ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Halil DÜZGÜN

DESIGNING OF A FUEL CELL VEHICLE (FCV)

DEPARTMENT OF MECHANICAL ENGINEERING

ADANA, 2008

ÇUKUROVA ÜNİVERSİTESİ
FEN BİLİMLERİ ENSTİTÜSÜ

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Halil DÜZGÜN

YÜKSEK LİSANS TEZİ

MAKİNE MÜHENDİSLİĞİ ANABİLİM DALI

Bu tez 19 / 12 / 2008 Tarihinde Aşağıdaki Jüri Üyeleri Tarafından Oybirliği İle Kabul Edilmiştir.

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ABSTRACT

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DEPARTMENT OF MECHANICAL ENGINEERING
INSTITUTE OF NATURAL AND APPLIED SCIENCES
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Decreasing of petrol and petrol derivative energy sources together with increasing of production cost of these sources, turning towards the alternative energy sources is seen on different places in the world. Attention is paid with environmental sensitiveness while searching for the new alternative energy sources. Hydrogen is an alternative energy source which is a clean energy source and environmentally friendly alternative to conventional fossil fuels.

In this study, two different fuel cell vehicles, which use hydrogen as fuel, have been designed to eliminate the exit of hazardous gases to atmosphere and to supply more efficient fuel usage and to show their performance to the automotive industry. Performances, fuel economy and emissions of these vehicles have been investigated.

Key Words: Fuel Cell, Hydrogen, Clean Energy

ÖZ

YÜKSEK LİSANS TEZİ

YAKIT HÜCRESİ İLE ÇALIŞAN ARAÇ TASARIMI

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Petrol ve türevi enerji kaynaklarının azalması ve üretim maliyetlerindeki artış ile beraber dünyanın birçok bölgesinde alternatif enerji kaynaklarına yönelme görülmektedir. Alternatif enerji kaynakları araştırılırken, yeni enerji kaynaklarının temiz enerji kaynağı olması yani çevreye duyarlılığı da ön plana çıkmaktadır. Hidrojen hem petrole alternatif olması hem de doğaya zararlı atık bırakmaması ile çevreye duyarlı alternatif bir enerji kaynağıdır.

Bu çalışmada otomotiv endüstrisinde beklenen daha yüksek yakıt ekonomisini ve performansını sağlamak ve çevreye atılan zararlı gazları ortadan kaldırmak için hidrojeni enerji kaynağı olarak kullanan yakıt pili ile çalışan iki ayrı araç tasarlanmıştır. İmalatı gerçekleştirilen bu araçların yol performansları, yakıt ekonomileri ve çevreye zararlı atık verip vermedikleri araştırılmıştır.

Anahtar kelimeler: Yakıt Pili, Hidrojen, Temiz Enerji

ACKNOWLEDGEMENTS

First of all, I am grateful to my supervisor Prof. Dr. Kadir AYDIN for his guidance to thesis subject and for his extensive advice.

I would like to thank Research Assistant Mustafa ÖZCANLI for his help and encouragement throughout my thesis.

I would also like to thank our laboratory technician Cevdet YILDIRIM for helping me on experimental studies.

And the friends with whom I worked together to produce these two vehicles under the name of Çukurova Hidromobil Group.

Last but not least, special thanks to my family for their insolvable supports.

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ABBREVIATIONS

BLDC	:	Brushless direct current
COS	:	Carbonly sulfide
CVC	:	Cell voltage checker
DC	:	Direct current
EV	:	Electric vehicle
FC	:	Fuel cell
FCV	:	Fuel cell vehicle
HEV	:	Hybrid electric vehicle
ICE	:	Internal combustion engine
LFL	:	Lower flammability limit
NGSR	:	Natural gas steam reforming
PEFC	:	Polymer elektrolyte fuel cell
PEM	:	Proton Exchange membran
PEMFC	:	Proton Exchange membran fuel cell
R&D	:	Research and development
slm	:	Standart liter per minute

NOMENCLATURE

A	:	Current
H	:	Height
L	:	Lenght
P	:	Power
r_w	:	Radius of Wheel
v	:	Speed
V	:	Voltage
w	:	Revolution
W	:	Width

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1. INTRODUCTION

Together with decreasing of present energy sources in the world, people and scientists started to investigate for new energy sources to use in vehicles. Although scientists have thought about the regaining of energy lost in vehicles with hybrid systems first, they achieved another type of energy producing device called as fuel cell, which is more advantageous than hybrid systems.

Fuel cells have emerged as one of the most promising technologies for meeting the new energy demands. They are environmentally clean, quiet in operation, and highly efficient for generating electricity. This shining new technology provides the impetus towards a huge market for power electronics and its related applications (Dekker, 2004).

In principle, a fuel cell operates like a battery. Unlike a battery, a fuel cell does not run down or require recharging. It will produce energy in the form of electricity and heat as long as fuel is supplied. A fuel cell consists of two electrodes sandwiched around an electrolyte. Oxygen passes over one electrode and hydrogen over the other, generating electricity, water and heat. Hydrogen fuel is fed into the anode of the fuel cell. Oxygen (or air) enters the fuel cell through the cathode. Hydrogen atoms, encouraged by a catalyst, split into a proton and an electron, which take different paths to the cathode. The proton passes through the electrolyte. The electrons create a separate current that can be utilized before they return to the cathode, to be reunited with hydrogen and oxygen in a molecule of water (Air Resources Board, 2002).

The main properties and the benefits of fuel cell, which have been under continuous investigation for preparing this technology to use in daily life, are silent operation, no emissions and low cost in fuel. No utilization of internal combustion engines in fuel cell vehicles (FCV) makes it simpler than present technologies.

Burning fossil fuels such as gasoline or diesel adds greenhouse gasses to the earth's atmosphere. Greenhouse gases trap heat and thus warm the earth because they prevent a significant proportion of infrared radiation from escaping into space. FCVs powered by pure hydrogen emit no greenhouse gases. If the hydrogen is generated by

reforming fossil fuels, some greenhouse gases are released, but much less than the amount produced by conventional vehicles.

Highway vehicles account for a significant share of the air pollutants that contribute to smog and harmful particulates. FCVs powered by pure hydrogen emit no harmful pollutants. FCVs that use a reformer to convert fuels such as natural gas, methanol, or gasoline to hydrogen do emit small amounts of air pollutants such as carbon monoxide.

Investigations and tests show that internal combustion engines in automobiles convert less than 20% of the energy in gasoline into power that moves the vehicle. Vehicles using electric motors powered by hydrogen fuel cells are much more energy efficient, utilizing 40-60% of the fuel's energy. Even FCVs that reform hydrogen from gasoline can use about 40% of the energy in the gasoline.

Fuel cell vehicles are much quieter than internal combustion engines although wind and road noise will still be present at higher speeds.

Protecting the environment, conserving the energy resources, saving money and to make more strength the energy security, FCV or similar technologies are needed. This study aims above facts.

2. PREVIOUS STUDIES

There are many equipments and criteria in the investigation of fuel cell vehicles such as hydrogen production methods, hydrogen storage, environmental effects, battery type, electrode type in fuel cell or transformation of hydrogen, etc. Below some preceding investigations are summarized devoting to original text and authors.

The hydrogen production from hydrolysis of sodium borohydride in alkaline solution has been extensively studied by Jai-Young Lee from Korea Advanced Institute of Science and Technology. As a result, it has studied that stylene-butadiene-rubber as a binder of catalyst electrode is very effective because their hydrophilic property promotes the infiltration of liquid fuel into the catalyst. The filamentary Ni mixed Co catalyst with superior performance of short initial waiting time and fast hydrolysis of sodium borohydride has been developed and showed a maximum hydrogen production rate of 96.3 ml/min-g. Also because hydrogen gas can be generated at room temperature and has a high purity more than 99.99%, it can be directly used as a fuel for PEMFC (Lee, 2003).

A survey of fuel cell experts in Japan is used to estimate the time required to develop major elemental technologies required for stationary and automotive applications of polymer electrolyte fuel cells (PEFC). The elemental technologies covered include electrolyte membranes, electrode catalysts, fuel reforming and hydrogen storage, to be applied in next-generation PEFC systems whose operating temperature is 120°C or higher. The survey also asks experts to gauge the effect of research and development (R&D) investment on the time required to develop a technology. Results are analyzed statistically to quantitatively compare success probabilities, time periods and the potential for R&D investment to reduce development time. The estimated net time period needed to reach performance and cost targets for both stationary and automotive PEFC systems averaged around 17 years. In general, the technology for electrolyte membranes is likely to be the most time consuming for R&D, thus accelerating its progress is effective for shortening

the total R&D period (Kosugi, 2003).

Wen Feng, from Tsinghua University, discussed the future of hydrogen infrastructure for fuel cell vehicles in China. It is believed that, China should make different plans of hydrogen infrastructure during different periods and in different regions. Besides, a case of application in Beijing is studied to find the best plan for Beijing to develop hydrogen infrastructure in 2008 when Olympic Games will be held. In the study of that case, 11 feasible plans are designed at first according to the current technology of production, storage and transportation of hydrogen in China (see Table 2.1.). After that, the energy, environmental and economic performances of these plans are evaluated with "life cycle assessment". Finally, the best plan in the case is picked out from all the aspects of energy, environment and economy (Feng, 2003).

Table 2.1. 11 plans of hydrogen infrastructure for fuel cell vehicles (Feng, 2003)

Plan No	Production Subsystem	Transportation Subsystem	Refueling Subsystem	Utilization Subsystem
1	Central factory: NGSR	Hydrogen gas cylinder by truck	Hydrogen gas cylinder	Hydrogen gas
2	Central factory: NGSR	Hydrogen gas by pipeline	Hydrogen gas tank	Hydrogen gas
3	Central factory: NGSR	Liquid hydrogen tank by truck	Liquid hydrogen tank	Liquid hydrogen
4	Central factory: NGSR	Hydride cylinder by truck	Hydride cylinder	Hydride
5	Central factory: coal gasification	Hydrogen gas cylinder by truck	Hydrogen gas cylinder	Hydrogen gas
6	Central factory: coal gasification	Hydrogen gas by pipeline	Hydrogen gas tank	Hydrogen gas
7	Central factory: coal gasification	Liquid hydrogen tank by truck	Liquid hydrogen tank	Liquid hydrogen
8	Central factory: coal gasification	Hydride cylinder by truck	Hydride cylinder	Hydride
9	Refueling stations: water electrolysis (industrial electricity)		Hydrogen gas tank	Hydrogen gas
10	Refueling stations: water electrolysis (valley electricity)		Hydrogen gas tank	Hydrogen gas
11	Central factory: methanol synthesis via natural gas	Methanol tank by truck	Methanol tank	Methanol reforming onboard

All fuel cells currently being developed for near term use in electric vehicles require hydrogen as a fuel. Hydrogen can be stored directly or produced onboard the vehicle by

reforming methanol, or hydrocarbon fuels derived from crude oil (e.g. gasoline, Diesel, or middle distillates). The vehicle design is simpler with direct hydrogen storage, but requires developing a more complex refueling infrastructure.

Ogden presented modeling results comparing three leading options for fuel storage onboard fuel cell vehicles and these are compressed gas hydrogen storage, onboard steam reforming of methanol and onboard partial oxidation (POX) of hydrocarbon fuels derived from crude oil.

Ogden has developed a fuel cell vehicle model, including detailed models of onboard fuel processors. This allows comparing the vehicle performance, fuel economy, weight, and cost for various vehicle parameters, fuel storage choices and driving cycles. The infrastructure requirements are also compared for gaseous hydrogen, methanol and gasoline, including the added costs of fuel production, storage, distribution and refueling stations. The delivered fuel cost, total lifecycle cost of transportation, and capital cost of infrastructure development are estimated for each alternative. Considering both, vehicle and infrastructure issues, possible fuel strategies leading to the commercialization of fuel cell vehicles are discussed. As a conclusion, he has found that hydrogen fuel cell vehicles are simpler in design, lighter in weight, more energy efficient and lower cost than those with onboard fuel processors for the same performance (Ogden, 1998).

One of the early designed fuel cell vehicles is a DAF 44 saloon car which has been extensively modified to study some of the problems associated with building, controlling and driving. A prototype hybrid car has been made, using as a power source two 12-cell hydrazine/air fuel batteries in conjunction with six conventional 6-cell lead-acid accumulators. The car has been successfully demonstrated on several occasions, and its performance has been measured. Some comparisons can be seen on Table 2.2. The performance of the car, in its present form, falls between that of today's internal combustion engined vehicles and that of secondary battery powered ones. However, unlike more conventional electric cars, it ranges under town driving conditions and at its steady cruising speed they are not limited by the quantity of stored electricity. Some general comments have been made on possible future developments with this project by M.R. Andrew who works in Thornton Research Center. Although power density is decreased by the requirements of the fuel cell auxiliaries (pumps, blowers, radiators and electrolyte sump), it is likely nevertheless

that with development, fuel cell systems will ultimately be able to compete with gasoline engines on a power/density basis (Andrew, 1970).

Table 2.2. Comparisons of Performance of Present Thornton Electric Car with that of Original Gasoline-Engined DAF 44 (Data in last column are expected performances of electric DAF car at target weight) (Andrew, 1970)

Item	Original DAF Car	Thornton Electric DAF Car	Estimeted for Car of 1180 kg
Weight, kg	940	1380	1180
Top speed, km/h	~110	~80	85
Acceleration, km/h/s			
at 32 km/h	~3,8	2,6	3,2
at 48 km/h	~2,9	1,3	1,6
at 64 km/h	~1,6	0,5	0,3
Time taken to go 16-48 km/h, s	5,3	8,3	
Max speed at no km/h from accumulators, drain	-	~40	45
Power consumption, kW			
at 32 km/h	-	7,5	4,5
at 48 km/h	-	10	8
at 64 km/h	-	16,5	11,5

Another research about using of fuel cells in passenger cars is studied by Richard K. Stobart in 1999. According to Stobart, fuel cell power for cars is appeared to be the most promising alternative power-train technology. Stobart approaches the subject some significant questions; can fuel cells deliver an efficiency which meets performance criteria? Others are social and concerned with the acceptability of the car to the buying public and its green credentials. As conclusions, he says that there are significant barriers faced by the fuel cell power vehicle, and he declares, apart from strictly technology issues there are the social and political questions around how the authorities will respond and how customers will react. Cost reduction must be continued to have aggressive targets to meet. Although economies of scale will help bring costs down, he believes that there will be no avoiding the arduous cycle of design and re-design, which will be needed to meet both performance and cost targets (Stobart, 1999).

