the electrolyte is, to all intents and purposes, solid and can be in any orientation. A major advantage is, of course, that the electrolyte does not need to be pumped around or 'dealt

with' in any way. There is also no problem of the internal 'short circuit' that can be the result of a pumped electrolyte. However, there is the problem of managing the product water, the evaporation of water, and the fact that water is used at the cathode. Essentially, the water problem is similar to that for *PEM* fuel cells, though 'inverted', in that water is produced at the anode and removed from the cathode. (In the *PEMFC*, water is produced at the cathode and removed from the anode by electro-osmotic drag). The fuel cell must be designed so that the water content of the cathode region is kept sufficiently high by diffusion from the anode. Generally though, the problem of water management is much less severe than with the *PEMFC*. For one thing, the saturated vapors pressure of *KOH* solution does not rise so quickly with temperature as it does with pure water. This means that the rate of evaporation is much less. In space applications, the advantages of greater mechanical simplicity mean that this approach is now used. However, for terrestrial applications, where the problem of carbon dioxide contamination of the electrolyte is bound to occur, renewal of the electrolyte must be possible. For this matrix-type cell, this would require a complete fuel cell rebuild. Also, the use of asbestos is a severe problem, as it is hazardous to health, and in some countries, its use is banned. A new material needs to be found, but research in this area is unlikely to be undertaken while the likelihood of its eventual use is so low[3].

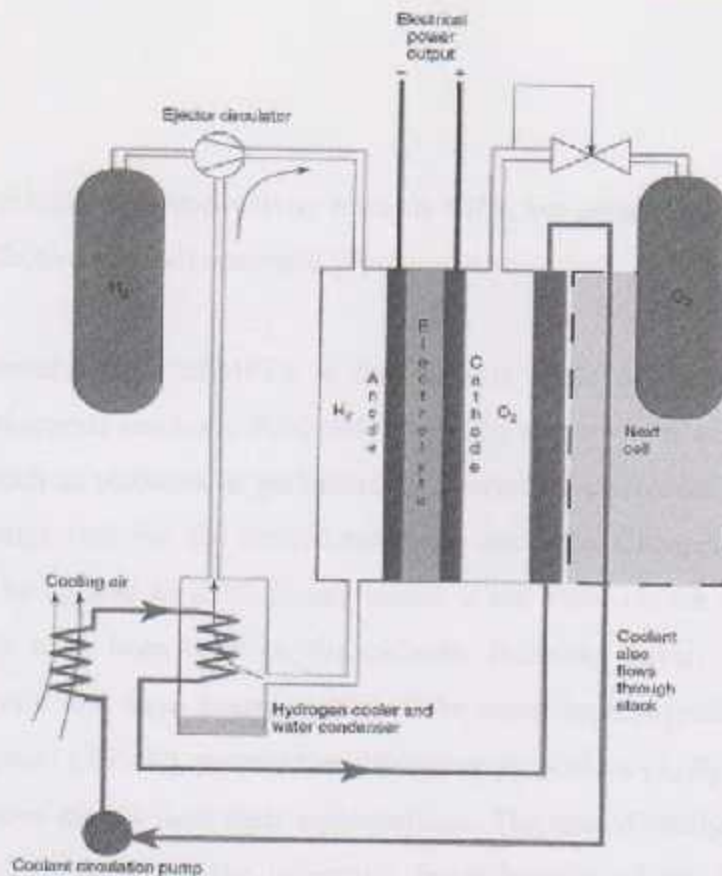


Figure (2.3): An alkaline electrolyte fuel cell with static electrolyte held in a matrix. This system uses pure oxygen instead of air.

In this project the mobile electrolyte is used, because the main advantage of using the mobile electrolyte is that it permits the electrolyte to be removed and replaced from time to time. This is necessary because, the carbon dioxide in the air will react with the potassium hydroxide electrolyte.

## 2.5 Electrode

AFC electrodes consist of two layers: a diffusion layer and an active layer. The diffusion layer allows diffusion of the reactant gases into the active layer. On the active layer the electrode reactions take place at a three-phase interface of the reactant gas, catalyst, and electrolyte. Thus, the active layer must allow partial penetration of the electrolyte into its pores, while the diffusion layer must be more hydrophobic to prevent leakage of the *KOH* electrolyte. The hydrophobic structure is created with use of polytetrafluoro-ethylene (*PTFE*, also known as Teflon), which is also used as a binder to prepare mechanically durable electrodes. Another common electrode material is carbon, which is used to enhance the electronic conductivity and the dispersion of the catalysts.



Carbon also exhibits catalytic activity towards *ORR*, but usually a more active catalyst is needed for effective fuel cell operation.[4]

A special feature of *AFCs* is that various kinds of catalysts can be used to facilitate the electrode reactions. Fuel cells where the electrolyte is acidic usually require a noble metal such as platinum or palladium as catalyst. The problem with noble metals is not only the high cost but the limited resources available. Cheaper and more abundant catalysts can be applied in *AFC*. Raney nickel is the usual choice for the anode, while various metals have been used on the cathode, including silver, *Co*, and *Mn*. Other cathode catalysts that have been mentioned are metal-loporphyrins,  $MnO_2$ , and metal oxides with spinel ( $AB_2O_4$ ), perovskite ( $ABO_3$ ), or pyrochlore ( $A_2B_2O_7$ ) structure. A and B denote various metals and their combinations. The use of catalysts other than noble metals is made possible by the inherently faster kinetics of the *ORR* in an alkaline electrolyte. Many materials also better tolerate the alkaline electrolyte used in *AFC* than the acidic electrolyte used in some other fuel cell[5].

As the electrode reactions take place at the three-phase interface of the reactant gas, catalyst, and electrolyte, this active interface area needs to be large. This further requires that the surface area of the catalyst is large. The properties of the catalyst, not only surface area but structure, particle size, porosity, and activity are greatly affected by the conditions chosen for the preparation. Precursor materials, temperature and duration of heat treatment and cooling, and the nature and pressure of the surrounding atmosphere are important parameters. In comparison with some other precursors such as chlorides and acetates, for example, nitrates have produced the most well-defined metal oxides and the highest surface areas. Drying of nitrates above their melting temperature has resulted in the formation of a dense material before decomposition has occurred and yielded low surface areas. Preparations at lower temperature usually require longer heating times, and the optimum temperature to produce the best catalyst has to be found experimentally. With the properties of materials so heavily influenced by conditions during the preparation, finding optimal conditions for the synthesis is key to a good result[5].

## 2.6 Bipolar Plates

Among the components of the fuel cell stack, the bipolar plate is considered to be one of the most costly and problematic. In addition to meeting cost constraints, bipolar plates must possess a host of other properties. The search for suitable, low cost bipolar plate materials is a key concern in stack development. The bipolar plate is a multi-functional component. Its primary function is to supply reactant gases to the gas diffusion electrodes (*GDEs*) via flow channels. The effectiveness of the reactant transport depends partially on the art of the flow field design, so an alternative name for the bipolar plate is the flow field plate.[2]

Bipolar plates must provide electrical connections between the individual cells. They have to remove the water produced at the cathode effectively. Bipolar plates must also be relatively impermeable to gases, sufficiently strong to withstand stack assembly, and easily mass produced. For transport applications, low weight and low volume are essential. As bipolar plates operate in constant contact with the acidic water (*PH* ~5) that is generated under the operating conditions of the stack, high chemical stability and corrosion resistance are required. Not only can oxides formed during corrosion migrate and poison the catalyst but they can also increase the electrical resistivity of the plates therefore result in reduced fuel cell performance. In addition, the bipolar plate material must be able to resist a temperature of 80°C or more, high humidity, and an electrical potential. To summarize, the bipolar plate technical design criteria or major constraints are as follows:[2]

1. Low cost (< \$2/plate)
2. Ease of gas flow
3. High electric conductivity ( $> 100 \text{ Scm}^{-1}$ )
4. Low impermeability to gases
5. High manufacturability
6. Reasonable strength
7. Low weight
8. Low volume
9. High chemical stability and corrosion resistance ( $< 16 \mu\text{Acm}^{-2}$ )

#### 10. Low thermal resistance.

Potential bipolar plate materials should meet all of these requirements and, in the long run, should be inexpensive and readily available for the purpose of mass production.

Generally speaking, graphite is an excellent material for fuel cell bipolar plates, but both the material cost and the processing cost are very high for large-scale production. Although graphite plates are not considered to be the most effective material for PEM fuel cell applications, they are preferred for space applications due to their superior corrosion resistance without coating when compared to metal plates. Now more attention is being paid to composites and metals. It has been concluded that the most promising for fuel cell commercialization are the graphite.[2]

polymer composites and metallic materials with coatings. Carbon polymer composites and sheet metal are potentially low-cost materials and are especially suitable for mass production because flow fields can be molded directly into carbon polymer composites, and thin sheet metal can be stamped to plates in an established mass production process. Nevertheless, there is still a great deal of work needed to obtain satisfactory bipolar plate materials. Not only should an optimal bipolar plate meet the property requirements above, but its fabrication process should also be easy fabrication and inexpensive. The art of the flow-field design of bipolar plates is another important feature for the performance of the fuel cells. The fate of potential materials will ultimately determined by all these factors. [2]

### 3.3 Efficiency and Power (Current) of a Hydrogen Fuel Cell



## Chapter Three

(continued from the previous page)

With a fuel cell, the energy is converted to electricity continuously. The fuel separator has already been mentioned, and the voltage and current are shown in Figure 3.17. The maximum power for hydrogen is 1.5 W per cm<sup>2</sup> of the cell area. The cell is shown in Figure 3.18.

### Voltage & Performance

(continued from the previous page)

In a fuel cell, the energy is converted to electricity continuously. The fuel separator has already been mentioned, and the voltage and current are shown in Figure 3.17. The maximum power for hydrogen is 1.5 W per cm<sup>2</sup> of the cell area. The cell is shown in Figure 3.18.

### Alkaline fuel cell

In a fuel cell, the energy is converted to electricity continuously. The fuel separator has already been mentioned, and the voltage and current are shown in Figure 3.17. The maximum power for hydrogen is 1.5 W per cm<sup>2</sup> of the cell area. The cell is shown in Figure 3.18.

### 3.1 Efficiency and Open Circuit Voltage of a Hydrogen Fuel Cell

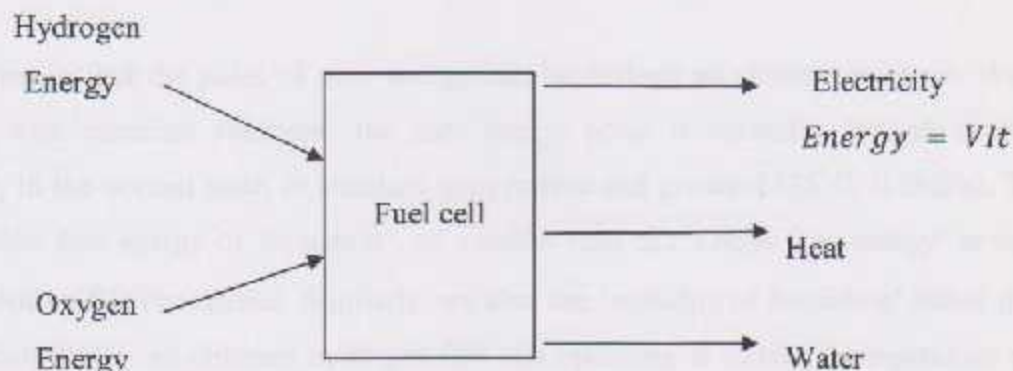


Figure (3.1) : Fuel cell input and outputs

With a fuel cell, such energy considerations are much more difficult to visualize. The basic operation has already been explained, and the input and outputs are shown in Figure (3.1). The electrical power and energy output are easily calculated from the well known Formulas [3]

$$Power = VI \text{ and } Energy = VIt \quad (3.1)$$

However, the energy of the chemical input and output is not so easily defined. At a simple level we could say that it is the 'chemical energy' of the  $H_2$ ,  $O_2$ , and  $H_2O$  that is in question. The problem is that 'chemical energy' is not simply defined – and terms such as enthalpy, Helmholtz function, and Gibbs free energy are used.[3]

In recent years the useful term 'energy' has become quite widely used, and the concept is particularly useful in high-temperature fuel cells. There are also older (but still useful) terms such as calorific value. In the case of fuel cells, it is the 'Gibbs free energy' that is important. This can be defined as the 'energy available to do external work, neglecting any work done by changes in pressure and/or volume' In a fuel cell, the 'external work' involves moving electrons round an external circuit\_ any work done by a change in volume between the input and output is not harnessed by the fuel cell. Exergy is all the external work that can be extracted, including that due to volume and pressure changes. Enthalpy, simply put, is the Gibbs free energy plus the energy connected with the

entropy. All these forms of 'chemical energy' are rather like ordinary mechanical 'potential energy' in two important ways. [3]

The first is that the point of zero energy can be defined as almost anywhere. When working with chemical reactions, the zero energy point is normally defined as pure elements, in the normal state, at standard temperature and pressure (25°C, 0.1MPa). The term 'Gibbs free energy of formation',  $G_f$ , rather than the 'Gibbs free energy' is used when adopting this convention. Similarly, we also use 'enthalpy of formation' rather than just 'enthalpy'. For an ordinary hydrogen fuel cell operating at standard temperature and pressure (STP),<sup>2</sup> this means that the 'Gibbs free energy of formation' of the input is zero – a useful simplification.[3]

The second parallel with mechanical potential energy is that it is the change in energy that is important. In a fuel cell, it is the change in this Gibbs free energy of formation,  $\Delta G_f$ , that gives us the energy released. This change is the difference between the Gibbs free energy of the products and the Gibbs free energy of the inputs or reactants.[]

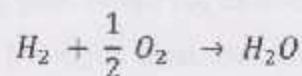
$$\Delta G_f = G_f \text{ of products} - G_f \text{ of reactants} \quad (3.2)$$

To make comparisons easier, it is nearly always most convenient to consider these quantities in their 'per mole' form. These are indicated by over the lower case letter, for example,  $(g_f)_{H_2O}$  is the molar specific Gibbs free energy of formation for water.