3. FUEL CELL TECHNOLOGY

3.1. Fuel Cell

Fuel cells are electrochemical devices that convert the chemical energy of a reaction directly into electrical energy. As a simply meaning, fuel cells are energy conversion devices which operate silently because of having non moving parts. The basic physical structure or building block of a fuel cell consists of an electrolyte layer in contact with a porous anode and cathode on either side. A schematic representation of a fuel cell with the reactant/product gases and the ion conduction flow directions through the cell is shown in Figure 3.1 (U.S. Department of Energy Office of Fossil Energy National Energy Technology Laboratory, 2000).

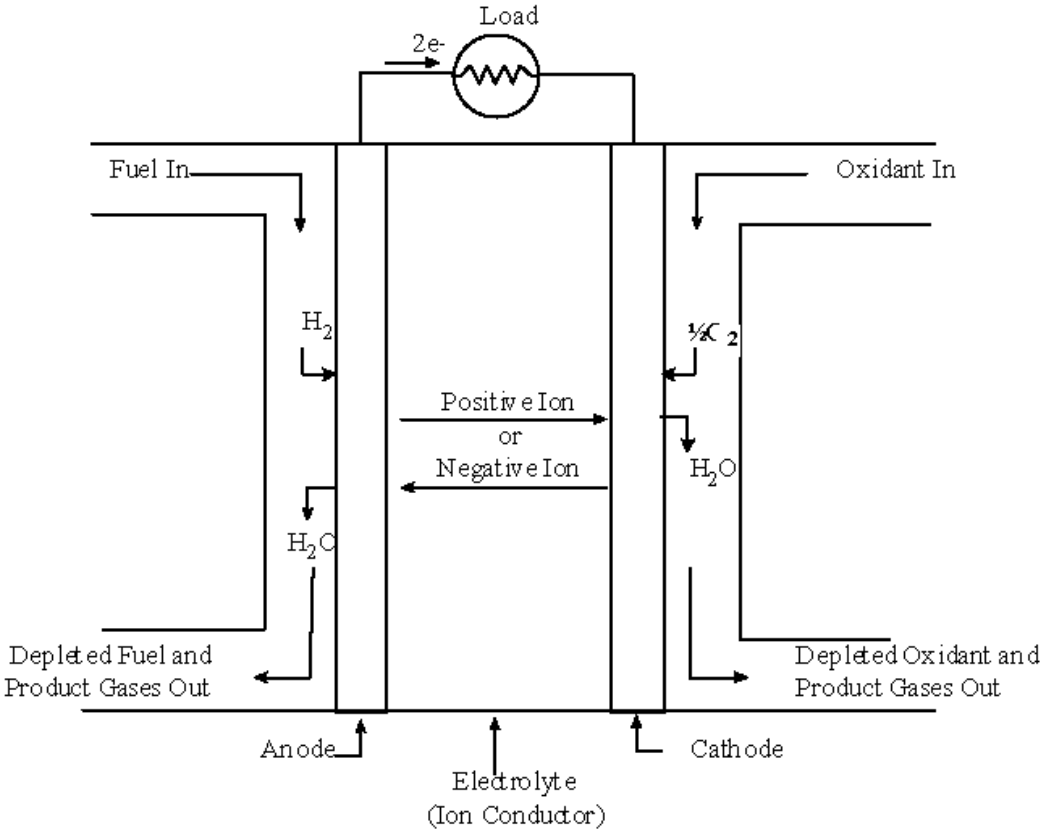


Figure3.1. Schematic representation of a fuel cell

The process is begun with feeding hydrogen to one catalyst electrode in which the separation of the hydrogen atoms is facilitated into electrons and protons. The protons or hydrogen ions are moved through the membrane towards the other

catalyst, which is being fed with oxygen. The stripped electrons cannot be passed through the membrane or electrolyte, so they must be routed through an external circuit. The external circuit is contained an electrical load such as a motor or light bulb, etc., and led to the other catalytic electrode, where the protons and electrons are recombined and bonded with oxygen to create water molecules (Hurley, 2002).

3.2. Types of Fuel Cells

Fuel cells are classified primarily by the kind of electrolyte they are employed. The kind of chemical reactions that take place in the cell, the kind of catalysts are required, the temperature range in which the cell operates, the fuel required, and other factors are determined by the kind of electrolyte. These characteristics, in turn, affect the applications for which these cells are most suitable. There are several types of fuel cells currently under development, each with its own advantages, limitations, and potential applications.

High-temperature fuel cells are operated at greater than 600^{o}C. The spontaneous internal reforming of light hydrocarbon fuels, such as methane, into hydrogen and carbon in the presence of water is permitted on these high temperatures.

The most prominent high-temperature fuel cells are:

- molten carbonate
- solid oxide

Low-temperature fuel cells typically are operated below 250^{o}C. Internal reforming is not permitted on these low temperatures, and therefore it is required an external source of hydrogen. On the other hand, they exhibit quick startup, suffer fewer materials problems and are easier to handle in vehicle applications.

The most prominent low-temperature fuel cells are:

- alkaline
- phosphoric acid
- proton exchange membrane (or solid polymer)

3.2.1. Molten Carbonate Fuel Cells

At the structure of the molten carbonate fuel cells, an electrolyte that conducts carbonate (CO_3^{2-}) ions from the cathode to the anode is used. This is the opposite of many other types of fuel cells, which conduct hydrogen ions from the anode to the cathode.

The electrolyte is composed of a molten mixture of lithium and potassium carbonates. This mixture is retained by capillary forces within a ceramic support matrix of lithium aluminates. At the fuel cell operating temperature, the electrolyte structure is a thick paste, and gas seals are provided by the paste at the cell edges.

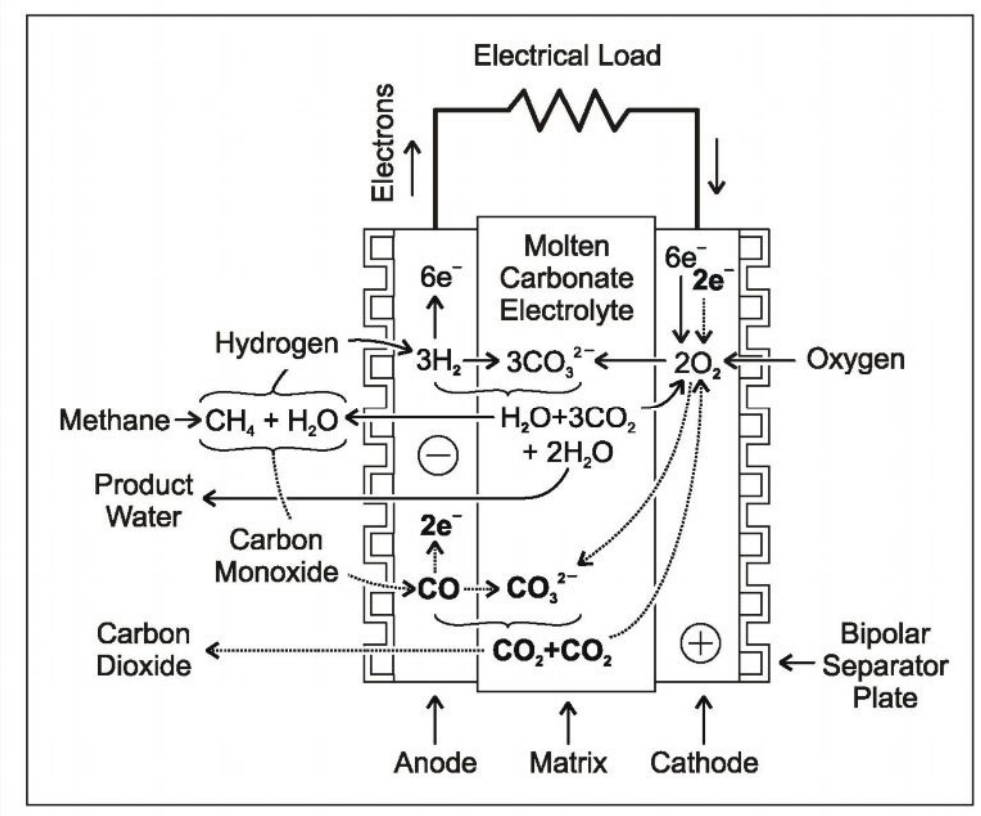


Figure3.2. Molten Carbonate Fuel Cell

Molten carbonate fuel cells are operated at about 650ºC and a pressure of 1 to 10 bar g. Each cell can produce up to between 0.7 and 1.0 VDC.

Molten carbonate fuel cells can be operated by using pure hydrogen or light hydrocarbon fuels. When a hydrocarbon, such as methane, is introduced to the anode in the presence of water, it absorbs heat and undergoes a steam reforming reaction:

$$CH_4 + H_20 \Rightarrow 3H_2 + CO$$

When using other light hydrocarbon fuels, the number of hydrogen and carbon monoxide molecules may change but in principle the same products result.

$$CH_4 + H_2O \Rightarrow 3H_2 + CO$$

When using other light hydrocarbon fuels, the number of hydrogen and carbon monoxide molecules may change but in principle the same products result.

The reactions at the anode are:

$$3H_2 + 3CO_3^2 \Rightarrow 3H_2O + 3CO_2 + 6e^- \quad (1)$$

This is the hydrogen reaction and occurs regardless of fuel.

$$CO + CO_3^{2-} \Rightarrow 2CO_2 + 2e^- \quad (2)$$

This is the carbon monoxide reaction and occurs only when using a hydrocarbon fuel.

The reaction at the cathode is:

$$2O_2 + 4CO_2 + 8e^- \Rightarrow 4CO_3^{2-}$$

This is the oxygen reaction and occurs regardless of fuel.

The CO_3^{2-} ion is drawn through the electrolyte from the cathode to the anode by the reactive attraction of hydrogen and carbon monoxide to oxygen, while electrons are forced through an external circuit from the anode to the cathode.

Combining the anode and cathode reactions, the overall cell reactions are:

$$2H_2 + O_2 \Rightarrow 2H_2O \quad (1)$$

This is the hydrogen reaction and occurs regardless of fuel.

$CO + {}^{1}/_{2}O_2 \Rightarrow CO_2$ (2)

This is the carbon monoxide reaction and occurs only when using a hydrocarbon fuel.

Thus, the fuel cell produces water, regardless of fuel, and carbon dioxide if using a hydrocarbon fuel. Both product water and carbon dioxide must be continually removed from the cathode to facilitate further reaction.

3.2.1.1. Advantages and Disadvantages

The advantages of molten carbonate fuel cells are that they:

- support spontaneous internal reforming of light hydrocarbon fuels
- generate high-grade waste heat
- have fast reaction kinetics (react quickly)
- have high efficiency
- do not need noble metal catalysts

The disadvantages are that they:

- require the development of suitable materials that are resistant to corrosion, are dimensionally stable, have high endurance and lend themselves to fabrication.
  Corrosion is a particular problem and can cause nickel oxide from the cathode to dissolve into the electrolyte, loss of electrolyte, deterioration of separator plates, and dehydration or flooding of the electrodes. All of these corrosion effects result in a decline in performance, limit cell life, and can culminate in cell failure. Use of a platinum catalyst overcomes some of these problems, but eliminates an important cost-saving advantage.
  Dimensional instability can cause electrode deformation that alters the active surface area and may cause loss of contact and high resistances between components.
- Have a high intolerance to sulfur. The anode in particular cannot tolerate more than 1-5 ppm of sulfur compounds (primarily H_2S and carbonyl sulfide-COS) in the fuel gas without suffering a significant performance loss.
- have a liquid electrolyte, which introduces liquid handling problems
- require a considerable warm up period

3.2.2. Solid Oxide Fuel Cells

Solid oxide fuel cells use an electrolyte that conducts oxide (O_2^-) ions from the cathode to the anode. This is the opposite of most types of fuel cells, which conduct hydrogen ions from the anode to the cathode.

The electrolyte is composed of a solid oxide, usually zirconia (stabilized with other rare earth element oxides like yttrium), and takes the form of a ceramic.

Solid oxide fuel cells are built like computer chips through sequential deposition of various layers of material. Common configurations include tubular and flat (planar) designs. The designs differ in the extent of dissipative losses within cells, in the manner of sealing between the fuel and oxidant channels, and in the manner that cell-to-cell electrical connections are made in a stack of cells. Metals such as nickel and cobalt can be used as electrode materials.

Solid oxide fuel cells operate at about 1000 ºC and a pressure of 1 bar g. Each cell can produce between 0.8 and 1.0 VDC.

Solid oxide fuel cells can operate using pure hydrogen or hydrocarbon fuels, just like molten carbonate fuel cells. This results in an inlet fuel stream comprised of hydrogen with or without carbon monoxide.

The reactions at the anode are:

$$H_2 + O^{2-} \Rightarrow H_2O + 2e^- \quad (1)$$

This is the hydrogen reaction and occurs regardless of fuel.

$$CO + O^{2-} \Rightarrow CO_2 + 2e^- \quad (2)$$

This is the carbon monoxide reaction and occurs only when using a hydrocarbon fuel.

The reaction at the cathode is:

$$^1/_2O_2 + 2e^- \Rightarrow O^{2-}$$

This is the oxygen reaction and occurs regardless of fuel.