Consider the basic reaction for the hydrogen/oxygen fuel cell:



which is equivalent to



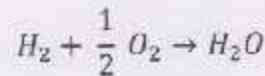
The 'product' is one mole of  $H_2O$  and the 'reactants' are one mole of  $H_2$  and half a mole of  $O_2$ . Thus,

$$\Delta g_f = g_f \text{ of products} - g_f \text{ of reactants}$$

So we have

$$\Delta g_f = (g_f)_{H_2O} - (g_f)_{H_2} - \frac{1}{2} (g_f)_{O_2}$$

This equation seems straightforward and simple enough. However, the Gibbs free energy of formation is not constant; it changes with temperature and state (liquid or gas). Table 3.1 below shows  $\Delta g_f$  for the basic hydrogen fuel cell reaction



**Table 3.1**  $\Delta g_f$  for the reaction  $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$  at various temperatures

Form of water product	Temperature (°C)	$\Delta g_f$ (kJmol <sup>-1</sup> )
Liquid	25	- 237.2
Liquid	80	- 228.2
Gas	100	- 226.1
Gas	200	- 225.2
Gas	400	- 220.4
Gas	600	- 210.3

Note that the values are negative, which means that energy is released. If there are no losses in the fuel cell, or as we should more properly say, if the process is reversible, then all this Gibbs free energy is converted into electrical energy. (In practice, some is also released as heat.) We will use this to find the reversible *OCV* of a fuel cell. For the hydrogen fuel cell, two electrons pass round the external circuit for each water molecule produced and each molecule of hydrogen used. So, for one mole of hydrogen used,  $2N$  electrons pass round the external circuit where  $N$  is Avogadro's number. If  $e^-$  is the charge on one electron, then the charge that flows is [12]

$$-2Ne = -2F \text{ coulombs} \quad (3.3)$$

F being the Faraday constant, or the charge on one mole of electrons. If E is the voltage of the fuel cell, then the electrical work done moving this charge round the circuit is

$$\text{Electrical work done} = \text{charge} \times \text{voltage} = -2FE \text{ joules} \quad (3.4)$$

If the system is reversible (or has no losses), then this electrical work done will be equal to the Gibbs free energy released  $\Delta g_f$ . So

$$\begin{aligned} \Delta g_f &= -2F \cdot E \\ E &= \frac{-\Delta g_f}{2F} \\ E^\circ &= -\frac{\Delta g_f^\circ}{nF} \\ &= -\frac{-273,000 \frac{\text{J}}{\text{mol}}}{(2 \text{ mole}^{-1} \text{ mol reactant}) \left(96,400 \frac{\text{C}}{\text{mol}}\right)} \end{aligned}$$

Where E is standard-state reversible voltage and  $\Delta g_f^\circ$  is the standard-state free-energy change for the reaction.

This fundamental equation gives the electromotive force (EMF) or reversible open circuit voltage of the hydrogen fuel cell. can be applied to other reactions too. The only step in the derivation that was specific to the hydrogen fuel cell was the '2' electrons for each molecule of fuel, which led to the 2 in the equation. If we generalize it to any number of electrons per molecule, we have the formula[12]

$$E = \frac{-\Delta g_f}{z F}$$

where z is the number of electrons transferred for each molecule of fuel.

Due to changes in Gibbs free energy one is able to obtain a higher cell voltage by increasing the reactant pressure and concentration. This is due to a higher reaction activity when either is increased which is best indicated by the Nernst equation:



$$E = E^{\circ} + \frac{RT}{2F} \ln \left( \frac{P_{H_2} P_{O_2}^{1/2}}{P_{H_2O}} \right) \quad (3.5)$$

Where

$E^{\circ}$  is the limit voltage at standard pressure.

$P_{O_2}$  is the partial pressure of oxygen on the cathode side expressed in [bar].

$P_{H_2O}$  is the partial pressure of water on the cathode side expressed in [bar].

$P_{H_2}$  is the partial pressure of hydrogen on the anode side expressed in [bar].

When using reactants mixed with inactive gases such as nitrogen in air, the partial pressure of oxygen falls which causes the cell voltage to drop. Equation also shows that high temperatures will degrade the performance of the stack while proper removal of the product, water, will have a positive effect.[3]

Assume operate a room temperature  $H_2 - O_2$  fuel cell on 3 atm pure  $H_2$  and 5atm air, thermodynamics predicts a cell voltage of 1.244V:

$$E = 1.23 - \frac{(8.314)(298.15)}{(2)(96400)} \ln \frac{1}{(3)(5 + 0.21)^{1/2}}$$

$$1.244 \text{ V} =$$

### 3.2 Fuel Cell Irreversibility's – Causes of Voltage Drop

The characteristic shape of the voltage/current density graphs of Figures( 3.2) results from four major irreversibilities. These will be outlined very briefly here and then considered in more detail in the sections that follow.[3]

1. Activation losses. These are caused by the slowness of the reactions taking place on the surface of the electrodes. A proportion of the voltage generated is lost in driving the chemical reaction that transfers the electrons to or from the electrode. This voltage drop is highly non-linear.[3]

2. Fuel crossover and internal currents. This energy loss results from the waste of fuel passing through the electrolyte, and, to a lesser extent, from electron conduction through the electrolyte. The electrolyte should only transport ions through the cell. However, a certain amount of fuel diffusion and electron flow will always be possible. Except in the case of direct methanol cells the fuel loss and current is small, and its effect is usually not very important. However, it does have a marked effect on the *OCV* of low-temperature cells.[3]

3. Ohmic losses. This voltage drop is the straightforward resistance to the flow of electrons through the material of the electrodes and the various interconnections, as well as the resistance to the flow of ions through the electrolyte. This voltage drop is essentially proportional to current density, linear, and so is called ohmic losses, or sometimes as resistive losses.[3]

4. Mass transport or concentration losses. These result from the change in concentration of the reactants at the surface of the electrodes as the fuel is used. And so this type of irreversibility is sometimes called concentration loss. Because the reduction in concentration is the result of a failure to transport sufficient reactant to the electrode surface, this type of loss is also often called mass transport loss. This type of loss has a third name – ‘Nernstian’. This is because of its connections with concentration, and the effects of concentration are modelled by the Nernst equation.[3]

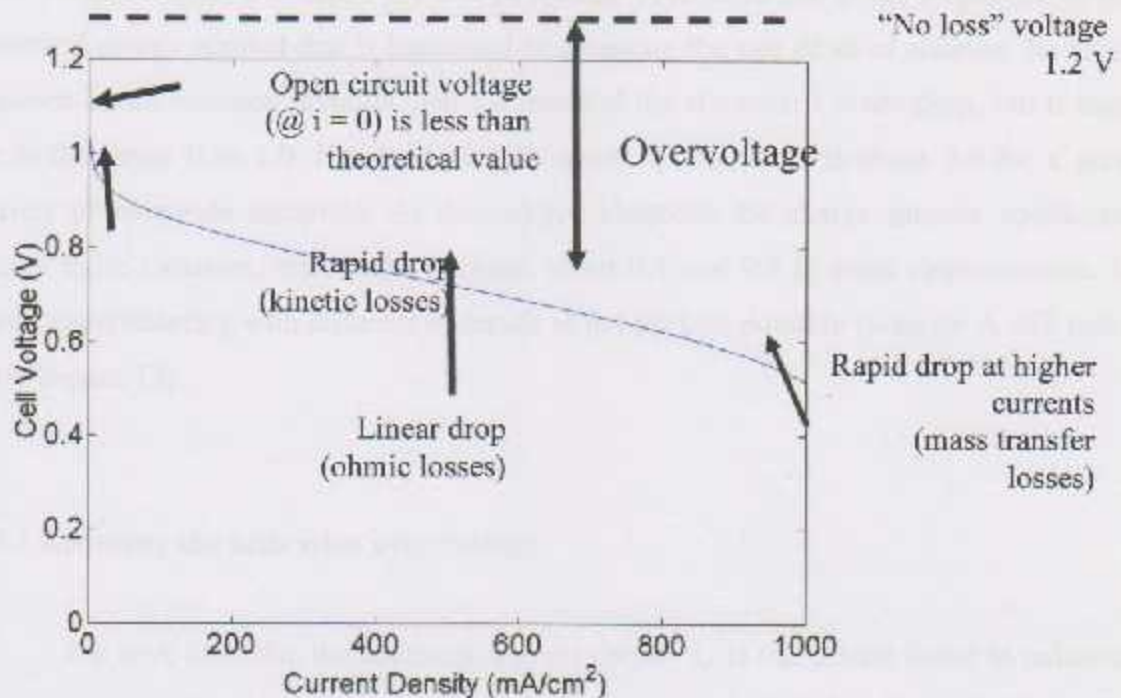


Figure (3.2): Graph showing the voltage for a typical low temperature, air pressure, fuel cell.

### 3.3 Activation Losses

In low- and medium-temperature fuel cells, activation overvoltage is the most important irreversibility and cause of voltage drop, and occurs mainly at the cathode. Activation overvoltage at both electrodes is important in cells using fuels other than hydrogen, such as methanol. At higher temperatures and pressures the activation overvoltage becomes less important. Whether the voltage drop is significant at both electrodes or just the cathode, the size of the voltage drop is related to the current density  $i$  by the equation [3]

$$V_{act} = A \ln \left( \frac{i}{i_0} \right) \quad (3.6)$$

Where  $A$  and  $i_0$  are constants depending on the electrode and cell conditions. This equation is only valid for  $i > i_0$ . The constant  $A$  in equation above is given by

$$A = \frac{RT}{2\alpha F} \quad (3.7)$$

The constant  $a$  is called the charge transfer coefficient and is the proportion of the electrical energy applied that is harnessed in changing the rate of an el reaction. Its value depends on the reaction involved and the material the electrode is made from, but it must be in the range 0 to 1.0. For the hydrogen electrode, its value is about 0.5 for a great variety of electrode materials. At the oxygen electrode the charge transfer coefficient shows more variation, but is still between about 0.1 and 0.5 in most circumstances. In short, experimenting with different materials to get the best possible value for  $A$  will make little impact. [3]

## 3.3 Reducing Losses

### 3.3.1 Reducing the activation over voltage

We have seen that the exchange current density  $i_0$  is the crucial factor in reducing the activation overvoltage. A crucial factor in improving fuel cell performance is, therefore, to increase the value of  $i_0$ , especially at the cathode. This can be done in the following ways:[12]

- **Raising the cell temperature.**

This fully explains the different shape of the voltage/current density graphs of low- and high-temperature fuel cells illustrated in Figures 3.2. For a low-temperature cell,  $i_0$  at the cathode will be about  $0.1 \text{ mA cm}^{-2}$ , whereas for a typical  $70^\circ\text{C}$  cell, it will be about  $10 \text{ mA cm}^{-2}$ , a 100-fold improvement.[12]

- **Using more effective catalysts.**

- **Increasing the roughness of the electrodes.**

This increases the real surface area of each nominal  $1 \text{ cm}^2$ , and this increases  $i_0$ .

- **Increasing reactant concentration,**

For example, using pure  $\text{O}_2$  instead of air. This works because the catalyst sites are more effectively occupied by reactants.