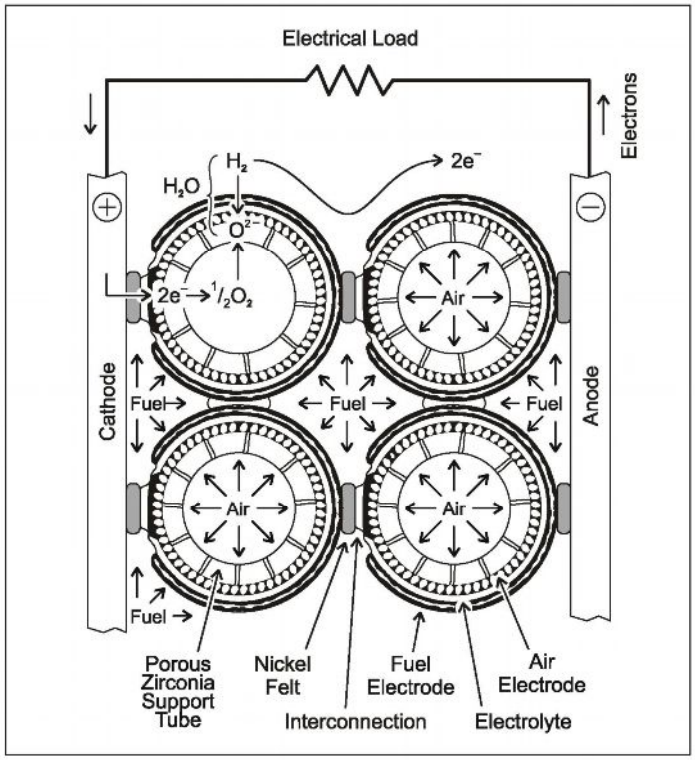


Figure3.3. Solid Oxide Fuel Cell (Tubular design)

The O^{2-} ion is drawn through the electrolyte from the cathode to the anode by the reactive attraction of hydrogen and carbon monoxide to oxygen, while electrons are forced through an external circuit from the anode to the cathode. Since the ions move from the cathode to the anode, this is the opposite of most types of fuel cells, the reaction products accumulate at the anode rather than the cathode.

Combining the anode and cathode reactions, the overall cell reactions are:

$$H_2 + {}^1/_2O_2 \Rightarrow H_2O \quad (1)$$

This is the hydrogen reaction and occurs regardless of fuel.

$$CO + {}^1/_2O_2 \Rightarrow CO_2 \quad (2)$$

This is the carbon monoxide reaction and occurs only when using a hydrocarbon fuel.

Thus, the fuel cell produces water, regardless of fuel, and carbon dioxide if using a hydrocarbon fuel. Both product water and carbon dioxide must be continually removed from the cathode to facilitate further reaction.

3.2.2.1. Advantages and Disadvantages

The advantages of solid oxide fuel cells are that they:

- Support spontaneous internal reforming of hydrocarbon fuels.
  Since oxide ions (rather than hydrogen ions) travel through the electrolyte, the fuel cells can in principle be used to oxidize any gaseous fuel.
- operate equally well using wet or dry fuels
- generate high-grade waste heat
- have fast reaction kinetics
- have very high efficiency
- can operate at higher current densities than molten carbonate fuel cells
- have a solid electrolyte, avoiding problems associated with handling liquids
- can be fabricated in a variety of self-supporting shapes and configurations
- do not need noble metal catalysts

The disadvantages are that they:

- Require the development of suitable materials that have the required conductivity, remain solid at high temperatures, are chemically compatible with other cell components, are dimensionally stable, have high endurance and lend themselves to fabrication.
  Few materials can operate at high temperatures and remain solid over long periods of time. Furthermore, the selected materials must be dense to prevent mixing of the fuel and oxidant gases, and must have closely matched thermal expansion characteristics to avoid delamination and cracking during thermal cycles.
- have a moderate intolerance to sulfur
  Solid oxide fuel cells are more tolerant to sulfur compounds than are molten carbonate fuel cells, but overall levels must still be limited to 50 ppm. This increased sulfur tolerance makes these fuel cells attractive for heavy fuels. Excess sulfur in the fuel decreases performance.
- do not yet have practical fabrication processes
- the technology is not yet mature

3.2.3. Alkaline Fuel Cells

Alkaline fuel cells use an electrolyte that conducts hydroxyl (OH^-) ions from the cathode to the anode. This is opposite to many other types of fuel cells that conduct hydrogen ions from the anode to the cathode.

The electrolyte is typically composed of a molten alkaline mixture such as potassium hydroxide (KOH). The electrolyte can be mobile or immobile.

Mobile alkaline electrolyte fuel cells use a fluid electrolyte that continuously circulates between the electrodes. The product water and waste heat dilute and heat the liquid electrolyte but are removed from the cell as the electrolyte circulates.

Immobile alkaline electrolyte fuel cells use an electrolyte that consists of a thick paste retained by capillary forces within a porous support matrix such as asbestos. The paste itself provides gas seals at the cell edges. Product water evaporates into the source hydrogen gas stream at the anode from which it is subsequently condensed. The waste heat is removed by way of a circulating coolant.

Alkaline fuel cells operate at about 65 to 220 ºC and a pressure of about 1 bar g. Each cell can produce up to between 1.1 and 1.2 VDC.

Alkaline fuel cells must operate using pure hydrogen free of carbon oxides.

The reactions at the anode are:

$$H_2 + 2K^+ + 2OH^- \Rightarrow 2K + 2H_2O \quad (1)$$

$$2K \Rightarrow 2K^+ + 2e^- \quad (2)$$

The reactions at the cathode are:

$$^1/_2O_2 + H_2O \Rightarrow 2OH \quad (1)$$

$$2OH + 2e^- \Rightarrow 2OH^- \quad (2)$$

The OH^- ion is drawn through the electrolyte from the cathode to the anode by the reactive attraction of hydrogen to oxygen, while electrons are forced through an external circuit from the anode to the cathode.

Combining the anode and cathode reactions, the overall cell reactions are:

$$H_2 + 2OH^- \Rightarrow 2H_2O + 2e^- \quad (1)$$

$$^1/_2O_2 + H_2O + 2e^- \Rightarrow 2OH^- \quad (2)$$

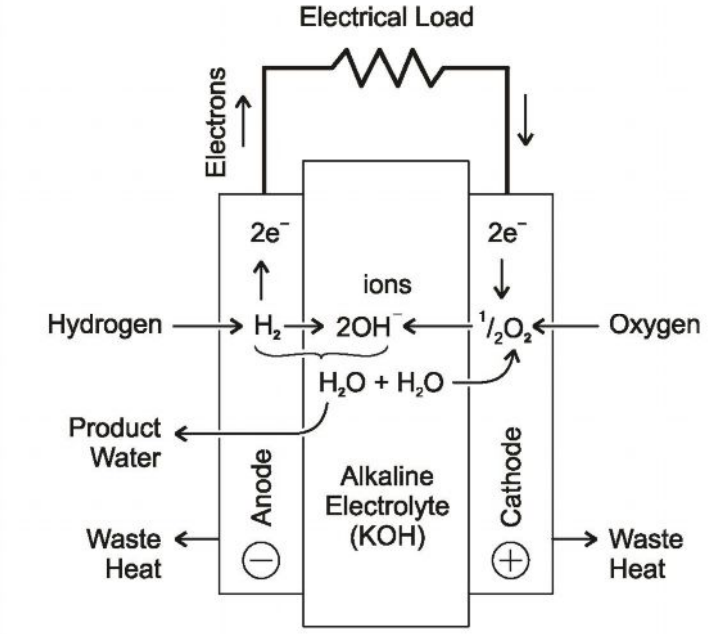


Figure 3.4. Alkaline Fuel Cell

Thus, the fuel cell produces water that either evaporates into the source hydrogen stream (in an immobile system) or is flushed out of the cells along with the electrolyte (in a mobile system). This water must be continually removed to facilitate further reaction.

3.2.3.1. Advantages and Disadvantages

The advantages of alkaline fuel cells are that they:

- operate at low temperature
- have fast startup times (50% rated power at ambient temperature)
- have high efficiency
- need little or no expensive platinum catalyst
- have minimal corrosion
- have relative ease of operation
- have low weight and volume

The disadvantages are that they:

- are extremely intolerant to CO_2 (about 350 ppm maximum) and somewhat intolerant of CO.

  This is a serious disadvantage and limits both the type of oxidant and fuel that can be used in an alkaline fuel cell. The oxidant must be either pure oxygen or air that has been scrubbed free of carbon dioxide. The fuel must be pure hydrogen due to the presence of carbon oxides in re-format.
- Have a liquid electrolyte, introducing liquid handling problems
- require complex water management
- have a relatively short lifetime

3.2.4. Phosphoric Acid Fuel Cells

Phosphoric acid fuel cells use an electrolyte that conducts hydrogen ions (H+) from the anode to the cathode. As its name implies, the electrolyte is composed of liquid phosphoric acid within a silicon carbide matrix material. (Some acid fuel cells use a sulfuric acid electrolyte.)

Phosphoric acid fuel cells operate at about 150 to 205 ºC and a pressure of about 1 bar g. Each cell can produce up to about 1.1 VDC.

Phosphoric acid fuel cells react hydrogen with oxygen.

The reactions at the anode are:

$$H_2 \Rightarrow 2H^+ + 2e^- \quad (1)$$

The reaction at the cathode is:

$$^1/_2O_2 + 2e^- + 2H^+ \Rightarrow H_2O \quad (2)$$

The H^+ ion is drawn through the electrolyte from the anode to the cathode by the reactive attraction of hydrogen to oxygen, while electrons are forced through an external circuit. Combining the anode and cathode reactions, the overall cell reaction is:

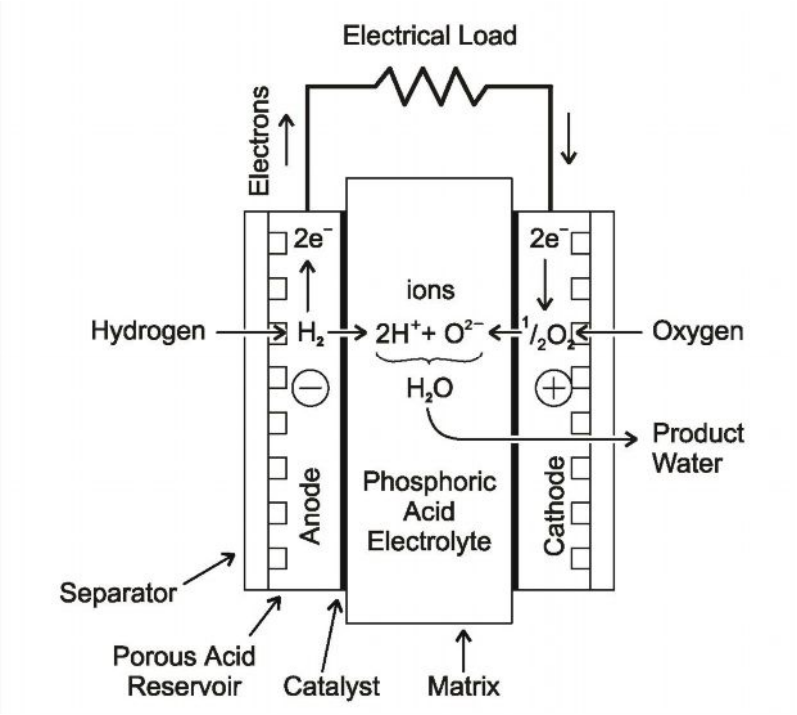


Figure 3.5. Phosphoric Acid Fuel Cell

$H_2 + {}^1/_2O_2 \Rightarrow H_2O$

Thus, the fuel cell produces water that accumulates at the cathode. This product water must be continually removed to facilitate further reaction.

3.2.4.1. Advantages and Disadvantages

The advantages of phosphoric acid fuel cells are that they:

- are tolerant of carbon dioxide (up to 30%). As a result, phosphoric acid fuel cells can use unscrubbed air as oxidant, and reformate as fuel.
- operate at low temperature, but at higher temperatures than other low-temperature fuel cells. Thus, they produce higher grade waste heat that can potentially be used in co-generation applications.
- have stable electrolyte characteristics with low volatility even at operating temperatures as high as 200ºC

The disadvantages are that they:

- can tolerate only about 2% carbon monoxide
- can tolerate only about 50 ppm of total sulfur compounds
- use a corrosive liquid electrolyte at moderate temperatures, resulting in material corrosion problems
- have a liquid electrolyte, introducing liquid handling problems. The electrolyte slowly evaporates over time.
- allow product water to enter and dilute the electrolyte
- are large and heavy
- cannot auto-reform hydrocarbon fuels
- have to be warmed up before they are operated or be continuously maintained at their operating temperature

3.2.5. Proton Exchange Membrane (PEM) Fuel Cells

Proton exchange membrane (PEM) (or "solid polymer") fuel cells use an electrolyte that conducts hydrogen ions (H+) from the anode to the cathode. The electrolyte is composed of a solid polymer film that consists of a form of acidified Teflon.

PEM fuel cells typically operate at 70 to 90 ºC and a pressure of 1 to 2 bar g. Each cell can produce up to about 1.1 VDC.

PEM fuel cells react hydrogen with oxygen.