- **Increasing the pressure.**

This is also presumed to work by increasing catalyst site occupancy. (This also increases the reversible open circuit voltage, and so brings a 'double benefit'.) Increasing the value of  $i_0$  has the effect of raising the cell voltage by a constant amount at most currents, and so mimics raising the open circuit voltage (*OCV*). The last two points in the above list explain the discrepancy between *OCV* and actual *OCV*. [12]

### 3.4 Ohmic Losses

The losses due to the electrical resistance of the electrodes, and the resistance to the flow of ions in the electrolyte, are the simplest to understand and to model. The size of the voltage drop is simply proportional to the current, that is,

$$V = IR$$

In most fuel cells the resistance is mainly caused by the electrolyte, though the cell interconnects or bipolar plates can also be important. To be consistent with the other equations for voltage loss, the equation should be expressed in terms of current density. To do this we need to bring in the idea of the resistance corresponding to  $1 \text{ cm}^2$  of the cell, for which we use the symbol  $r$ . (This quantity is called the area specific resistance or ASR.) The equation for the voltage drop then becomes [3]

$$V_{ohm} = ir \quad (3.8)$$

Where  $i$  is, as usual, the current density. If  $i$  is given in  $\text{mAcm}^{-2}$ , then the area-specific resistance,  $r$ , should be given in  $\text{k}\Omega\text{cm}^2$ , it is possible to distinguish this particular irreversibility from the others. Using such techniques it is possible to show that this 'ohmic' voltage loss is important in all types of cell, and especially important in the case of the solid oxide fuel cell (*SOFc*). Three ways of reducing the internal resistance of the cell are as follows: [3]

- The use of electrodes with the highest possible conductivity.
- Good design and use of appropriate materials for the bipolar plates or cell interconnects.
- Making the electrolyte as thin as possible. However, this is often difficult, as the electrolyte sometimes needs to be fairly thick as it is the support onto which the

electrodes are built, or it needs to be wide enough to allow a circulating flow of electrolyte. In any case, it must certainly be thick enough to prevent any shorting of one electrode to another through the electrolyte, which implies a certain level of physical robustness.[3]

### 3.5 Mass Transport or Concentration Losses

If the oxygen at the cathode of a fuel cell is supplied in the form of air, then it is self evident that during fuel cell operation there will be a slight reduction in the concentration of the oxygen in the region of the electrode, as the oxygen is extracted. The extent of this change in concentration will depend on the current being taken from the fuel cell, and on physical factors relating to how well the air around the cathode can circulate, and how quickly the oxygen can be replenished.[3]

This change in concentration will cause a reduction in the partial pressure of the oxygen. Similarly, if the anode of a fuel cell is supplied with hydrogen, then there will be a slight drop in pressure if the hydrogen is consumed as a result of a current being drawn from the cell. This reduction in pressure results from the fact that there will be a flow of hydrogen down the supply ducts and tubes, and this flow will result in a pressure drop due to their fluid resistance.[3]

This reduction in pressure will depend on the electric current from the cell (and hence  $H_2$  consumption) and the physical characteristics of the hydrogen supply system. In both cases, the reduction in gas pressure will result in a reduction in voltage. However, it is generally agreed among fuel cell researchers that there is no analytical solution to the problem of modeling the changes in voltage that works satisfactorily in all cases. One approach that does yield an equation that has some value and use is to see the effect of this reduction in pressure (or partial pressure). These give the change in *OCV* caused by a change in pressure of the reactants. In equation we saw that the change in voltage caused by a change in hydrogen pressure only is

$$\Delta V = \left(\frac{RT}{2F}\right) \ln \left(\frac{P_2}{P_1}\right)$$

Now, the change in pressure caused by the use of the fuel gas can be estimated as follows. We postulate a limiting current density  $i_1$  at which the fuel is used up at a rate equal to its maximum supply speed. The current density cannot rise above this value, because the fuel gas cannot be supplied at a greater rate. At this current density the pressure would have just reached zero. If  $P_1$  is the pressure when the current density is zero, and we assume that the pressure falls linearly down to zero at the current density  $i_1$ , then the pressure  $P_2$  at any current density  $i$  is given by the formula [3]

$$P_2 = P_1 \left(1 - \frac{i}{i_1}\right)$$

If we substitute this into equation (given above), we obtain

$$\Delta V = \left(\frac{RT}{2F}\right) \ln \left(1 - \frac{i}{i_1}\right) \quad (3.9)$$

This gives us the voltage change due to the mass transport losses. We have to be careful with signs here, and the term inside the brackets is always less than 1. So if we want an equation for voltage drop, we should write it as

$$V_{trans} = \left(\frac{-RT}{2F}\right) \ln \left(1 - \frac{i}{i_1}\right)$$

Now the term that in this case is  $RT/2F$  will be different for different reactants. For example, for oxygen it will be  $RT/4F$ . In general, we may say that the concentration or mass transport losses are given by the equation

$$V_{trans} = -B \ln \left(1 - \frac{i}{i_1}\right) \quad (3.10)$$

Where  $B$  is a constant that depends on the fuel cell and its operating state. For example, if  $B$  is set to  $0.05V$  and  $i_1$  to  $1000\text{mAcm}^{-2}$ , then quite a good fit is made to curves such as those of Figures 3.1. and 3.2. However, this theoretical approach has many weaknesses, especially in the case of fuel cells supplied with air rather than pure oxygen – which is the vast majority.

There are also problems with lower-temperature cells, and those supplied with hydrogen mixed with other gases such as carbon dioxide for the fuel. No account is taken for the production and removal of reaction products, such as water, and neither is any account taken of the build-up of nitrogen in air systems. Another approach that has no claim for a theoretical basis, but is entirely empirical, has become more favoured lately, and yields an equation that fits the results very well. This approach uses equation 3.9 below because it gives a very good fit to the results, provided the constants  $m$  and  $n$  are chosen properly.[3]

$$V_{trans} = m \exp (ni) \quad (3.11)$$

The value of  $m$  will typically be about  $3 \times 10^{-5}$  V, and  $n$  about  $8 \times 10^{-3} \text{ cm}^2 \text{ mA}^{-1}$ . Although the equations 3.9 and 3.10 look very different, if the constants are chosen carefully the results can be quite similar. However, equation 3.10 can be used to give a better fit to measured results, and so this will be used in the rest of this chapter, and appears to be quite widely used in the fuel cell community. The mass transport or concentration overvoltage is particularly important in cases where the hydrogen is supplied from some kind of reformer, as there might be a difficulty in increasing the rate of supply of hydrogen quickly to respond to demand. Another important case is at the air cathode, if the air supply is not well circulated. A particular problem is that the nitrogen that is left behind after the oxygen is consumed can cause a mass transport problem at high currents – it effectively blocks the oxygen supply.

### 3.6 Combining the Irreversibilities

It is useful to construct an equation that brings together all these irreversibility's. We can do so and arrive at the following equation for the operating voltage of a fuel cell at a current density  $i$ .

$$\begin{aligned} V &= E - V_{ohm} - V_{act} - V_{trans} \\ V &= E - ir - A \ln \left( i + \frac{i_0}{i} \right) + m \exp (ni) \end{aligned} \quad (3.12)$$



In this equation,  $E$  is the reversible  $OCV$ .  $i_n$  is the internal and fuel crossover equivalent current density,  $A$  is the slope of the Tafel line,  $i_o$  is either the exchange current density at the cathode if the cathodic overvoltage is much greater than the anodic or it is a function of both exchange current densities,  $m$  and  $n$  are the constants in the mass-transfer overvoltage equation 3.10.  $r$  is the area-specific resistance. Although correct, this equation is often simplified in a useful and practical way. [4]

The crossover current  $i_n$  is usually very small, and although useful for explaining the initial fall in voltage, it has little impact on operating losses of fuel cells at working currents. It is also very difficult to measure. We can also largely account for the term resulting from  $i_o$  if we assume that the current is always greater than this exchange current. Because of the crossover current, this is nearly always the case. The equation for the activation overvoltage is rearranged to [4]

$$V_{act} = A \ln \left( \frac{i}{i_o} \right) = A \ln(i) - A \ln(i_o) \quad (3.13)$$

Because the second half of this equation is a constant, we can deal with this by postulating a real, practical, open circuit voltage  $E_{oc}$  that is given by the equation

$$E_{oc} = E + A \ln(i_o) \quad (3.14)$$

$E$  is the theoretical, reversible, open circuit voltage.

Note that  $E_{oc}$  will always be less than  $E$  because  $i_o$ , being small, will generate negative logarithms. If we substitute equations 3.12 and 3.13 into 3.11 and remove  $i_n$ , we obtain

$$V = E_{oc} - ir - A \ln(i) + m \exp(ni) \quad (3.15)$$

The power that the fuel cell produced is about 2KW. And each cell voltage is about 0.8V dependant on the curve. Where  $n$  is the number of cells in this project is about 30 cells.

$$I = \frac{P_e}{n * V_c}$$

$$I = \frac{2 \times 10^3}{0.8 + 30}$$

$$= 83.33 \text{ A}$$

$$i = 265 \text{ mAcm}^{-2}$$

$$\text{area} = \frac{I}{i}$$

$$\text{area} = 315 \text{ cm}^2$$

This equation is simple, yet has been found to give an excellent fit with the results of real fuel cells. Those for one cell from a Ballard Mark V fuel cell stack are taken from Laurencelle. It is simple to model this equation using a spreadsheet (such as EXCEL), or programs such as MATLAB, or graphics calculators. However, it must be borne in mind that the logarithmic model does not work at very low currents, especially at zero. It is best to start the plots with a current of 1.0mAcm<sup>-2</sup>. As an example, we have given below the MATLAB script file that was used to produce the graph in Figure 3.2.

```

Eoc=1.031, A=0.03, r=0.000245, m=2.11E-5, n=0.008
i = linspace(1,1000,200)
v = Eoc - r * i - A * log(i) - m * exp(n * i)
plot (i,v)

```

### 3.7 Effect of Cell Life

The endurance of the cell stack is of primary concern for SOFCs. As SOFC technology has continued to approach commercialization, research in this area has increased and improvements made. The Siemens Westinghouse state-of-the-art tubular design has been validated by continuous electrical testing of over 69,000 hours with less than 0.5 percent voltage degradation per 1,000 hours of operation. This tubular design is based on the early calcia-stabilized zirconia porous support tube (PST). In the current technology, the PST has been eliminated and replaced by a doped lanthanum manganite air electrode tube. These air electrode-supported (AES) cells have shown a power density increase of approximately 33 percent over the previous design. Siemens Westinghouse AES cells have shown less than 0.2 % voltage degradation per 1,000 hours in a 25 kW stack operated for over 44,000 hours (23,56), and negligible degradation in the 100 kW stack operated in the Netherlands and Germany (>16,000 hours).