The reactions at the anode are:

$$H_2 \Rightarrow 2H^+ + 2e^- \quad (1)$$

The reaction at the cathode is:

$$^1/_2O_2 + 2e^- + 2H^+ \Rightarrow H_2O \quad (2)$$

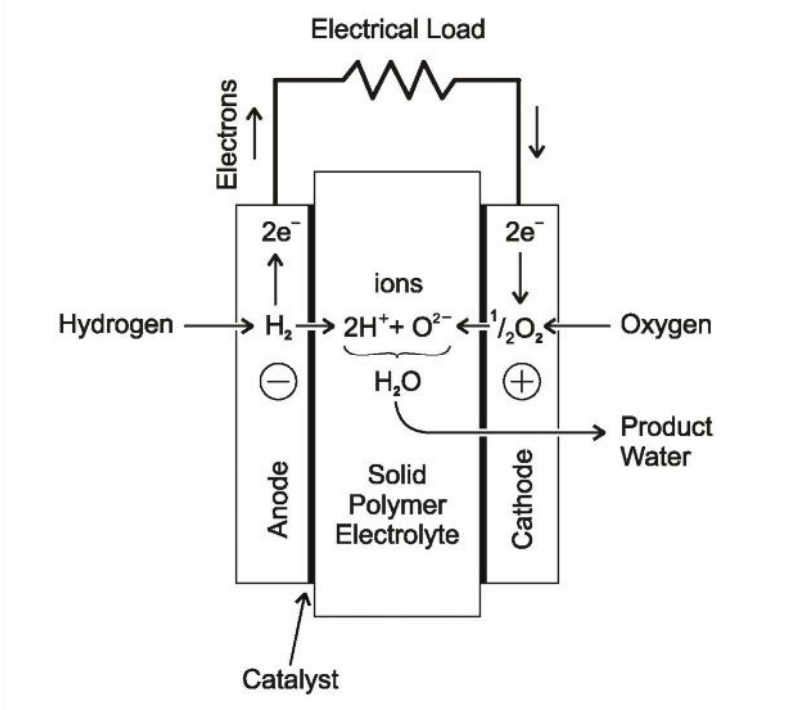


Figure 3.6. PEM Fuel Cell

The H^+ ion is drawn through the electrolyte from the anode to the cathode by the reactive attraction of hydrogen to oxygen, while electrons are forced through an external circuit. Combining the anode and cathode reactions, the overall cell reaction is:

$$H_2 + {}^1/_2O_2 \Rightarrow H_2O$$

Thus, the fuel cell produces water that accumulates at the cathode. This product water must be continually removed to facilitate further reaction.

3.2.5.1. Direct Methanol PEM Fuel Cells

PEM fuel cells can also run using methanol fuel directly, rather than hydrogen. Although the energy released during this reaction is less than when using pure hydrogen, it results in a much simpler fuel storage system and circumvents the need to produce hydrogen.

In a direct methanol PEM fuel cell, the cells are supplied with a liquid mixture of methanol and water at the anode, and air at the cathode. At 130 ºC, a noble catalyst immediately decomposes the methanol according to the reaction:

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

Oxygen, from the air, ionizes and reacts with the hydrogen to form water:

$$^3/_2O_2 + 6e^- + 6H \Rightarrow H_2O$$

Combining the anode and cathode reactions the overall cell reaction results in pure water and carbon dioxide. This technology is still in its infancy, but holds great promise for the future.

3.2.5.2. Advantages and Disadvantages

The advantages of PEM fuel cells are that they:

- are tolerant of carbon dioxide. As a result, PEM fuel cells can use unscrubbed air as oxidant, and reformate as fuel.
- operate at low temperatures. This simplifies materials issues, provides for quick startup and increases safety.
- use a solid, dry electrolyte. This eliminates liquid handling, electrolyte migration and electrolyte replenishment problems.
- use a non-corrosive electrolyte. Pure water operation minimizes corrosion problems and improves safety.
- have high voltage, current and power density
- operate at low pressure which increases safety
- have good tolerance to differential reactant gas pressures
- are compact and rugged
- have relatively simple mechanical design
- use stable materials of construction

The disadvantages are that they:

- can tolerate only about 50 ppm carbon monoxide
- can tolerate only a few ppm of total sulfur compounds
- need reactant gas humidification

  Humidification is energy intensive and increases the complexity of the system. The use of water to humidify the gases limits the operating temperature of the fuel cell to less than water's boiling point and therefore decreases the potential for co-generation applications.
- use an expensive platinum catalyst
- use an expensive membrane that is difficult to work with

4. MATERIAL AND METHOD

In this study, a prototype car which works with hydrogen is designed and tested in road way. Before designing some main criteria, equipments are investigated and designated. First of all a present fuel cell is selected and technical properties and design criteria of the car are decided according to power of this fuel cell and fuel cell environmental equipments. During experiments and tests, proper pressured hydrogen is supplied to the fuel cell unit from the solid hydrogen canister to produce electricity for the vehicle.

Beside of the fuel cell parts, known vehicle structures, chassis, steering wheel, brakes, etc. are other materials, systems for designing of the car. One of the other main parts is an electrical motor which is used to move the vehicle. Fuel cell is a device that produces electricity and since this produced energy will be used, an electrical motor will be needed. During the designing procedure, some CAD programs are used.

4.1. Selection of the Fuel Cell and Nexa Power Module

PEM fuel cells are stated most proper fuel cell type for the vehicles as comparison of the fuel cell types in last section. After gaining of this knowledge, Nexa Power Module from Ballard Power Systems which is a PEM fuel cell type is selected for this study.

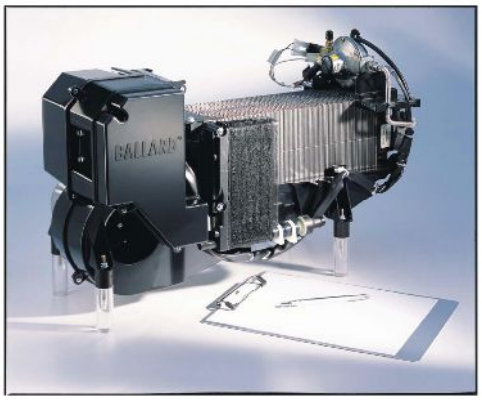


Figure 4.1. Nexa Power Module

The fundamental component of the Nexa-Ballard fuel cell consists of two electrodes, as usual the anode and the cathode, separated by a polymer membrane electrolyte. Each of the electrodes is coated on one side with a thin platinum catalyst layer. The membrane electrode assembly is formed by the electrodes, catalyst and membrane together. A single fuel cell consists of a membrane electrode assembly and two flow field plates, as shown in Figure 4.2.

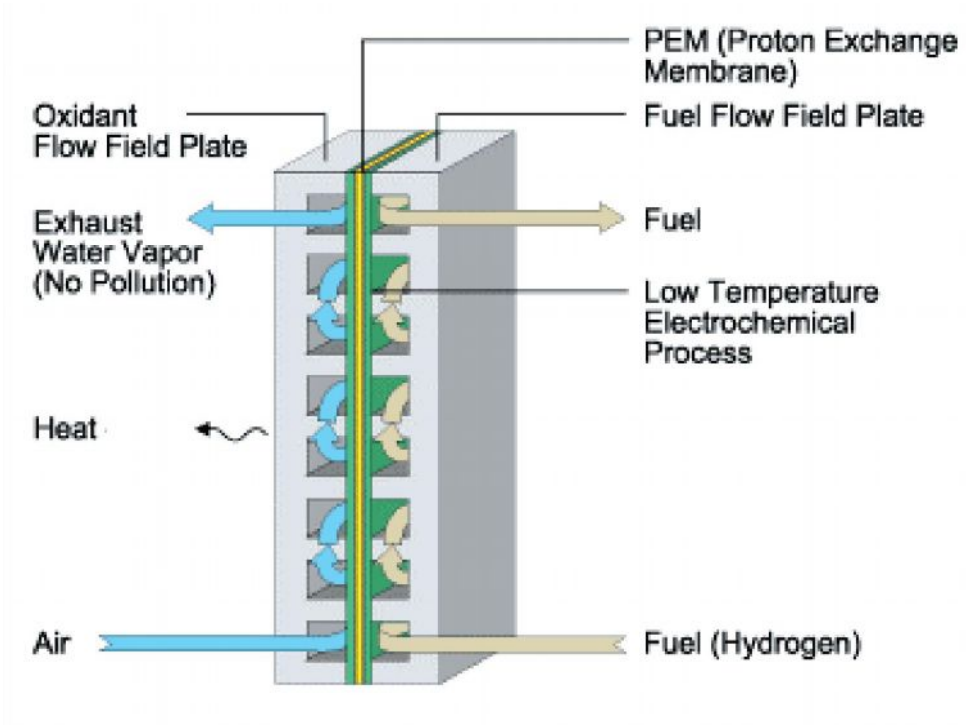


Figure 4.2. PEM Fuel Cell principles

Gases (hydrogen and air) are supplied to the electrodes on either side of the membrane through channels formed in the flow field plates. Hydrogen is flowed through the channels to the anode where the platinum catalyst promotes its separation into protons and electrons. The free electrons are conducted in the form of usable electric current through an external circuit, while the protons migrate through the membrane electrolyte to the cathode. At the cathode, oxygen from the air, electrons from the external circuit and protons are combined to form pure water and heat.

Individual fuel cells are combined into a fuel cell stack to provide the required electrical power. About 1 volt at open circuit and about 0.6 volts at full load are produced in a single fuel cell. Cells are stacked together in series to provide the required output voltage. In turn, the output current of a fuel cell is proportional to its active area. Consequently, the fuel cell stack geometry can be tailored to provide the desired output voltage, current and power characteristics.

The 1,200 Watt Nexa power module which is shown in Figure 4.1 was first introduced in 2001. It is the world's first volume-produced PEM fuel cell designed for integration into a wide variety of stationary and portable power generation applications.

Table 4.1. Nexa Power Module Specifications (Nexa User Guide, 2001)

Performance	Rated net output power	1,200W
	Heat dissipation	1,600W (at rated net output)
	Current	46 Amps DC (at rated net output)
	Voltage	26 Volts DC (at rated net output)
	Lifetime	1,500 hours
Fuel	Gaseous hydrogen	99.99%, dry
	Supply pressure	0.7 to 17.2 bar
Operating	Ambient temperature	3 to 30 ^{o}C
	Humidity	0% to 95% non-condensing
Environment	Indoor outdoor locations	Unit must be protected form inclement weather, sand, dust, marine and freezing conditions
Certification	USA and Canada	UL, CSA
Emissions	Pure water (vapor and liquid)	Maximum 0.74 lt per hour (at rated net output)
	CO, CO2, Nox, SO2 particulates	0 ppm
	Noise	72 dBA @ 1 m
Physical	Dimensions (mm)	559 x 254 x 330
	Weight	12.24 kg

The Nexa power module enables original equipment manufacture products to be used to generate power in an indoor environment not possible with the conventional internal combustion engine (ICE) generators. Up to 1,200 watts of unregulated DC electric power by converting hydrogen (H_2) fuel and oxygen (O_2)

from the ambient air in a non-combustive electrochemical reaction is generated with the Nexa power module. The by-products of this electrochemical power generation are safe heat and water. The quiet operation and compact size make it ideal for integration into a car as an uninterruptible power supply system. Unlike battery-powered devices with limited run-times, capable of producing full power in back-up operations or intermittent electrical power is given by Nexa power module as long as hydrogen fuel is supplied to the unit. Main technical and physical specifications of Nexa power module is drawn in Table 4.1.

The Nexa system schematic is illustrated in Figure 4.3. The Nexa power module system boundary and important interface connections to the DC module are also shown on the diagram. Hydrogen, oxidant air, and cooling air must be supplied to the unit, as shown in Figure 4.3. Exhaust air, product water and coolant exhaust is emitted. Unregulated DC power for interfacing is produced with external power conditioning equipment by Nexa power module. Battery power must be supplied for start up and shut down requirements. Finally, a communications interface must be provided to the Nexa unit for providing start/stop signals and for receiving serial port communications.

The Nexa fuel cell stack has been sized to provide 1.2 kW of net output power. The output voltage varies with power, ranging from about 43 V at system idle to about 26 V at full load. During Nexa system operation, the fuel cell stack voltage is monitored for diagnostic, control and safety purposes, as shown in Figure 4.3. In addition, a cell voltage checker (CVC) system monitors the performance of individual cell pairs and detects the presence of a poor cell. The Nexa unit will shut down if a cell failure or a potentially unsafe condition is detected in the fuel cell stack.

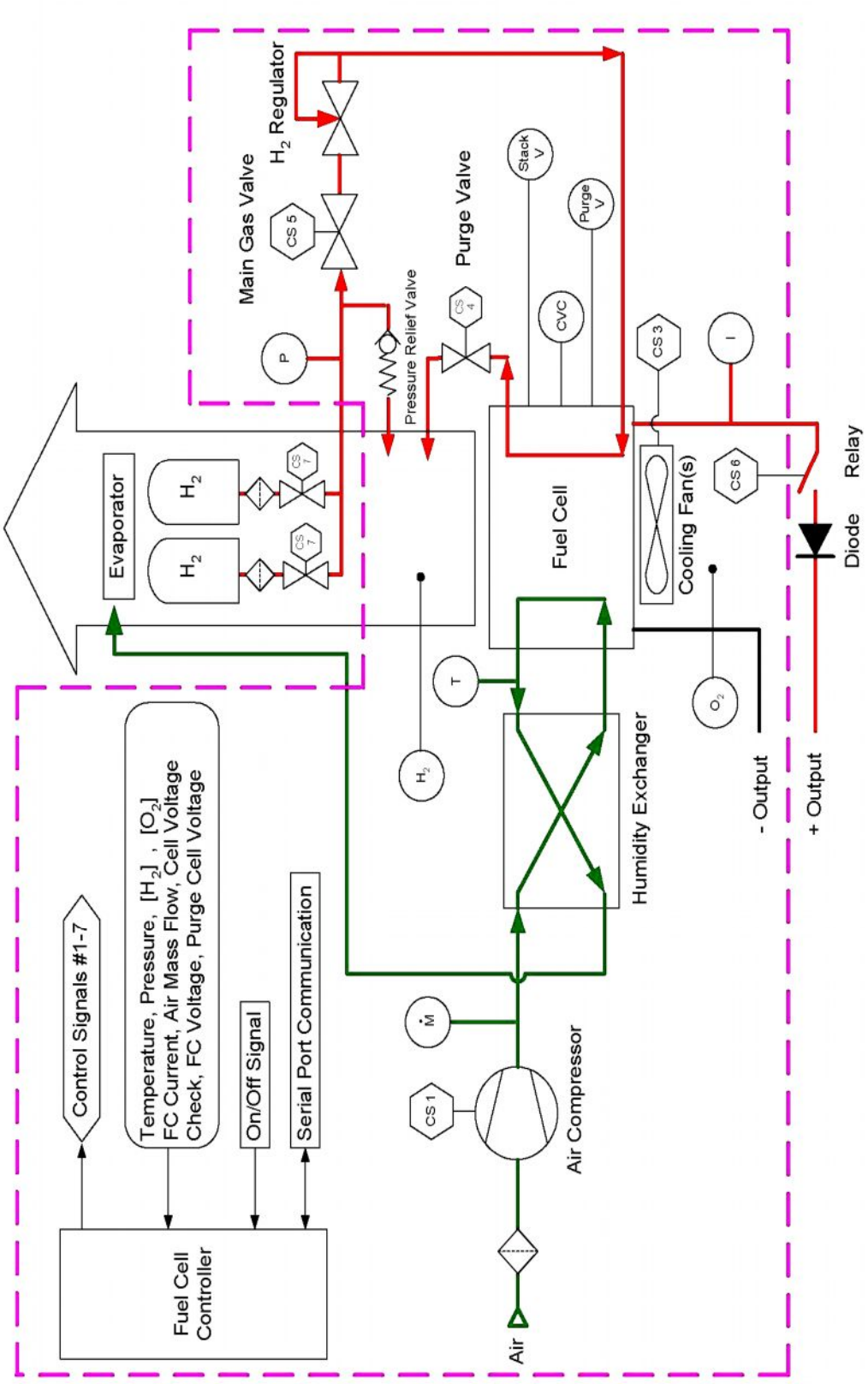


Figure 4.3. Nexa Power Module system schematic

The Nexa power module is operated on pure, dry hydrogen from any suitable source. The supply of hydrogen to the fuel cell stack is monitored and regulated by the fuel-supply system, as shown in Figure 4.3. The fuel supply subsystem is comprised of the following components:

- A pressure transducer monitors fuel delivery conditions to ensure an adequate fuel supply is present for Nexa system operation.
- A pressure relief valve protects downstream components from over-pressure conditions.
- A solenoid valve provides isolation from the fuel supply during shut down.
- A pressure regulator maintains appropriate hydrogen supply pressure to the fuel cells.
- A hydrogen leak detector monitors for hydrogen levels near the fuel delivery subassembly. Warning and shut down alarms are implemented for product safety.

The fuel cell stack is pressurized with hydrogen during operation. The regulator assembly continually replenishes hydrogen, which is consumed in the fuel cell reaction. Nitrogen and product water in the air stream slowly migrates across the fuel cell membranes and gradually accumulates in the hydrogen stream. The accumulation of nitrogen and water in the anode results in the steady decrease in performance of certain key fuel cells, which are termed "purge cells". In response to the purge cell voltage, a hydrogen purge valve at the stack outlet is periodically opened to flush out inert constituents in the anode and restore performance.

Only a small amount of hydrogen purges from the system, less than one percent of the overall fuel consumption rate. Purged hydrogen is discharged into the cooling air stream before it leaves the Nexa system, as shown in Figure 4.3. Hydrogen quickly diffuses into the cooling air stream and is diluted to levels many times less than the lower flammability limit. The hydrogen leak detector, situated in the cooling air exhaust, ensures that flammable limits are not reached. This feature permits safe, indoor operation of the Nexa power module.

A small compressor provides excess oxidant air to the fuel cell stack in order to sustain the fuel cell reaction. An intake filter protects the compressor and downstream components from particulate in the surrounding air. The compressor speed is adjusted to suit the current demand of the fuel cell stack. Larger currents require more airflow. A downstream sensor measures air mass flow rate and controls fine-tune the compressor speed to suit the required current demand.

Oxidant air is humidified before reaching the fuel cells to maintain membrane saturation and prolong fuel cell lifetime. A humidity exchanger transfers both fuel cell product water and heat from the wet cathode outlet to the dry incoming air.

Excess product water is discharged from the system, as both liquid and vapor, in the oxidant air exhaust. Product water must be managed through end-use integration design. Excess water may be evaporated passively into the surrounding environment, as shown in Figure 4.3. Alternatively, product water can be drained and collected.

The Nexa fuel cell stack is air-cooled. A cooling fan located at the base of the unit blows air through vertical cooling channels in the fuel cell stack. The fuel cell operating temperature is maintained at 65°C by varying the speed of the cooling fan. The fuel cell stack temperature is measured at the cathode air exhaust, as shown in Figure 4.3.

Hot air from the cooling system may be used for thermal integration purposes. Heat rejected in the air can be used for integration with metal hydrides, for evolving hydrogen. Hot air may also be used for space heating in some cases.
The cooling system is also used to dilute hydrogen that is purposely purged from the Nexa™ module during normal operation. Hydrogen is released into the cooling air stream by way of the purge solenoid valve, as shown in Figure 4.3. The hydrogen quickly diffuses into the cooling air and is diluted to levels far below the Lower Flammability Limit (LFL) of hydrogen is the smallest amount of hydrogen that will support a self-propagating flame when mixed with air and ignited. At concentrations less than the LFL, there is insufficient fuel present to support combustion. The LFL of hydrogen is 4% by volume) of hydrogen. For safety, a hydrogen sensor is located within the cooling air outlet stream and provides feedback to the control system. The control system generates warning and alarm signals if the hydrogen concentration approaches 25% of the LFL.

4.1.1 Nexa Power Module Safety Systems

High pressured hydrogen and hydrogen systems are very dangerous for applications in daily life. So, Nexa power module has been equipped lots of safety instruments and structure explained below.

The Nexa power module has automatic provisions to ensure operator safety and prevent equipment damage. A warning or alarm occurs when an unusual or unsafe operating condition occurs, depending on severity. During a warning, the power module continues to operate and the controller attempts to remedy the condition. During an alarm, the controller initiates a controlled shutdown sequence. The Nexa power module employs the following monitoring and shut down mechanisms to ensure safe fuel cell operation is maintained at all times:

- Fuel cell operating parameters are continuously monitored to ensure they stay within desired limits. These include fuel cell stack operating temperature, fuel cell stack current, output voltage and fuel supply pressure. Warnings and shut down alarms are implemented on each of these parameters

- A Cell Voltage Checker (CVC) system continuously monitors the operation and performance of individual cell pairs. The presence of a failing cell will cause the Nexa system to shut down.

- A hydrogen leak detector is implemented within the fuel delivery subassembly. Imbedded properly into the cooling air stream, this sensor can also detect excessive hydrogen purge amounts or the presence of an external fuel leak in the fuel cell stack. The Nexa system will shut down automatically if a hydrogen leak is detected.

- The Nexa power module comes equipped with an oxygen sensor for measuring ambient oxygen concentrations. This feature prevents users from operating the Nexa power module in non-ventilated areas, where oxygen depletion may become a safety concern. The power module shuts down automatically when low ambient oxygen concentration levels are measured.

In addition to warnings and alarms, other safety features are included to the design of the Nexa power module:

- A fuel shutoff solenoid valve closes whenever the power module is shut down. This isolates the fuel supply and prevents hydrogen from entering the fuel cell stack in the event of an alarm shutdown.
- Under normal operation, hydrogen released by way of the purge solenoid valve mixes with the cooling air stream, where it quickly diffuses and dilutes to levels far below the LFL of hydrogen. This eliminates the potential formation of a flammable gas mixture in the cooling air flow and permits indoor operation.
- A pressure relief valve discharges hydrogen into the cooling air stream during overpressure conditions to protect the fuel cell stack from damage. When the relief valve opens, the hydrogen concentrations measured in the cooling air stream exceed the hydrogen sensor alarm setting, and the power module shuts down.

4.2. Selection of the Hydrogen Storage Canister and Ovonic Metal Hydride Solid Hydrogen Storage Technology

There are basically three practical options for storing hydrogen and they are in high pressure compressed gas, in an ultra-low temperature cryogenic liquid state, and in solid-state metal hydride alloys. The energy of compression to store the hydrogen in the high-pressure vessel is required by high pressure hydrogen gas storage. Because of the increased pressure, a greater threat of system leak and the possibility of explosion is posed with this method. A significant amount of energy is consumed by liquefaction of hydrogen. Storing hydrogen in the solid-state form is safer than the previous two options. The technologies of utilizing a high efficient heat exchanger and high capacity metal hydride powder materials are involved with this type of hydrogen storages. The most effective solid-state hydrogen storage technology using high-capacity metal hydride materials is produced to store hydrogen safely and economically by ECD Ovonic.

According to above comparison of hydrogen storage type solid-state form is

decided to proper application for our study and Ovonic metal hydride canisters shown below figure have been used in this project.

Proprietary metal hydride technology is utilized by Ovonic portable canisters to safely store hydrogen in a compact manner at low pressure.

When hydrogen is bonded to the metal alloy powder contained in the canister, it is stored in a solid state at densities many times greater than traditional compressed gas storage.



Figure 4.4. Ovonic metal hydride solid-state hydrogen canisters

Some basic technical and physical specifications of the Ovonic hydrogen canisters are listed below chart briefly. 900 standard (std.) liters capacity hydrogen canister is selected for our project because of more amount of hydrogen capacity, proper weight and dimensions for our vehicle design. More amount of hydrogen means that more fuel, consequently longer distance travel with the vehicle.

Table 4.2. Specifications of Ovonic metal hydride solid-state hydrogen canisters (Nexa User Guide, 2002)

Hydrogen Storages		Hydrogen Storage 70	Hydrogen Storage 220	Hydrogen Storage 900
*Hydrogen storage capacity *nominal condition dependent *if refilling @ 10 barg	g std. liters std. liters	6.5 70 approx. 50	20 220 approx. 150	80 900 approx. 600
Discharge rate, nominal equivalent FC stack power	slm W	1.4 100	3.5 250	7 500
Diameter	mm	51	64	90
Length (incl. quick coupler)	mm	205	305	425
Weight	kg	0,8	2,2	7
Settled pressure @ 25 °C	barg	17		
Refilling pressure	barg	max. 17		
Refilling time		less than 2 hours in flowing ambient air		
Hydrogen quality for refilling		5.0 or better		
Connection		Quick coupler, type Parker Q4CY		
Operating temperature	°C	0 ... +75		
Storage temperature	°C	-29 ... + 54		
Safety devices		Manual shut-off and thermal / pressure relief certified to CGA S-1.1		

4.2.1. Advantages of Solid Hydrogen Storage

Solid hydrogen storage systems offer several advantages over both compressed and liquid hydrogen storage systems. Some of the advantages of solid hydrogen storage systems include:

- Safety
- Low pressure operation
- Compactness
- No cryogenic temperatures or "boil-off"
- Scalability to virtually any size
- Tailor ability of delivery pressure
- Utilization of waste heat
- High volumetric energy storage density
- Long cycle life

4.3. Selection of the Electrical Motor and Brushless DC Motor

A BLDC motor drive is consisted mainly of the brush-less DC machine, a DSP-based controller, and a power electronics-based power converter, as shown in Figure 4.5. The position of the machine rotor is sensed by position sensors H1, H2 and H3. The rotor position information is fed to the DSP-based controller, which, in turn, supplies gating signals to the power converter by turning on and turning off the proper stator pole windings of the machine. In this way, the torque and speed of the machines are controlled.

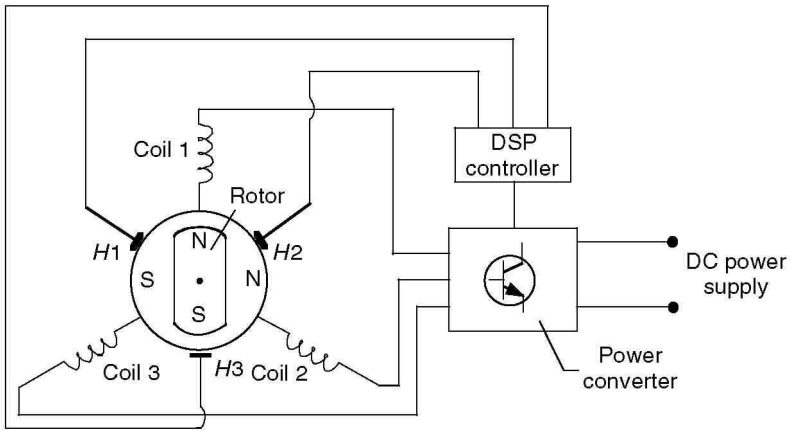


Figure 4.5. BLDC motor

BLDC machines can be categorized by the position of the rotor permanent magnet, the way in which the magnets are mounted on the rotor. The magnets can either be surface-mounted or interior-mounted.

Figure 4.6(a) shows the surface-mounted permanent magnet rotor. Each permanent magnet is mounted on the surface of the rotor. It is easy to build, and specially skewed poles are easily magnetized on this surface-mounted type to minimize cogging torque. But there is a possibility that it will fly apart during high-speed operations.

Figure 4.6(b) shows the interior-mounted permanent magnet rotor. Each permanent magnet is mounted inside the rotor. It is not as common as the surface-mounted type but it is a good candidate for high-speed operations. Note that there is inductance variation for this type of rotor because the permanent magnet part is equivalent to air in the magnetic circuit calculation.