## 4.1 Design of System and Components

The layout of the fuel cell system is shown on the attached drawing. The system design has naturally not been such a chronological process as the following description would give an impression of. A lot of suppliers have been contacted and many iterative design modifications have been made. The components chosen might seem common to many but aspects like material demands have discarded many potential suppliers who mostly did not have any experience with hydrogen. A database has been created where most of the contacted suppliers have been listed with information regarding component type, price, and availability. [10]

In general 5 subsystems are to be build which are shown in figure 4.1. Above each arrow a symbol representing the process inputs and the internal states, which is going to be controlled by the subsystems around the fuel cell is shown. In the following the description of the system will be divided into these 5 sub groups which is also the case as well in the database as in the enclosed drawing. [10]

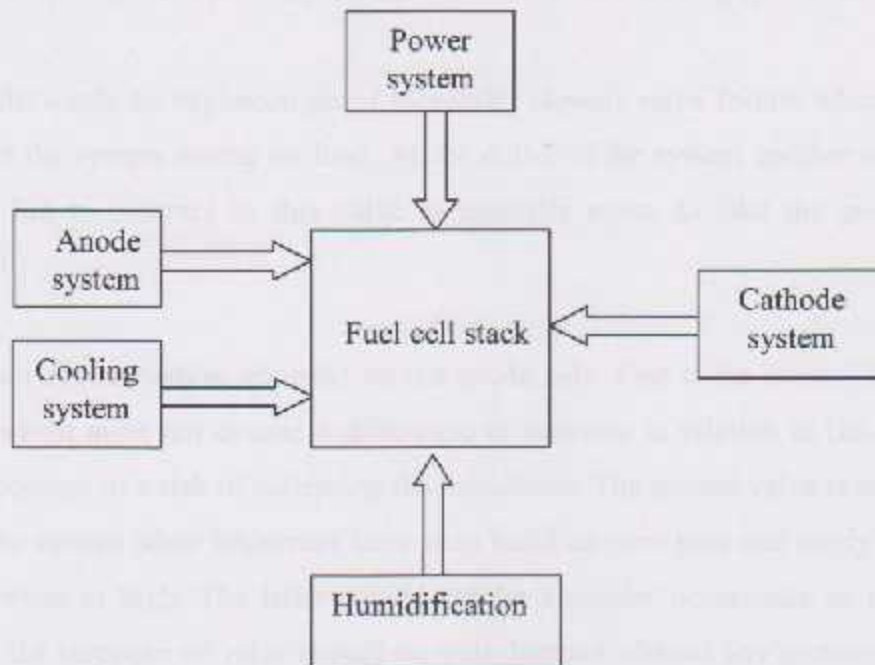


Figure (4.1): A schematic of the five subsystems interact with the fuel cell

## 4.2 Anode Side

The main concern, when designing the anode side, is that it has to provide a safe way of supplying hydrogen for the fuel cell. As mentioned previously the humidity of the membrane is of major importance for the ion conductivity. Some fuel cell systems are supplied with water on both the anode side as well as to the cathode side. If top performance is desired this will be a good idea but on the other hand it adds significantly to the complexity of the system, and so it has been decided to test the fuel cell without humidification on the anode side. Instead it has been chosen to let the anode and the cathode gas streams flow in the opposite direction of each other causing a more even distribution of water throughout the fuel cell. [10]

A hydrogen bottle is placed as the first component on the anode side which is connected in parallel with a nitrogen bottle. This is used for flushing the system after use. This is due to a little amount of oxygen diffusing through the membrane when the system is stopped for longer periods of time. After some time (days or weeks) all the hydrogen will have been consumed and only condensed water is left causing system cavitation. [10]

Afterwards an explosion proof (normally closed) valve follow which will safely disconnect the system during no load. At the outlet of the system another security valve is placed but in contrary to this valve is normally open, to take the pressure of the system. [10]

Two control valves are used on the anode side. One is for controlling the anode pressure which must not exceed a difference in pressure in relation to the cathode side pressure because of a risk of collapsing the membrane. The second valve is used for partly purging the system when impurities have been build up over time and partly for taking of pressure when to high. The latter should not be a regular occurrence as under normal operation the response of valve should be well damped without any pressure over shoot. [10]

#### 4.2.1 Hydrogen Usage

The rate of usage of hydrogen is derived in a way similar to oxygen, except that there are two electrons from each mole of hydrogen. [3]

$$H_2 = \frac{I_n}{2F} \text{ moles } s^{-1} \quad (4.1)$$
$$H_2 \text{ usage} = \frac{P_e}{2V_c F} \text{ moles } s^{-1}$$

The molar mass of hydrogen is  $2.02 \times 10^{-3} \text{ kg mole}^{-1}$ , so this becomes

$$H_2 \text{ usage} = \frac{2.02 \times 10^{-3} \cdot P_e}{2V_c F}$$
$$= 1.05 \times 10^{-9} \cdot \frac{P_e}{V_c} \text{ kg } s^{-1}$$

At stoichiometric operation. Obviously, this formula only applies to a hydrogen-fed fuel cell. In the case of a hydrogen/carbon monoxide mixture derived from a reformed hydrocarbon, things will be different, depending on the proportion of carbon monoxide present. The result can be transformed to a volume rate using the density of hydrogen, which is  $0.084 \text{ kgm}^{-3}$  at normal temperature and pressure (NTP).[3]

For in the project the power is 2 kw the hydrogen usage to work 50h can be calculated and storage in the bottle, calculate the volume of .

$$H_2 = 1.05 \times 10^{-9} \cdot \frac{P_e}{V_c} \text{ kg } s^{-1}$$
$$H_2 = 1.05 \times 10^{-9} \cdot \frac{2 \times 10^3}{0.8} \text{ kg } s^{-1}$$
$$= 2.625 \times 10^{-6} \text{ kg } s^{-1}$$
$$= 2.625 \times 10^{-6} \times 50 \times 3600$$
$$= 0.472500 \text{ kg for 50h}$$



### 4.3 Cathode Side

In contrast to the anode side the cathode side will need two actuators to control both pressure and stoichiometric air flow, since only approximately 20% volume of atmospheric air is oxygen. Hence the loop cannot be closed as on the anode side, and while the fuel cell output voltage is heavily dependent on the air stoichiometric flow, more oxygen than needed will have to be pumped through the system. [10]

This is done by use of a compressor and two control valves to adjust the pressure. The compressor is of the rotary vane type compressor.

To be able to control the output of the compressor a frequency inverter (Danfoss VLT) is implemented. The frequency to the compressor is controlled by a signal pic micro (controller).

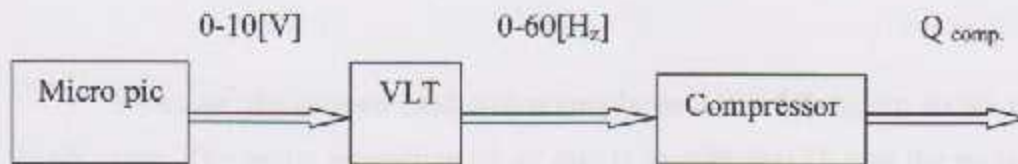


Figure (4.2): Basic setup of the compressor.

The major demands for the compressor are that the flow should be variable, it should be able to deliver pressures up to two [bars] and it should be oil-free as oil tends to block the pores in the gas diffusion layer of the fuel cell.

#### 4.3.1 Oxygen and Air Usage

From the basic operation of the fuel cell, we know that four electrons are transferred for each mole of oxygen.[3]

$$\text{charge} = 4F * \text{amount of } O_2 \quad (4.2)$$

Dividing by time, and rearranging

$$O_2 \text{ usage} = \frac{I}{4F} \text{ moles } s^{-1} \quad (4.3)$$

This is for a single cell. For a stack of  $n$  cells

$$O_2 \text{ usage} = \frac{I n}{4F} \text{ moles } s^{-1}$$

However, it would be more useful to have the formula in  $kg s^{-1}$ , without needing to know the number of cells, and in terms of power, rather than current. If the voltage of each cell in the stack is  $V_c$ , then[3]

$$\text{Power, } P_e = V_c \times I \times n \quad (4.4)$$

$$I = \frac{P_e}{V_c \times n}$$

$$O_2 \text{ usage} = \frac{P_e}{4 V_c F} \text{ moles } s^{-1}$$

Changing from moles  $s^{-1}$  to  $kg s^{-1}$

$$\begin{aligned} O_2 \text{ usage} &= \frac{32 \times 10^{-3} \cdot P_e}{4 V_c F} \text{ kg } s^{-1} \\ &= \frac{8.29 \times 10^{-8} \times P_e}{V_c} \text{ kg } s^{-1} \end{aligned}$$

However, the oxygen used will normally be derived from air, so we need to adapt to air usage. The molar proportion of air that is oxygen is 0.21, and the molar mass of air is  $28.97 \times 10^{-3} \text{ kg mole}^{-1}$ .

$$\text{Air usage} = \frac{8.29 \times 10^{-8} \times P_e}{0.21 \times 4 \times V_c \times F} \quad (4.5)$$

$$= \frac{3.57 \times 10^{-7} \times P_e}{V_c} \text{ kg } s^{-1}$$

For the project the power is 2kw the flow rate usage to produce the power . input flow rate and flow out .  $V_c = 0.8$  voltage

$$\begin{aligned} \text{Air usage} &= \frac{3.57 \times 10^{-7} \times 2000}{0.8} \text{ kgs}^{-1} \\ &= 8.925 \times 10^{-4} \text{ kg } s^{-1} \end{aligned}$$



## 4.4 Cooling System

As mentioned previously the fuel cell system should be maintained at a temperature of approximately 70°C by use of water cooling system where the difference temperature between inlet and outlet does not exceed 5°C. However the latter is considered to be a design parameter as proper design can solve this issue.[10]

### 4.4.1 Heat rate

Heat is produced when a fuel cell operates, that if all the enthalpy of reaction of a hydrogen fuel cell was converted into electrical energy then the output voltage would be.[3]

1.48V if the water product was in liquid form  
or 1.25V if the water product was in vapour form.

It clearly follows that the difference between the actual cell voltage and this voltage represents the energy that is not converted into electricity – that is, the energy that is converted into heat instead. [3]

The cases in which water finally ends in liquid form are so few and far between that they are not worth considering. So we will restrict ourselves to the vapour case. However, please note that this means we have taken into account the cooling effect of water evaporation. It also means that energy is leaving the fuel cell in three forms: as electricity, as ordinary ‘sensible’ heat, and as the latent heat of water vapour. For a stack of  $n$  cells at current  $I$ , the heat generated is thus[3]

$$\text{Heating rate} = nI (1.25 - V_c) W \quad (4.6)$$

In terms of electrical power, this becomes

$$\text{Heating rate} = P_e \left( \frac{1.25}{v_c} - 1 \right) W$$

$$\text{Heating rate} = 2k \left( \frac{1.25}{0.8} - 1 \right) W$$

$$= 1125 W$$

Generally speaking effort have been put in the design of the cooling system. The water pump have been selected in such a way that at maximum flow it should be able to remove approximately 1.125 [kW] of heat at a maximum difference temperature of 5°C.[10]

$$P_{fc, loss} = \dot{m}_{water, pump} * c_{p, water} T_{fc} \quad (4.7)$$

$$\dot{m}_{water, pump} = \frac{P_{fc, loss}}{c_{p, water} T_{fc}}$$

$$c_{p, water} = 4192$$

$$\dot{m}_{water, pump} = \frac{1125}{4192 * 5}$$

$$\dot{m}_{water, pump} = 0.0536 \text{ kg s}^{-1}$$

$$\dot{m}_{water, pump} = 3.22 \text{ L. m}^{-1}$$

#### 4.5 Humidification System

The primary goal of the humidification system is to supply the air stream with up to 5 [kg/h] of water to humidify the incoming stream. It is assumed in the following that the output humidity should be kept at approximately 100%. Usually the outlet air stream would be fed through a condenser to keep a closed water management system, where no refilling of water where necessary. Since the water content in fully humidified air doubles approximately every 15°C the air need not be cooled very much to recirculate most of the water. However as this would add to system complexity it is left out of concern.[10]

A diaphragm water pump is delivering pressurized water to a atomizer nozzle which is injecting water into the system to humidify the incoming air. Several methods of humidification have been examined including bubblers, used for laboratory test stands. In contrary the water injection method is a very compact solution where direct control of humidification state is possible. The main drawback is that the mist cannot be fed directly into the fuel cell unless the atomization mist is very fine. Consequently energy has to be supplied to evaporate the water externally. Otherwise the water injection could have been done directly into the fuel cell which in turn would have lowered the need for cooling as well. where it is also shown that at full load the amount of waste heat released from the fuel cell matches the amount of energy needed for vaporization of the water droplets.

The following system description pattern is a little modified using your language and your needs. The following system description pattern is a little modified using your language and your needs. The following system description pattern is a little modified using your language and your needs.

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## Chapter five

# The components and functionality

## 5.1 System Descriptions

The following system descriptions pertain to a multi application using pure hydrogen stored as a medium pressure gas. This information represents the most complete description currently available, although it cannot cover all hardware configurations and variations.

These system descriptions indicate the basic functionality of each system, the type of components required, and their interrelationships. Specific fuel cell differ from these descriptions in a variety of details depending on the state of the art at the time of manufacture, constraints imposed by the specific bus chassis, and the level of component integration.

Fuel cell consists of three main parts, this parts is anode side ,cathode side and electrolyte systems , for each part, one entrance and exit, and all the bold of us is a complete system for the unit, and the process of connectivity and control every system and process integration between systems is building the cell is full, while the cell need to be other things to work control and integration between the parts of a whole.

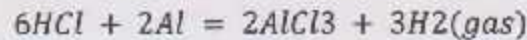
For the purpose of clarity, transducers, switches and other incidental components are not included in the descriptions.

## 5.2 Anode system (cycle of fuel )

### 5.2.1. Fuel Storage and production System

The fuel storage system receives stores and dispenses the hydrogen fuel. The fuel storage system consists of a fueling circuit, the storage cylinders, a high pressure circuit and a motive pressure circuit.

The hydrogen production that occur by the reaction between the acid and metal to produce the pure hydrogen , the hydrochloric acid (37%) is used in addition to aluminum ,according to this equation to produce H<sub>2</sub> .