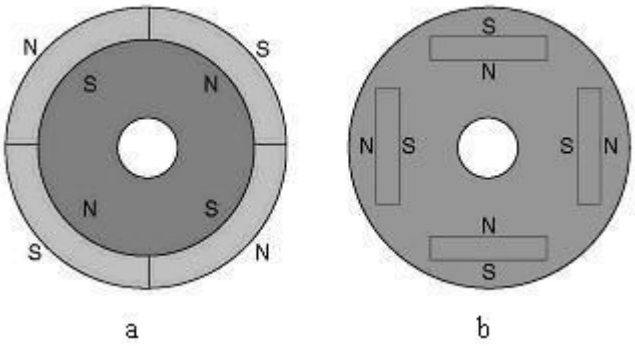


Figure 4.6. Surface and interior mounted magnet rotor

4.3.1. Advantageous and Disadvantageous of BLDC Motor

By using high-energy permanent magnets as the field excitation mechanism, a permanent magnet motor drive can be potentially designed with high power density, high speed, and high operation efficiency. These prominent advantages are quite attractive to the application on electric and hybrid electric vehicles. Of the family of permanent magnetic motors, the brush-less DC (BLDC) motor drive is the most promising candidate for EV and HEV application. The major advantages of BLDC motor include:

- High efficiency: BLDC motors are the most efficient of all electric motors. This is due to the use of permanent magnets for the excitation, which consume no power. The absence of a mechanical commutator and brushes means low mechanical friction losses and therefore higher efficiency.
- Compactness: The recent introduction of high-energy density magnets (rare-earth magnets) has allowed achieving very high flux densities in the BLDC motor. This makes it possible to achieve accordingly high torques, which in turns allows making the motor small and light.
- Ease of control: The BLDC motor can be controlled as easily as a DC motor because the control variables are easily accessible and constant throughout the operation of the motor.
- Ease of cooling: There is no current circulation in the rotor. Therefore, the rotor of a BLDC motor does not heat up. The only heat production is on the stator, which is easier to cool than the rotor because it is static and on the periphery of the motor.
- Low maintenance, great longevity, and reliability: The absence of brushes and mechanical commutators suppresses the need for associated regular maintenance and suppresses the risk of failure associated with these elements. The longevity is therefore only a function of the winding insulation, bearings, and magnet life-length.
- Low noise emissions: There is no noise associated with the commutation because it is electronic and not mechanical. The driving converter switching frequency is high enough so that the harmonics are not audible.

However, BLDC motor drives also suffer from some disadvantages such as:

- Cost: Rare-earth magnets are much more expensive than other magnets and result in an increased motor cost.
- Limited constant power range: A large constant power range is crucial to achieving high vehicle efficiencies. The permanent magnet BLDC motor is incapable of achieving a maximum speed greater than twice the base speed.
- Safety: Large rare-earth permanent magnets are dangerous during the construction of the motor because they may attract flying metallic objects

toward them. In case of vehicle wreck, if the wheel is spinning freely, the motor is still excited by its magnets and high voltage is present at the motor terminals that can possibly endanger the passengers or rescuers.

- Magnet demagnetization: Magnets can be demagnetized by large opposing mmfs and high temperatures. The critical demagnetization force is different for each magnet material. Great care must be exercised when cooling the motor, especially if it is built compact.
- High-speed capability: The surface-mounted permanent magnet motors cannot reach high speeds because of the limited mechanical strength of the assembly between the rotor yoke and the permanent magnets.

A main criterion to selection of electrical motor for our study is efficiency. Beside of this, compactness, ease controlling and cooling, low maintenance and noise emission put BLDC motor at the top of the electric motor selection list.

In this study, three BLDC electrical motor is used, one of them is for a prototype three wheels vehicle and the other two are for a prototype urban concept (four wheels) vehicle. The motor for the three wheels vehicle is a present one on the market as a BLDC hub type electrical motor which's power is 2000W. Other technical data is given below.

Type: BLDC Hub (surface-mounted permanent magnets) Motor
Model: 60V 2000W ARX
Voltage: 60V
Torque: 103 Nm max.
Efficiency: %91 on laboratory conditions

The second and third motors for urban concept vehicle are also BLDC motor but interior-mounted magnet electrical motor. The data power, voltage and the current interval was calculated by us for the four wheels vehicle according to weight and aerodynamic structures of the vehicles. Before designing the second vehicle, aim was designing of an economical and also fast urban concept car. Data for these motors are :

1st (Economical One)

Type: BLDC (interior-mounted permanent magnets)

Model: 24 V 500 W

Voltage: 24 V

Efficiency: %90 on laboratory conditions

2nd (Fast One)

Type: BLDC (interior-mounted permanent magnets)

Model: 24 V 1000 W

Voltage: 24 V

Efficiency: %90 on laboratory conditions

4.4. Designing of a Fuel Cell Vehicle

A fuel cell car is such as an electrical car in which electricity is produced from hydrogen fuel by the fuel cell stacks. If the capacity of the fuel cell is enough, exceed produced electricity can be stored on back up batteries to use instantaneously power consumption conditions or when hydrogen fuel is not enough. But in our study, back up batteries is not used to see the performance of the vehicle when it is supported directly with the fuel cell. The electricity flow scheme and working principle can be seen below figure.

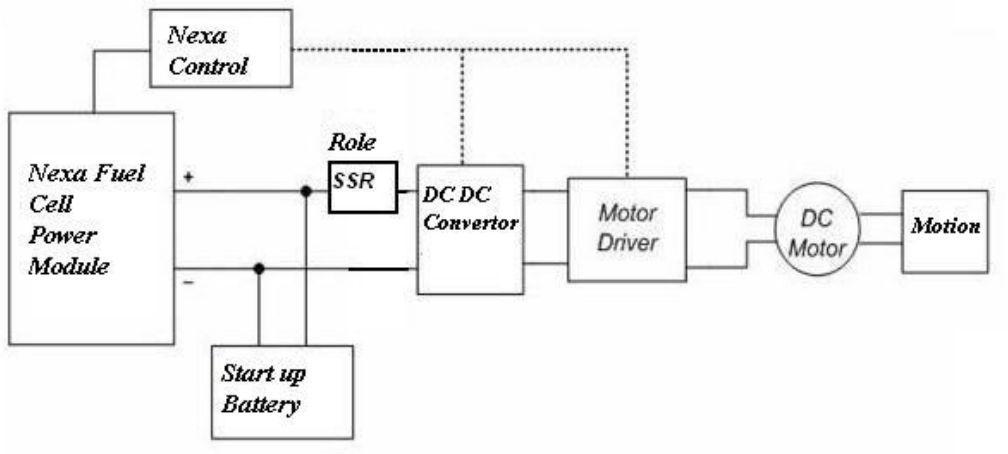


Figure 4.7. Fuel cell vehicle energy flow scheme

4.4.1. Chassis Design and Production

4.4.1.1 Chassis Design of Three Wheels Vehicle

Since both of the vehicle, three wheels and the four wheels, being prototype dimensions of the vehicle are compact as a person can be located in it. After drawing on a Cad program, chassis of the three wheels vehicle is seen in Figure 4.8. In Figure 4.9, dimensions of the chassis are given.

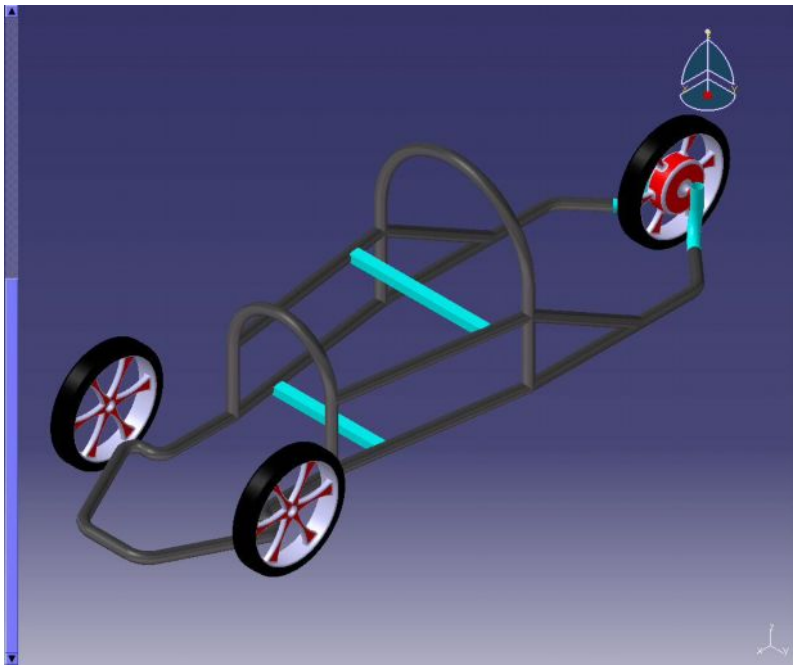


Figure 4.8. Chassis of three wheels prototype vehicle

The scope of designing this vehicle is reach to high speeds on road. To reach this speeds some main design criteria are considered as aerodynamic structure, weight and road friction. According to aerodynamic rules, cross section area must be designed in minimum dimensions and weight of the car must also be as low as possible. To minimize road friction, three wheels are placed on vehicle. St 37 stainless steel pipe is used as chassis material to obtain proper mechanical strength. The chassis material has strength of 350 MPa of load under static load conditions. Manufacturing process of the chassis can be seen in Figure 4.10.

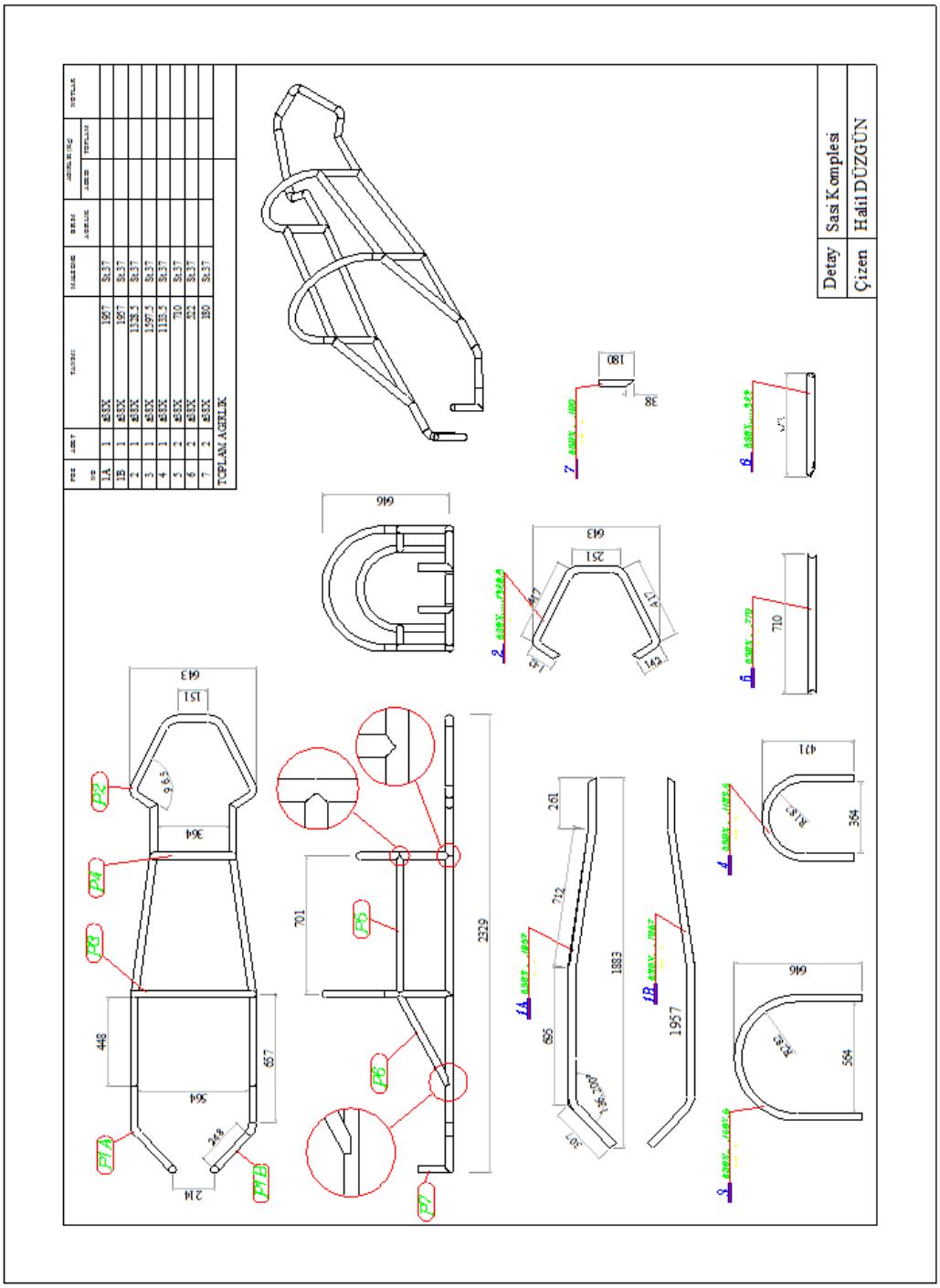


Figure 4.9. Dimensions and manufacturing plan of the chassis for three wheels vehicle



a



b

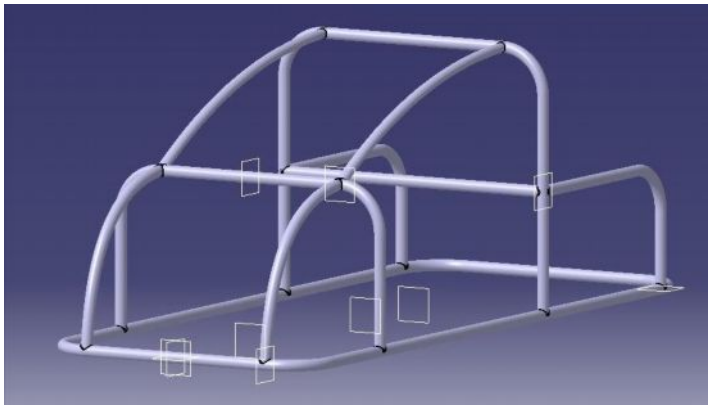


c

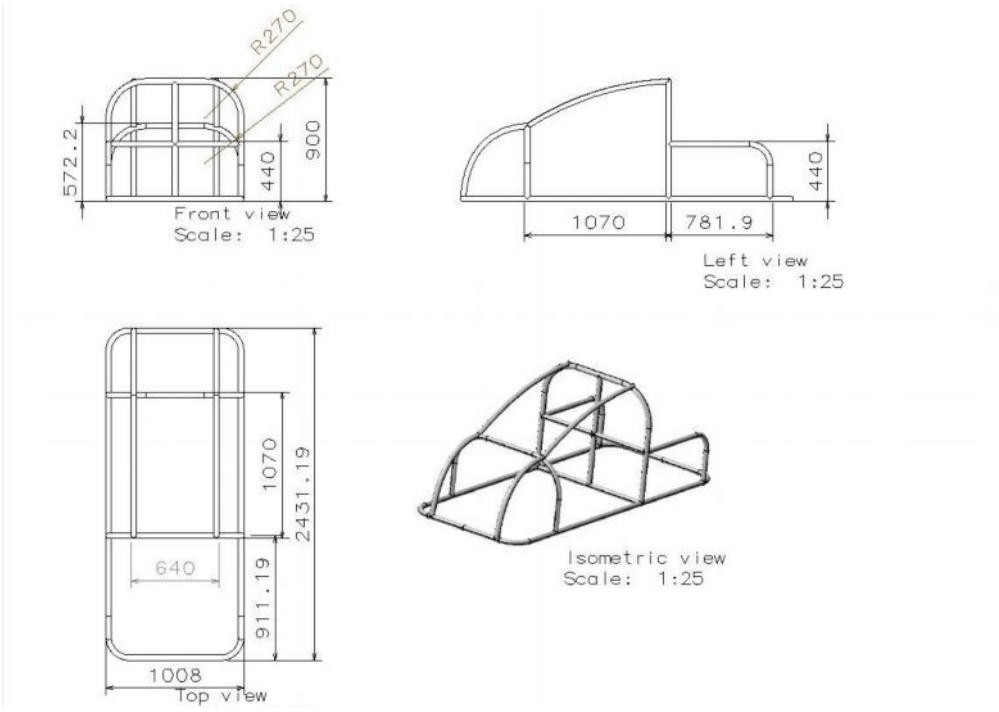
Figure 4.10. Manufacturing stages of chassis