According to equation above, adding 150 ml of (HCl) hydrochloric acid (37%) and aluminum. the hydrogen produced is

*The concentration of 150 ml of HCL is 11.6 mol /l*

$$\text{number of moles} = \text{con.} * \text{volum}$$

$$= (11.6)(0.15)$$

$$= 1.74 \text{ moles of HCL will reacts}$$

6 mol of HCL gives 3 mol of H<sub>2</sub>, and then 1.74 mol of HCL will gives 0.87 mol of H<sub>2</sub>.

#### **A: Hydrogen cylinder**

the anode side is used to supply the hydrogen to the fuel cell, the hydrogen is storage in special tank, where the temperature and pressure are important in this case, the tank contains about 3l of H<sub>2</sub>.

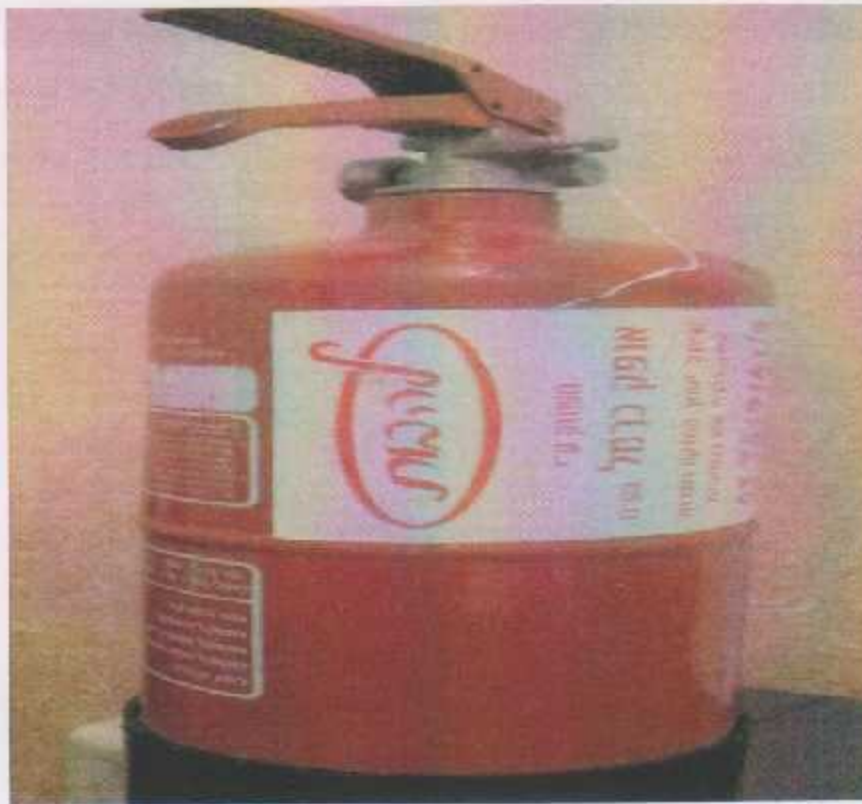


Figure (5-1): hydrogen cylinder

**B: hand valve**

The hydrogen is passed to the hand valve, which used to control the flow of the hydrogen, and used for the safety.



Figure (5-2): hand valve

### **C: Regulator**

The regulator used to control the pressure of hydrogen and oxygen in restricted range about (0.5-10) bar.

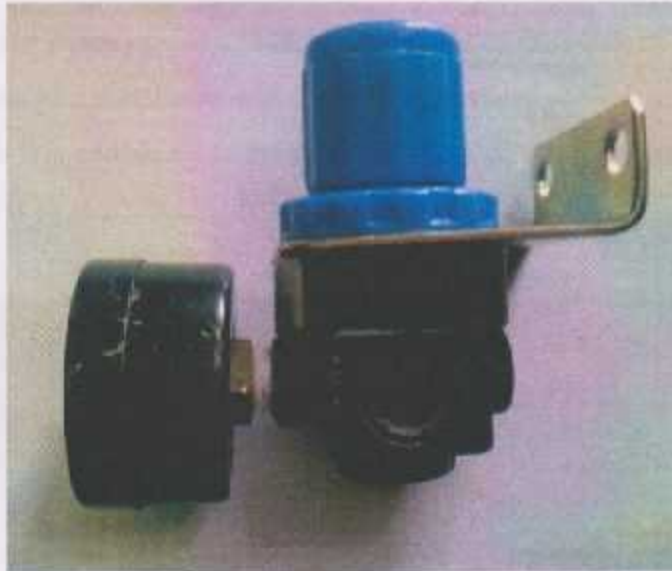


Figure (5-3): regulator

### **D: One Directional**

After there one directional valve (check valve) used to force the hydrogen to flow in one direction.



figure (5-4): one directional

### **F: Distributor input**

The hydrogen moved to distributor, where used to distribute the hydrogen to all the cells in parallel with the same pressure regulator on the inside of the catalyst.

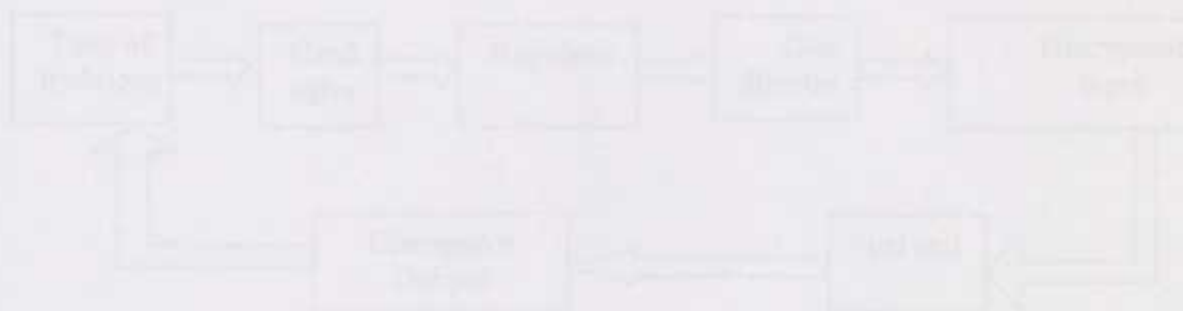
Distributor consists of a metal pipe and connections, where connected by welding, have a high pressure until it is connected to the cell. The outer diameter of metal pipe is (4 mm), and inner diameter is (2 mm)



Figure (5-5) : Distributor input

### **H: Distributor output**

The output Distributor is the same as the input Distributor, but the output distributor is recycle to the Distributor input, and separated between the input and output by one direction valve, then connected to the Hydrogen return in the cell





## 5.2.2 The pressure of the hydrogen (H<sub>2</sub>)

The pressure of each cell in anode side system, from the previous calculation in chapter four for the power of the one cell (35.828 W).

$$\begin{aligned} H_2 \text{ usage} &= 1.05 \times 10^{-9} \cdot \frac{P_g}{V_c} \text{ kg s}^{-1} \\ &= 4.7 \times 10^{-8} \text{ Kg s}^{-1} \end{aligned}$$

$$\begin{aligned} \text{Number of moles} &= \frac{\text{mass}}{\text{Molar mass}} \\ &= \frac{4.7 \times 10^{-8}}{2} \\ &= 2.35 \times 10^{-8} \text{ mol/s}^{-1} \end{aligned}$$

From the ideal gas law

$$PV = mRT$$

Where:

P: pressure of hydrogen

V: volume of hydrogen in each cell

m: number of moles

T: temperature of hydrogen

$$\begin{aligned} P &= \frac{m \cdot r \cdot T}{V} \\ P &= \frac{2.35 \times 10^{-8} \cdot (25 + 273) \cdot 8.314}{845 \times 10^{-7}} \\ &= 0.69 \text{ bar} \end{aligned}$$

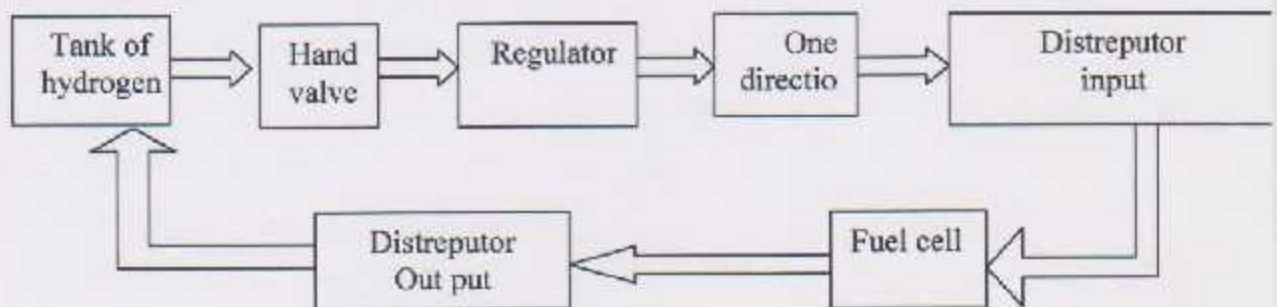


Figure (5-6) : anode cycle

### 5.3 Cathode side

The cathode side used to supply the oxygen to the fuel cell. In this side the oxygen is supply as  $O_2$  where it is used in this project. In the other hand the air is supply to the cathode, in this case the compressor is used to pressurize the air in the tank at certain pressure. and using a  $CO_2$  scrubber to remove the carbon hydroxide from the air. The components of cathode side are the same as the components of the anode side but the cathode used the ( $O_2$ ).

The tank is containing 3l of oxygen in pressure larger than the hydrogen used in the anode side. Output the cathode not used the cycle, but the output of ( $O_2$ ) is leaked into the air by the egoist controllable of the pressure manual as shown in the figure below.



Figure (5-7): egoist

### 5.3.1 The pressure of hydrogen in each cell in anode side system

For the previous calculation in chapter four for the power of the one cell (35.828 W),

$$\begin{aligned} &= \frac{8.29 \times 10^{-8} * P_e}{v_c} \text{ kg s}^{-1} \\ &= 3.7126765 * 10^{-6} \text{ kgs}^{-1} \\ \text{Number of moles} &= \frac{\text{mass}}{\text{Molar mass}} \\ &= \frac{3.7126765 * 10^{-6}}{16} \\ &= 2.32 * 10^{-7} \text{ mol/s}^{-1} \end{aligned}$$

From the ideal gas law

$$PV = mRT$$

Where:

P: pressure of hydrogen

V: volume of hydrogen in each cell

m: number of moles

T: temperature of hydrogen

$$P = \frac{m * r * T}{V}$$

$$P = 6.8 \text{ bare}$$

## 5.4 Electrodes

In this project used the compound electrodes, which is consist several catalyst materials, and will be described each one as follows:

### 5.4.1 A: Rolled electrodes

Modern electrodes tend to use carbon-supported catalysts, mixed with PTFE, which are then rolled out onto a material such as nickel mesh. The PTFE acts as a binder,

and its hydrophobic properties also stop the electrode from flooding and provide for controlled permeation of the electrode by the liquid electrolyte. A thin layer of PTFE is put over the surface of the electrode to further control the porosity and to prevent the electrolyte passing through the electrode, without the need to pressurize the reactant gases, as has to be done with the porous metal electrodes. Carbon fiber is sometimes added to the mix to increase strength, conductivity, and roughness. Such an electrode is shown in Figure. (3)



Figure (5-8): electrode

#### **5.4.2 B: iron-chromium-nickel alloys**

Austenitic stainless steels are iron-chromium-nickel alloys which are hardenable only by cold working. Nickel is the main element varied within the alloys of this class while carbon is kept to low levels. The nickel content may be varied from about 4% to 22% - higher values of nickel are added to increase the ductility of the metal. When chromium is increased to raise the corrosion resistance of the metal, nickel must also be increased to maintain the austenitic structure.