4.4.1.2. Chassis Design of Four Wheels Vehicle

Production of an economical car is aimed at the design of an urban concept vehicle. Again, weight is the main criterion when material is selected for the chassis. This time aluminum is selected as chassis material because of the specific weight of it. After designing of the chassis, it is loaded with static force on a computer analyzing program and reading value is 75 MPa for the selected material. The drawing and the dimensions can be seen in Figure 4.11.



a



b

Figure 4.11. Chassis of four wheels vehicle

4.4.2. Body Design

4.4.2.1. Body Design of Three Wheels Vehicle

The same aerodynamic rules are considered in the design of vehicle body. It must be compact, must have small cross sectional area and low weight again. Fiber glass is chosen as body material for this study due to its physical properties. Body design of the vehicle can be seen in Figure 4.12.

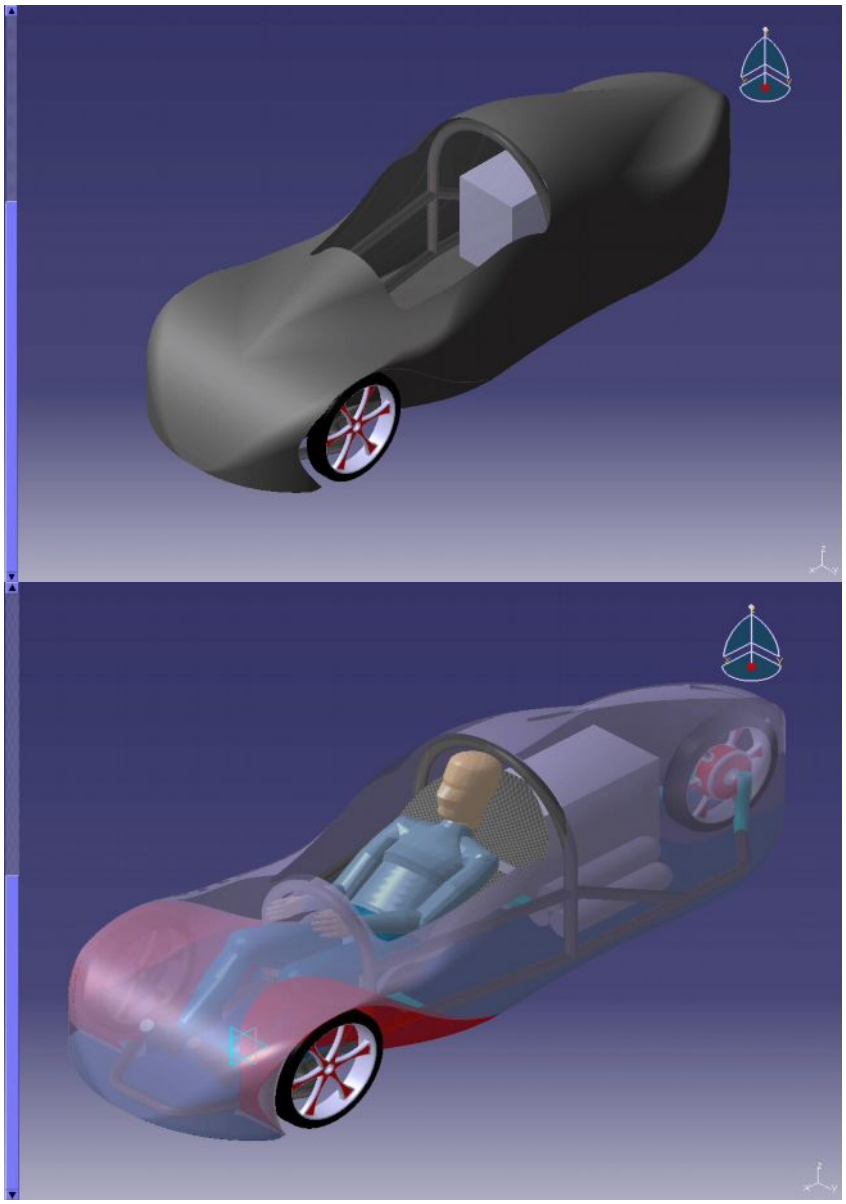


Figure 4.12. Body of the three wheels vehicle



Figure 4.13. Clay mould of the body



Figure 4.14. Body after painting

4.4.2.2. Body Design of Four Wheels Vehicle

Specific weight of the body material is considered as a main criterion in the selection. The lightest material must be selected for the body as soon as possible. Carbon fiber material is decided as most proper material to produce the lowest weight vehicle body. The urban concept vehicle can be seen completely in Figure 4.15 when it was raced for Çukurova University at Tübitak organization in İzmir.



Figure 4.15. Urban concept vehicle

4.5. Laboratory Test Equipments and Setting Up

After designing, assembling and road tests, all of the electrical motors and fuel cell equipments are settled up to see the characteristic properties of motors in laboratory conditions. These experiments can supply data to us for the comparison of data given by the motor producers and road tests.

Below figures show the settling up of test equipments in the laboratory. Power of 2000 W and 500 W electrical motors tests are done in laboratory of

mechanical engineering department and power of 1000 W motor is tested in laboratory of electrical and electronic engineering department of Çukurova University.



Figure 4.16. 2000 W and 500 W motors assembled with fuel cell

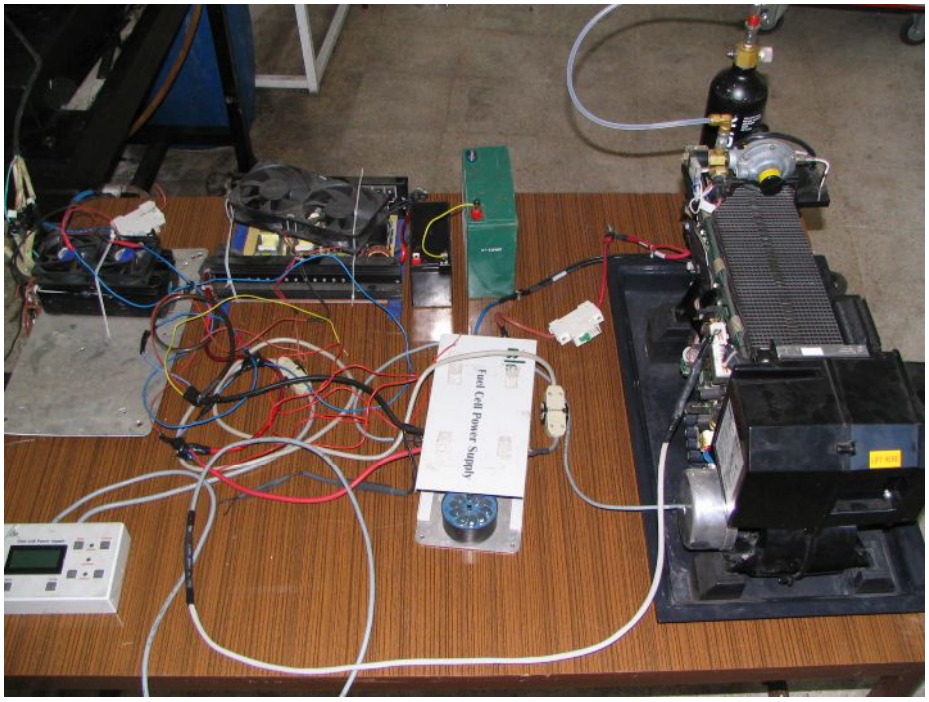


Figure 4.17. 2000 W and 500 W motors assembled with fuel cell

In Figures 4.18, 4.19 and 4.20, it can be seen that electric motor is mounted with a magnetic breaker for loading torque to motor. There is a software program named as Nexa OEM in which all data are taken during the experiments.