These alloys are slightly magnetic in the cold-worked condition, but are essentially non-magnetic in the annealed condition in which they are most often used. The austenitic types feature adaptability to cold forming, ease of welding, high-temperature service, and, in general, the highest corrosion resistance. Following are brief descriptions of some of our most commonly ordered stainless steels:

Type 304 stainless steel has lower carbon to minimize carbide precipitation. It is less heat sensitive than other 18:8 steels. Used in high-temperature applications. Machinability- 45%. Drawing or stamping - very well. Welding - very good, tough welds. And the other properties in appendix A

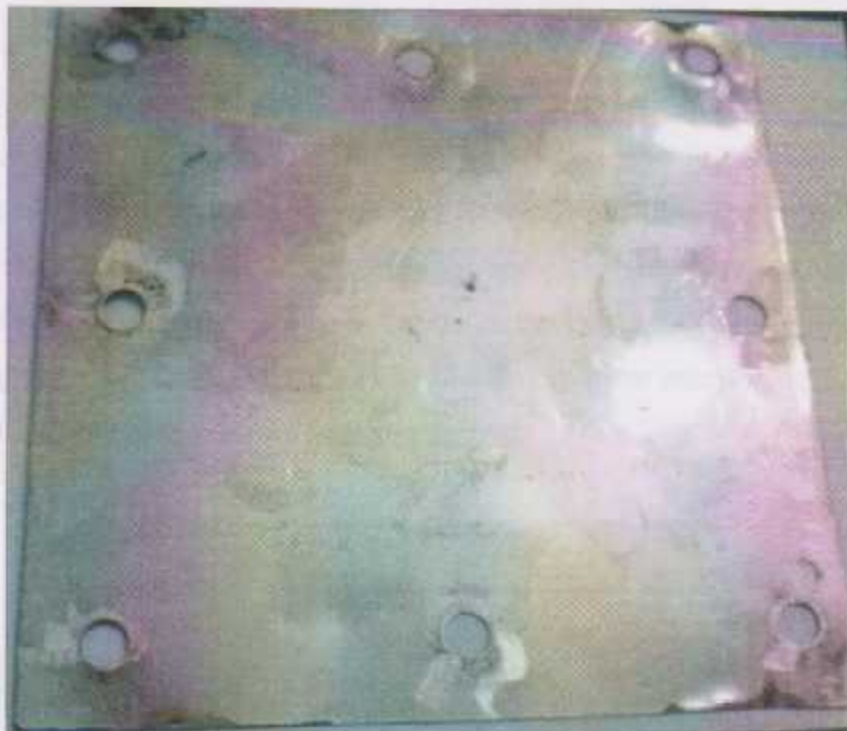


Figure (5-9) : steel alloy

#### **5.4.3 C: The catalytic converter consists of several components:**

1. The core, or substrate. The core is often a ceramic honeycomb in modern catalytic converters, but stainless steel foil honeycombs are also used. The honeycomb surface increases the amount of surface area available to support the catalyst, and therefore is often called a "catalyst support". The ceramic substrate was invented by Rodney Bagley.

Irwin Lachman and Ronald Lewis at Corning Glass, for which they were inducted into the National Inventors Hall of Fame in 2002.

2. The washcoat. A washcoat is used to make converters more efficient, often as a mixture of silica and alumina. The washcoat, when added to the core, forms a rough, irregular surface, which has a far-greater surface area than the flat-core surfaces do, which then gives the converter core a larger surface area, and therefore more places for active precious-metal sites. The catalyst is added to the washcoat (in suspension) before being applied to the core.
3. The catalyst itself is most often a precious metal. Platinum is the most-active catalyst and is widely used. It is not suitable for all applications, however, because of unwanted additional reactions and/or cost. Palladium and rhodium are two other precious metals used. Platinum and rhodium are used as a reduction catalyst, while platinum and palladium are used as an oxidation catalyst. Cerium, iron, manganese and nickel are also used, although each has its own limitations. Nickel is not legal for use in the European Union (because of its reaction with carbon monoxide). Copper can be used everywhere except North America, where its use is illegal because of the formation of dioxin.



Figure (5-10) : Converter

All the electrodes will be expands in the previous that used in project. The catalytic converter, silicon, and carbon will mixed of one cell (one cell tow plates) as follows:

- The catalytic converter: take about 33g of catalyst, where the percentage in one centimeter is 0.097
- Carbon : used 2g bwoder of carbon to improve the electrical conductivity and carbon row about 40g for one cell
- Silicon : used 2 type of silicon first is solvent-free and the second is heating silicon

### 5.5 Electrolyte and Cooling system

The electrolyte in the project is circulated to permits the electrolyte to be removed and replaced from time to time, in the other hand the electrolyte is used to cooling the fuel cell.

In this project 7mol of KOH is produced from 3l of water, then the mass of KOH is produced from this equation

$$\text{molarity} = \frac{\text{number of moles}}{\text{volum}}$$

$$7 = \frac{\text{number of moles}}{3l}$$

$$\text{number of moles} = 21$$

$$\text{number of moles} = \frac{\text{mass}}{\text{Molar mass}}$$

$$21 = \frac{m}{56}$$

The mass that added to 3l of water to produced 7M of KOH is 1176 g.

In each cell the electrolyte is 0.1352 liter, and then the electrolyte in 10 cells is 1.352 liter as this equation.

$$\text{Volum of electrolyte in each cell} = l * d * h$$

$$\begin{aligned}
 &= 0.13 * 0.13 * 0.008 \\
 &= 0.0001352 \text{ m}^2 \\
 &= 0.01352 \text{ l}
 \end{aligned}$$

$$\begin{aligned}
 \text{Volum of electrolyte in 10 cells} &= l * d * h * 10 \\
 &= 0.001352 \text{ m}^2 \\
 &= 1.352 \text{ l}
 \end{aligned}$$

Where:

L: is the cell length

d: is the cell high

h: is the cell width

In this project used 3l of electrolyte to cooling the cell in cooling cycle as shown below.

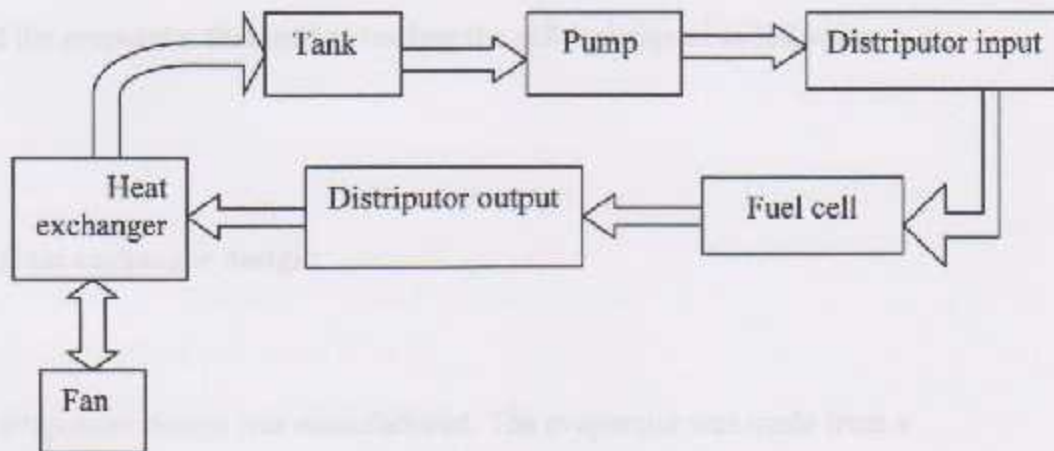


Figure (5-11) : electrolyte & cooling cycle

Where the heat that produced from fuel cell is produced by this equation from chapter four.

$$\begin{aligned}
 \text{Heating rate} &= P_e \left( \frac{1.25}{v_c} - 1 \right) W \\
 &= 500 \left( \frac{1.25}{0.8} - 1 \right)
 \end{aligned}$$



$$= 281.25 \text{ W}$$

$$= 0.28125 \text{ KW}$$

Generally speaking effort has been put in the design of the cooling system. The water pump have been selected in such a way that at maximum flow it should be able to remove approximately 0.28125 [kW] of heat at a maximum difference temperature of 5°C. [10]

$$P_{fc, loss} = \dot{m}_{\text{water, pump}} * c_{p, \text{water}} T_{fc} \quad (5.7)$$

$$\dot{m}_{\text{water, pump}} = \frac{P_{fc, loss}}{c_{p, \text{water}} T_{fc}}$$

$$c_{p, \text{water}} = 4192$$

$$\dot{m}_{\text{water, pump}} = \frac{281.25}{4192 * 5}$$

$$\dot{m}_{\text{water, pump}} = 0.0134 \text{ kg s}^{-1}$$

$$\dot{m}_{\text{water, pump}} = 3.22 \text{ L m}^{-1}$$

And the evaporator that used to cooling the cell is designed as following.

### 5.6 Heat exchanger design:

An evaporator design was manufactured. The evaporator was made from a Aluminum tube

- $S_n$ : Transverse tube spacing [m]

$$S_n = \frac{\text{evaporator height}}{\text{number of rows}} = \frac{0.05}{2} = 0.025 \text{ [m]}$$

- $S_p$ : Longitudinal tube spacing [m]

$$S_p = \frac{\text{evaporator width}}{\text{number of column}} = \frac{0.2}{7} = 0.0286 \text{ [m]}$$

- $f_{\text{in length}}(L_f) = (S_n - D_o)$

- Finewidth =  $W_f = (S_p - D_o)$
- number of fins in row = 70 fins
- fin pitch =  $P_f = \frac{40}{70} = 0.571$  [cm]
- Finethickness =  $t_f = 0.03$  [cm]
- bare tube thickness =  $t_b = P_f - t_f$

Design the evaporator required many calculations such as fluid mechanical calculation, thermal calculation and area calculation, the sequence of design start with fluid mechanical calculation, in thermal calculation will be used the convection heat transfer equations for outer surface neglected the small thermal radiation from the wall until reaching area calculation

(5.7)

Where

Q: heat transfer through the evaporator [W],

$h_o$ : External convection heat transfer coefficient [ $W/m^2C^\circ$ ],

A: surface area of heat transfer [ $m^2$ ],

$T_w$ : Outer evaporator wall temperature [ $C^\circ$ ],

$T_\infty$ : free air temperature.

To determine the external convection heat transfer coefficient can be as the following equations, In order to calculate the total The heat that transferred through the evaporator was determined in chapter three and its value was  $Q_e = 693$  [W], so:

$$h_o = \frac{Nu \cdot k}{D} \quad (5.8)$$

Where

Nu: nusselts number,

K: thermal conductivity of air at entrance of evaporator [W/m °C],

D: outer diameter of evaporator [m].

The Nusselts number can be calculated by the equation:

$$Nu = C(Re)^N Pr^{1/3} \quad (5.9)$$

Where

Re: Reynolds number,

Pr: Prandtl number of air at film temperature,

(C, N): constants can be obtain from table (A-8) according the following considerations.

- $S_p/d = 28.6/10 = 2.86$ .
- $S_n/d = 25/10 = 2.5$ .

From In line arrangement tube banks table(C =0.366, N=0.595)

$$Re = \frac{\rho \cdot V_{max} \cdot D}{\mu} \quad (5.10)$$

Where

$\rho$  :density of air at film temperature [kg/m<sup>3</sup>],

$V_{max}$ : Maximum velocity of air between the evaporator tubes [m/s],

D: outer diameter of the evaporator tubes [m],

$\mu$  :dynamic viscosity of air at film temperature [Pa. s].

For flows normal to in -line tube banks the maximum flow velocity can be calculated as the following.

$$V_{max} = V_{\infty} \frac{S_n}{S_n - D} \quad (5.11)$$

Where

$V_{\infty}$ : is the free air velocity entering the evaporator [m/s], can be calculated by the following equation:

$$V_{\infty} = \frac{\dot{V}}{A} \quad (5.12)$$

Where

$\dot{V}$  : Flow rate of air through the evaporator [m<sup>3</sup>/s],  $\dot{V}=50$  [cfm] = 0.02359 [m<sup>3</sup>/s] from fan manufacturer company,

A: cross sectional area of evaporator [m<sup>2</sup>].

- $A = 0.4 * 0.05 = 0.02$  [m<sup>2</sup>]
- $V_{\infty} = \frac{0.02359}{0.02} = 1.18$  m/s
- $V_{max} = 1.048 * 0.025 / (0.025 - 0.01) = 1.967$  [m/s]

### First evaporator

The properties of air are evaluated at the film temperature, which at entrance to the tube bank is :

$$T_f = \frac{T_w + T_{\infty}}{2} \quad (5.13)$$

Where

$T_f$  : Film temperature [C<sup>o</sup>],

$T_w$  : wall surface temperature [C<sup>o</sup>], assume that it equal the refrigerant temperature,

$T_{\infty}$ : free air temperature [C<sup>o</sup>].

- $T_f = \frac{-10+0}{2} = -5$  [C<sup>o</sup>] = 268 [K]

Then from (table A-12):

- $\rho = 1.292 \text{ [kg/m}^3\text{]}$
- $\mu = 1.725 \cdot 10^{-5} \text{ [kg/m.s]}$
- $K = 0.0243 \text{ [W/m.C}^\circ\text{]}$
- $Pr = 0.715$
- $Re = \frac{1.295 \cdot 1.967 \cdot 0.01}{1.725 \cdot 10^{-5}} = 1476.7$
- $Nu = 0.366 \cdot (1476.7)^{0.595} \cdot (0.715)^{1/3} = 25.2$
- $ho = \frac{25.2 \cdot 0.0243}{10 \cdot 10^{-3}} = 61.24 \text{ [W/m}^2\text{C}^\circ\text{]}$

heat transfer from one element (one fin and one bare tube) the following equation is used:

$$Q_{total} = Q_{fin\ act} + Q_{original} \quad (5.14)$$

Where

$Q_{total}$  : The total heat transfer from the element [W],

$Q_{finact}$  : Actual heat transfer rate per fin [W],

$Q_{original}$  : Heat transfer rate from tube without fin [W],

$Q_{original}$  : Can be calculated by the equation:

$$Q_{orig} = ho \cdot A_{orig} \cdot (T_w - T_{\infty}) \quad (5.15)$$

Where

$ho$ : external convection heat transfer coefficient [W/m<sup>2</sup>C<sup>o</sup>],

$A_{original}$  : The outer surface area of bare tube [m<sup>2</sup>],

$T_w$ : Outer evaporator wall temperature [C<sup>o</sup>],

$T_{\infty}$ : free air temperature:

- $A_{original} = \pi * D * L = \pi * 10 * 10^{-3} * 5.4 * 10^{-3} = 1.696 * 10^{-4} [m^2]$
- $Q_{original} = 61.24 * 1.696 * 10^{-4} * (0 - -10) = 0.104 [W]$

$Q_{fin}$  Can be calculated by the equation:

(5.16)

Where

$Q_{fin}$  : Theoretical heat transfer rate per fin [W],

A fin's surface area for fin [ $m^2$ ];

- $A_{fin} = 2(S_n * S_p - A_{pip}) = 2[0.025 * 0.0286 - \frac{\pi}{4} (0.01)^2] = 12.73 * 10^{-4} [m^2]$
- $Q_{fin} = 61.24 * 12.73 * 10^{-4} * (0 - -10) = 0.778 [W]$

Now, Fin efficiency are calculated by below equations:

$$\eta_f = \frac{\tanh(mL_f)}{mL_f}$$

$$L_f = \left(\frac{L_f}{2}\right) \left[ +0.35 \ln \frac{(\frac{D_0}{2} + \frac{L_f}{2})}{\frac{D_0}{2}} \right]$$

- $L_f = \left(\frac{0.015}{2}\right) \left[ 1 + 0.35 \ln \frac{(\frac{0.01}{2} + \frac{0.015}{2})}{\frac{0.01}{2}} \right] = 0.01 [m]$

$$m = \sqrt{\frac{h * P}{kA}}$$

Where

h :external convection heat transfer coefficient [ $W/m^2.C^\circ$ ],

k: thermal conductivity of aluminum fin ,[ $W/m.C^\circ$ ],

P: perimeter of the fin[m],

A: surface area for convection of fin [ $m^2$ ]:

- $P = 2 * t + 2 * L = (2 * 0.3 * 10^{-3}) + (2 * 0.02) = 0.0406 [m]$
- $A = t * L = 0.3 * 10^{-3} * 0.02 = 6 * 10^{-6} [m^2]$ .

Applied equations (4.17) and (4.19),  $m, \eta_f$  and equal:

$$m = \sqrt{\frac{61.24 * 0.0406}{202 * 6 * 10^{-6}}} = 45.25$$

$$\eta_f = \frac{\tanh(45.25 * 0.01)}{45.25 * 0.01} = 0.94$$

So, the heat transfer flow from the fin is:

$$Q_{finact} = Q_{fin} * \eta_f$$

- $Q_{finact} = 0.776 * 0.94 = 0.729 [W]$

Now the total heat transfer from the element is:

$$\square Q_{total} = 0.729 + 0.104 = 0.833 [W]$$

Now the number of elements that needed to perform the evaporator load can be determined by dividing the total heat transfer through the evaporator by the element total heat transfer, by using the following equation:

$$n = \frac{Q_e}{q_{total}} \quad (5.21)$$

$$n = \frac{645.2}{0.833} = 774.5 \text{ elements}$$

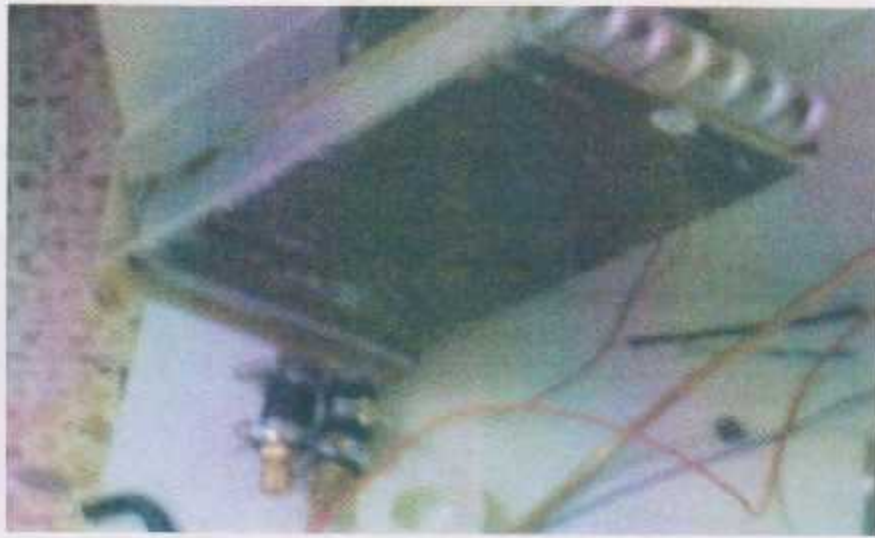


figure (5-12) : Heater

Number of elements in available evaporator =  $(N \cdot R)$ , where N: number of elements in rows, R: number of rows, number of elements in available evaporator =  $70 \cdot 14 = 980$  elements [that is enough]

## 5.7 Fuel cell assembly

In this project used wax to made champers for electrolyte, hydrogen, and oxygen. Where each fuel cell consists:

1. Two wax for forming room electrolyte with area  $(13 \cdot 13 \text{ cm}^2)$  and width 8mm
2. Two wax for forming room hydrogen with area  $(13 \cdot 13 \text{ cm}^2)$  and width 6mm



3. Two wax for forming room oxygen with area ( $13 \times 13 \text{ cm}^2$ ) and width 6mm

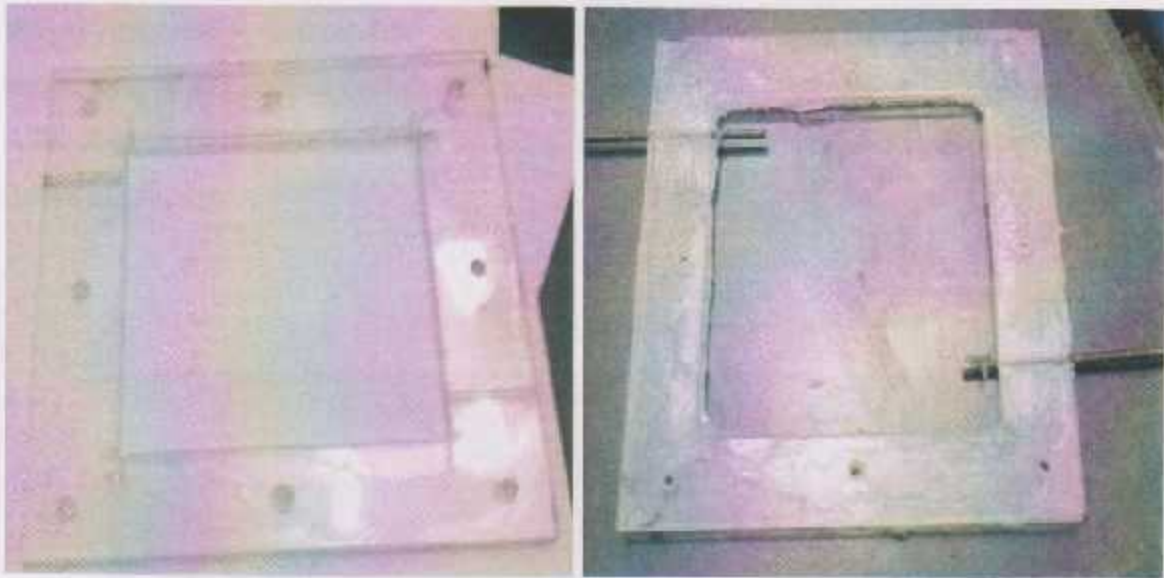


Figure (5-13) : The room design

Used wax to forming fuel cell because it is easy deformation, high isolation, and its high temperature equals to the temperature that produce from the cell.



Figure (5-14) : electrode

Where separate between these three room by using the electrode which describe in the previous slides, then separate among these fuel cell ( cathode side of first fuel cell from anode side of the second fuel cell ) by using alloy steel that connect fuel cells in series. After there collect these fuel cell by using two peace of wood, and finally by 8 bolts as following figures.

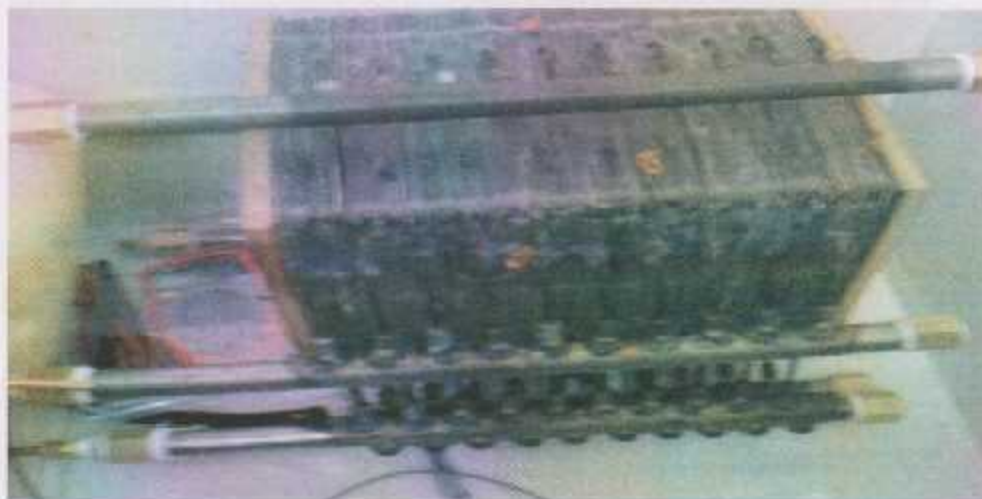


Figure (5-15) : Fuel cells

Used silicon to connect the electrode and wax, because it is high temperature, and used two pipes (4mm) to provide the cell by hydrogen. One for input and the other for output, and the same for electrolyte and oxygen. Then used input distributor for electrolyte, where connect between this distributor and input pipe (4mm) by nibbles, Also used the same technique for hydrogen and oxygen. The tank of oxygen is connect by sinusoid valve and regulator then connect to the input distributor, where the same technique for the hydrogen.

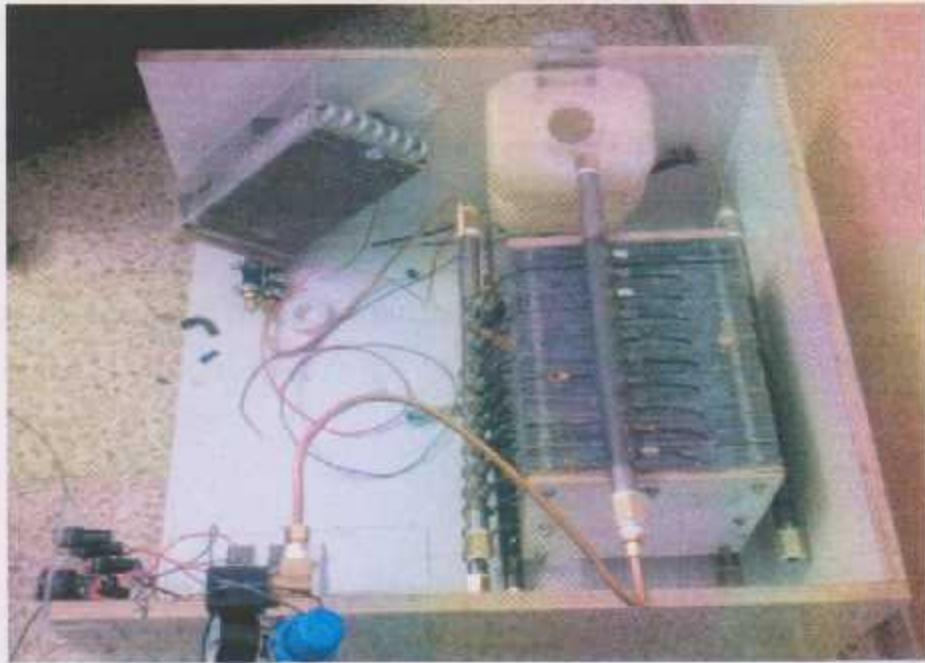


Figure (5-15) : Fuel cells and other components (A)

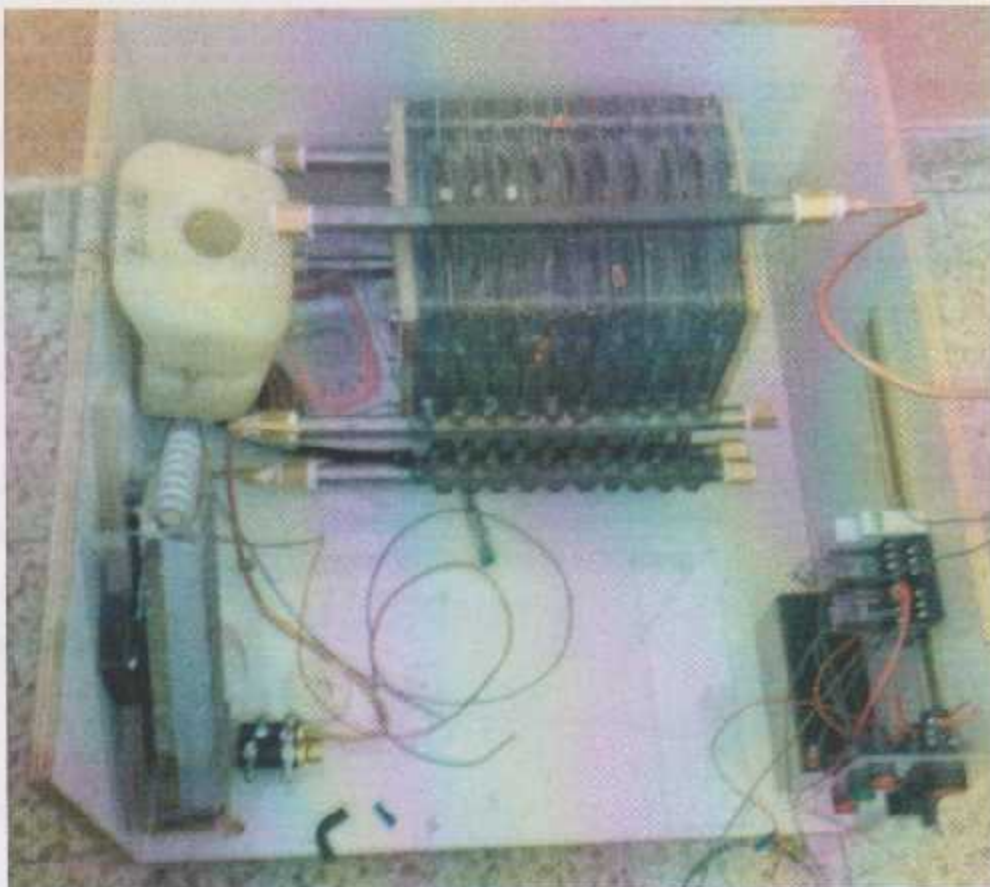


Figure (5-16): Fuel cells and other components (B)

## 5.8 Control system

In this project used the traditional control, because it is simple and used manual control in the pressure and flow, because the automatic control is high cost and not available.

Design the automatic control for the fan, pump, and sinusoid. Where the fan and pump used in cooling system, and electro line cycle sinusoid used to turn on/off the system.

### Circuit components:

1. push button used for emergency and turn off the system.
2. where set/reset switch used to disconnect the battery charge and stop the system (battery full charge reset all the system).
3. In the first, used 12V battery to turn on the system, after 15s used relay (12V and maximum current 5A) to disconnect this battery and connect the system in the battery that charge from the system.
4. used timer to synchronization between charge and discharge (5 mode) as explained in appendix B

This circuit used to turn (on/off) fuel cell system which consists fan, pump, and two sinusoid valves. The system is turn on by using 12V battery at the beginning, after there the system is turned by the major battery of the system that charging by using timer which disconnect the 12V battery and connect the charged battery, then rise the voltage to 12 V and used the chopper to rise the voltage

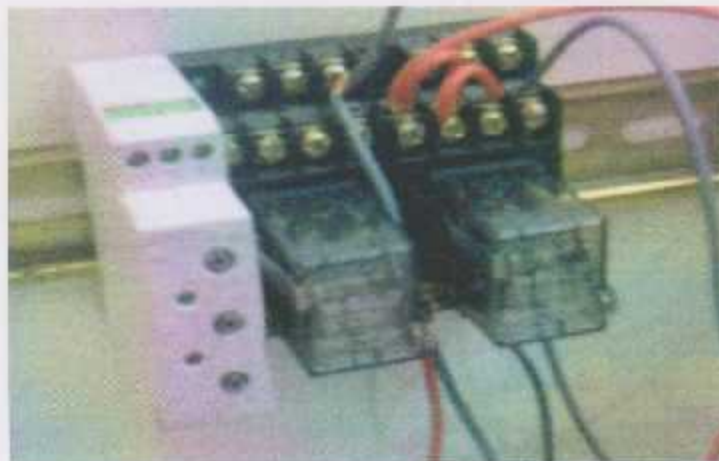


Figure (5-17): relay and timer

to 24 V and charging two battery ,to used the power for any application or inverted the voltage to AC voltage by using inverter .

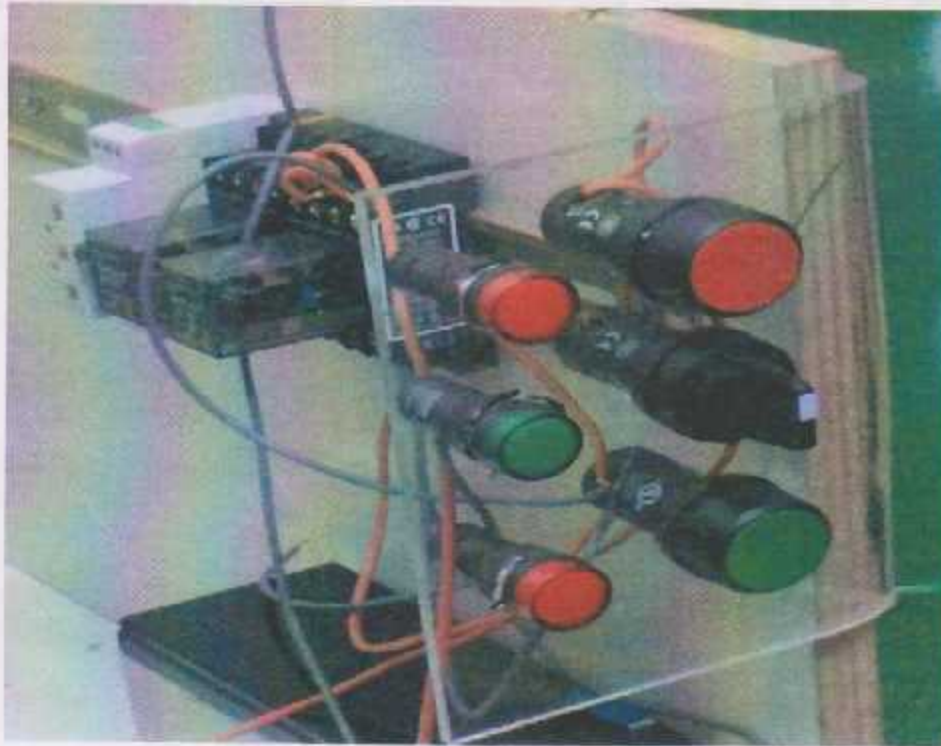


Figure (5-18) : assembly and component the control circuit

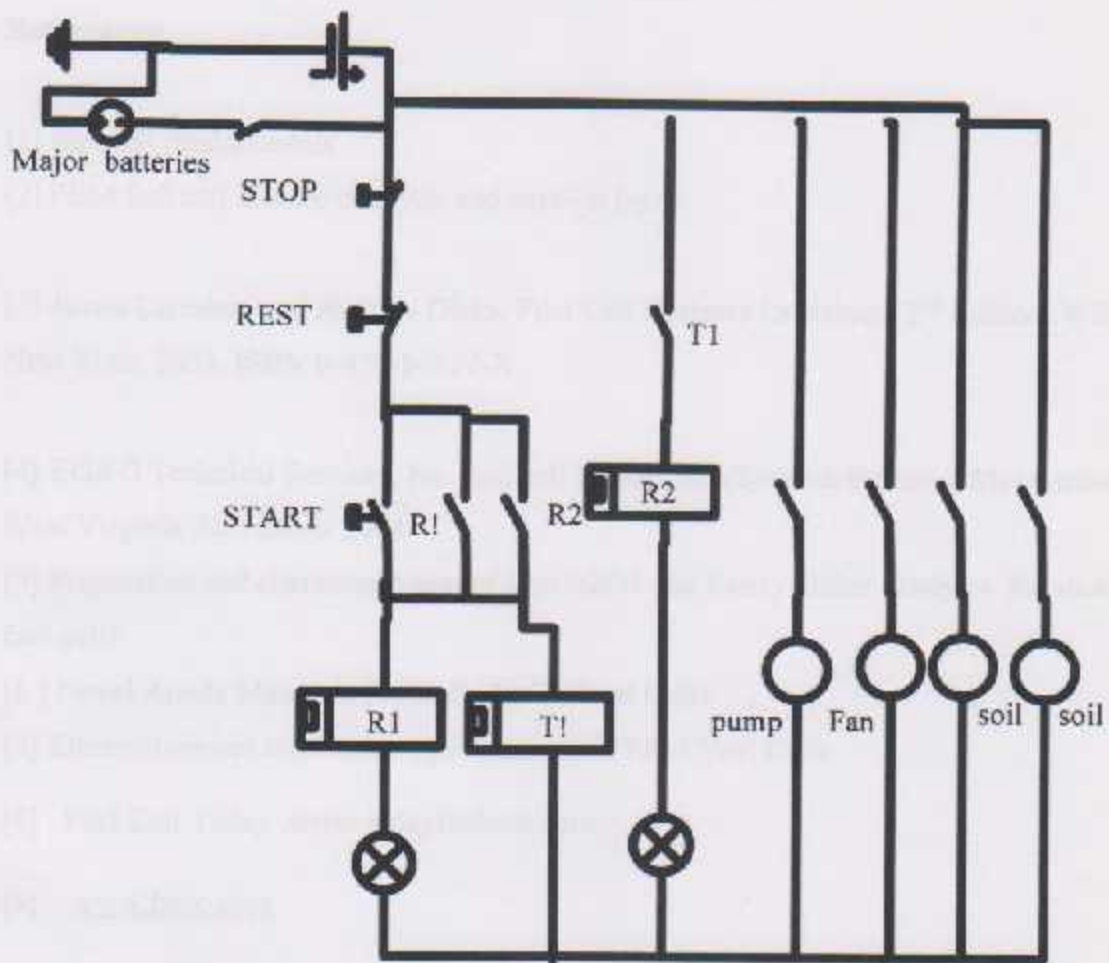


Figure (5-19): control circuit

## References:

- [1] fuel cell fundamentals
- [2] PEM fuel cell Electro catalysts and catalyst layers
  
- [3] James Larminie and Andrew Dicks, Fuel Cell Systems Explained, 2<sup>nd</sup> Edition, Wiley, New York, 2003, ISBN 0-470-84857-X
  
- [4] EG&G Technical Services, Inc. fuel cell Handbook, (Seventh Edition), Morgantown, West Virginia ,November 2004
- [5] Preparation and characterization of MnCo<sub>2</sub>O<sub>4</sub> and Raney nickel catalysts for alkaline fuel cells
- [6] Novel Anode Materials For Solid Oxide Fuel Cells
- [7] Electrochemical Impedance Spectroscopy in PEM Fuel Cells
- [8] Fuel Cell Today .[www.todayfuelcell.com](http://www.todayfuelcell.com)
- [9] . [www.fctec.com](http://www.fctec.com)
  
- [10] . Aalborg University (AAU) and the companies Danfoss and Sauer-Danfoss (Nordborg) A/S "Design and Control of Fuel Cell System for Transport Application" October 2001 in Berlin
  
- [11].[http://www.ballard.com/about\\_ballard/industry\\_relations/strategic\\_alliances.htm](http://www.ballard.com/about_ballard/industry_relations/strategic_alliances.htm)
  
- [12]. Gregor Hoogers, Fuel Cell Technology Hand Book , New York Washington ,2003 ,ISBN 0-8493-0877-1
  
- [13] . [http://en.wikipedia.org/wiki/Catalytic\\_converter](http://en.wikipedia.org/wiki/Catalytic_converter)