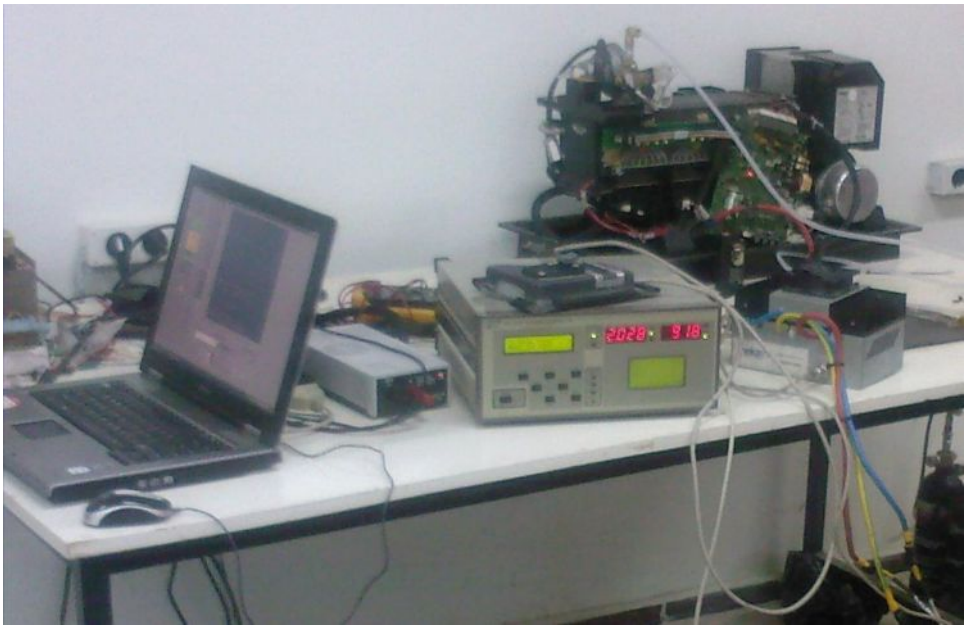


Figure 4.18. 1000 W motor assembled with fuel cell and computer

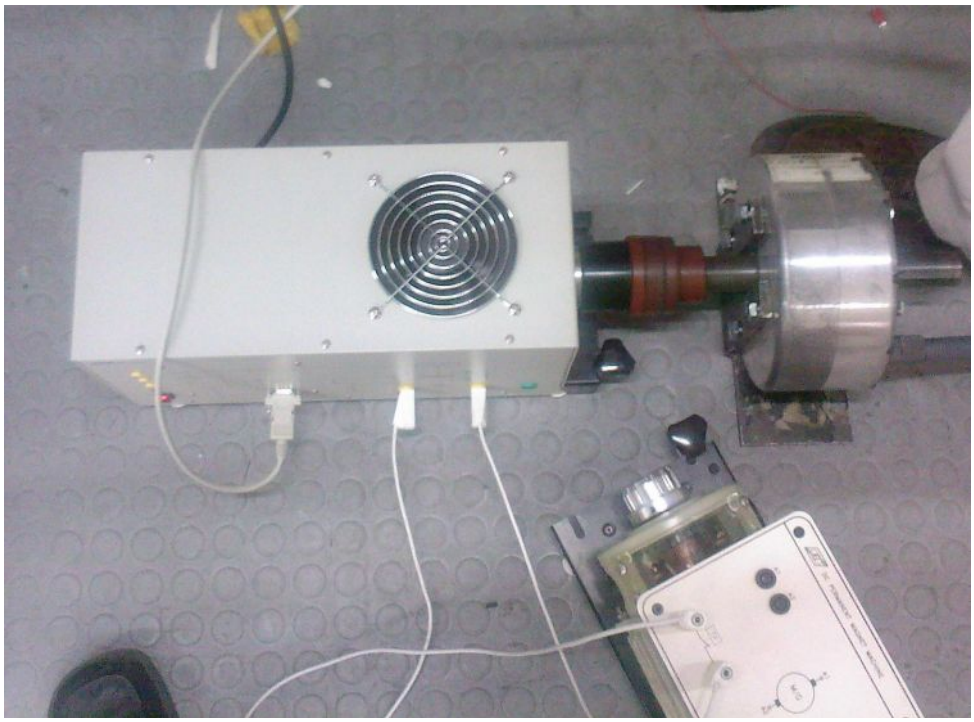


Figure 4.19. 1000 W Motor assembled with fuel cell and magnetic dynamometer

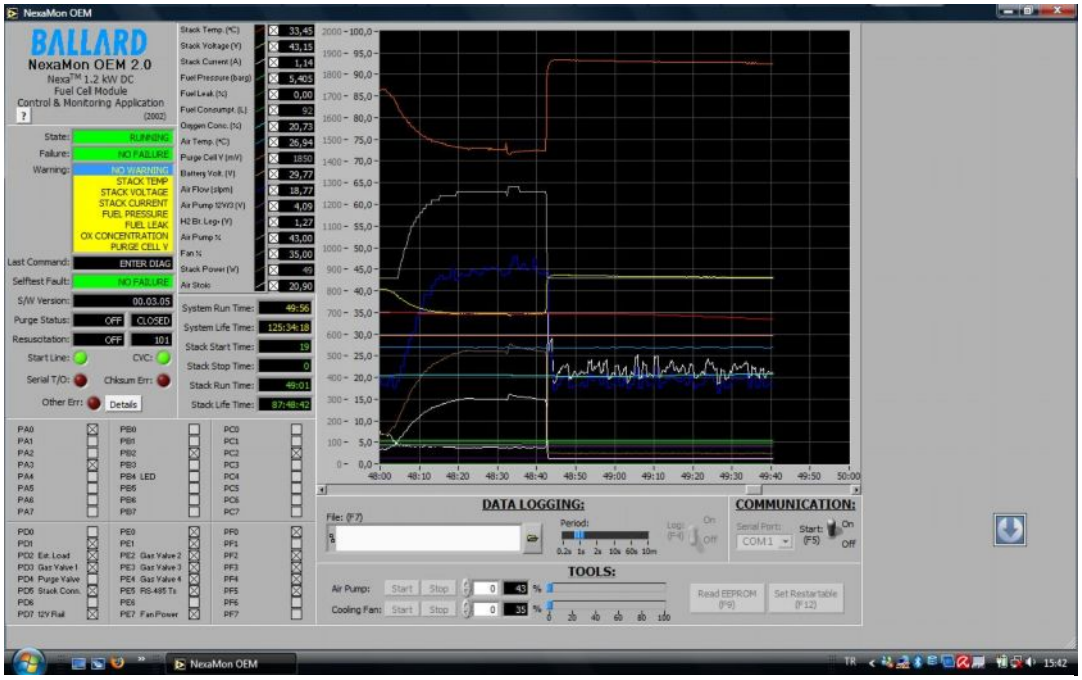


Figure 4.20. Nexa OEM screen

All of the data, stack voltage, stack current, purge voltage, stack temperature, oxygen concentration, air temperature, canister pressure, hydrogen consumption, etc. are shown and graphed by the Nexa OEM software program on the computer screen. These data are used to make tables and draw graphs for experiment in the result and discussion section.

4.6. Road Tests and Entered Competitions

Some road tests and some race organizations were also used as method to see and compare the results for this study. One of them international and two of them national as total three race organizations were participated with our vehicles. Aims of races are different between domestic and abroad. National one is a speed race in a definite circuit organized by Tübitak which is an official science department in Turkey and international one is a fuel economy race named as Shell-Eco Marathon which is organized by Shell Company.

Our prototype vehicle is used in speed race organized by Tübitak in 2007 and finished race in second sequence with nearly 73 km/h maximum speed. Main

difference between the first vehicle and ours is weight. They have nearly 80 km/h speed with a 150 kg weight vehicle.



Figure 4.21. Second rank award on Tübitak race organization in 2007.



Figure 4.22. A photo from Tübitak Hidromobil'07 race.



Figure 4.23. Group photo from starting of Tübitak organization in 2007.



Figure 4.24. Start-finish road before race- 2007.



Figure 4.25. Technical control area after race-2007.

First five vehicle had three wheels design and this is advantageous to reach the high speeds with less amount of friction on road. Other criterion is thought of fuel cell power to select proper electrical motor for the vehicle.

Urban concept vehicle was also raced in Tübitak organization with 1000 W of electrical motor next year, in 2008. Some problems were occurred with our 1000 W of electrical motor during organizations. The traction force to move the vehicle in start could not be supplied by the electrical motor. After road and laboratory tests, it is seen that torque supplied by the motor is not enough to move the vehicle at the beginning of the motion. These tests data is given next section on a table and torque-motor speed relation is shown on a graph.

Some photos related our urban vehicle can be seen below from Tübitak Hidromobil'08 organization on Pınarbaşı Race Runway in İzmir.



Figure 4.26. Start-Finish line-İzmir 2008



Figure 4.27. Start-Finish line with other participants – İzmir 2008.



Figure 4.28. Technical control area – İzmir 2008.



Figure 4.29. Waiting for the paddock – İzmir 2008.



Figure 4.30. Çukurova Hydromobile Group – İzmir 2008.

The other organization attended by Çukurova Hydromobile Group is an international fuel economy race which is organized by Shell every year in different countries since 1976. There are some differences between Tübitak and Shell organizations in race format and technical rules. It is mentioned that Tübitak organization is a speed race but Shell organization is a fuel economy race. According to this criterion, 500 W electrical motor which has less energy consumption during operating than 1000 W electrical motor is selected for our vehicle to race in competition.

848 km / hydrogen equivalent per liter gasoline (H/g) was consumed by the first rank vehicle after it had been calculated end of the race. 729 km by the second and 453 km by the third vehicles had been achieved for H/g. According to this result, some criteria can be seen to consume less amount of fuel if properties of the urban vehicles comparing each other. If it is realized that 70 kg, 120 kg and 125 kg of vehicle weights in sequence of award rank and using of same fuel cells, main criterion is weight of the vehicles to save the fuel economy. Beside the weight, mechanical design, aerodynamic structure and also proper motor selections are the other criterion to achieve the economical consumption of the fuel.

Fourth best degree was obtained by our urban vehicle in urban concept but

none finishing of lap could not supply us any rank in the organization in France.

There are also ICE vehicles in the competition to race and their best grades for consuming fuel are 299 km per liter of ethanol, 291 km per liter of gasoline and 286 km per liter of diesel. If it is compared with hydrogen grades big efficiency difference and fuel economy can easily be seen.

Some photos of our urban concept vehicles in Sheel Eco Marathon organizations are seen below as it is in pit area, technical controls or in lap when racing.



Figure 4.31. Start-Finish line – Nogaro 2008.



Figure 4.32. Start-Finish line – Nogaro 2008.



Figure 4.33. Technical Controls – Nogaro 2008.



Figure 4.34. Side of the circuit – Nogaro 2008.



Figure 4.35. Waiting for runnig – Nogaro 2008.



Figure 4.36. Waiting for starting on the circuit – Nogaro 2008.



Figure 4.37. Runnig on the circuit – Nogaro 2008.



Figure 4.38. Working on vehicle in pit area – Nogaro 2008.



Figure 4.39. Working on vehicle in pit area – Nogaro 2008.

Technical Proporties of Prototype Vehicle

Motor	:	DC Brusless HUB Motor (16 kg)
Torque	:	103 Nm max.
Power	:	2 KW max.
Fuel Cell	:	1200 W Ballard Nexa PEM Fuel Cell(13 kg)
Hydrogen Storage	:	3 x 900 Lt Metal Hydride Solid Canasters (21 kg)
Supercapacitor	:	1 Farad (Approx. 5 kg)
Dimensions	:	LxWxH: 2613x820x690
		r_w: 420 mm
		Axe Distance: 1935 mm
Weight	:	172 kg
Brakes	:	Front; two pieces of hydrolic disk
		Rear; one piece of hydrolic disk
Safety Structures	:	Safety belt
		Hydrogen Sensor
		Air Exit Window
		Roll bar & Roll cage (in FIA Standarts)
		Fire Extinguisher
		Emergency Button

Technical Proporties of Urban Vehicle

Motor	:	DC Brusless Motor (15 kg)
Power	:	1) 500 W max. 2) 1000 W max.
Fuel Cell	:	1200 W Ballard Nexa PEM Fuel Cell(13 kg)
Hydrogen Storage	:	1) 1 x 200 bar Metal Hydride Solid Canaster 2) 3 x 900 Lt Metal Hydride Solid Canasters (21 kg)
Supercapacitor	:	1) 1 Farad (Approx. 5 kg)
Dimensions	:	LxWxH : 2431x1200x690
		r_w: 440 mm
		Axe Distance: 1850 mm
Weight	:	154 kg
Brakes	:	Front; two pieces of hydrolic disk
		Rear; two pieces of hydrolic disk
Safety Structures	:	Safety belt
		Hydrogen Sensor
		Air Exit Window
		Roll bar & Roll cage (in FIA Standarts)
		Fire Extinguisher
		Emergency Button

5. RESULT AND DISCUSSION

5.1. Test Result of 2000W Electric Motor in Laboratory Conditions

Fuel cell, hydrogen storage canisters, DC-DC converter, batteries, electrical motor and fuel cell control unit is established for the experiment in laboratory. Below data are recorded in unloaded condition for the 2000 W electric motor.

Table 5.1. Test results of 2000W electric motor without load

Revolution(rpm)	Current(A)	Stack Voltage(V)	Stack Temperature(^oC)	H_2 Consumption (lt/min.)	H_2 Canister Pressure (bar)
50	2,2	40	32,4	0,7	11,6
100	2,4	39,9	32,6	0,796	11,6
150	2,5	39,7	32,8	0,783	11,6
200	2,8	39,5	32,8	0,893	11,6
300	3,8	38,5	33	1,395	11,6
400	5,6	37,7	33,5	2,062	11,6
500	8,1	36,6	34,2	2,97	11,6
600	11,6	35,5	35,3	4,878	11,6
700	15	34,6	37,7	4,166	11,4
800	21,4	33	39,7	5,94	10,7
850	23	32,9	42,6	6,316	8,7

Above experiment is done when environmental temperature is 32^oC and the hydrogen storage pressure is 11. 6 bar.

When the results are examined on a graph, current increases and, voltage decreases with the increase in the motor rotation. This is an expected result and since current increases and voltage decreases to equalize the motor supplying power. It is verified again with these values. Graph can be seen in Figure 5.1.

It is shown in Figure 5.2 that when motor rotation is increased, stack temperature also increases. Due to forcing of the fuel cell this result is again expected. When motor is accelerated hydrogen consumption is increased to produce more electricity for electrical motor by the fuel cell power module.

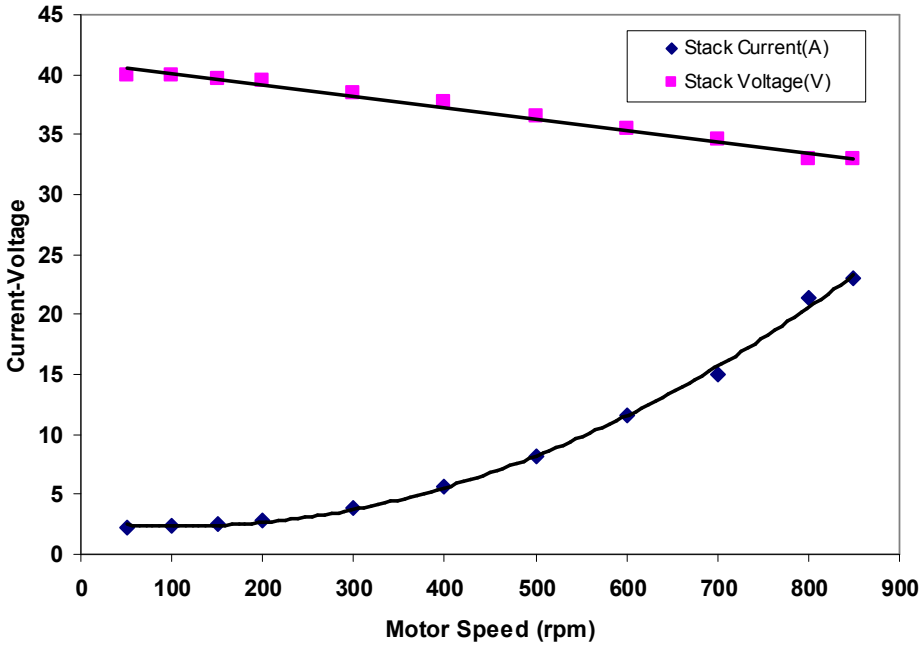


Figure 5.1. Motor speed-current-voltage diagram

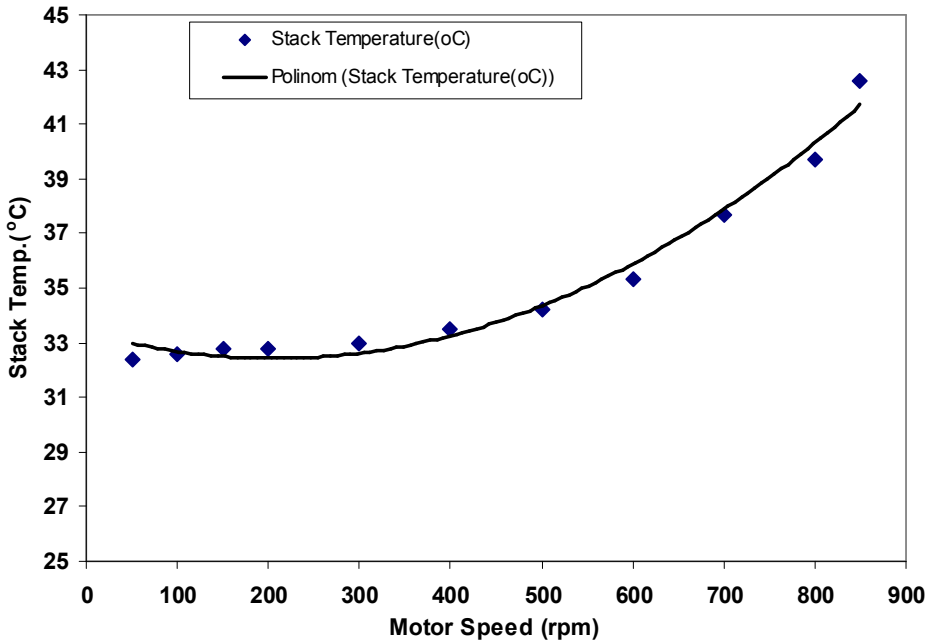


Figure 5.2. Motor speed-temperature diagram

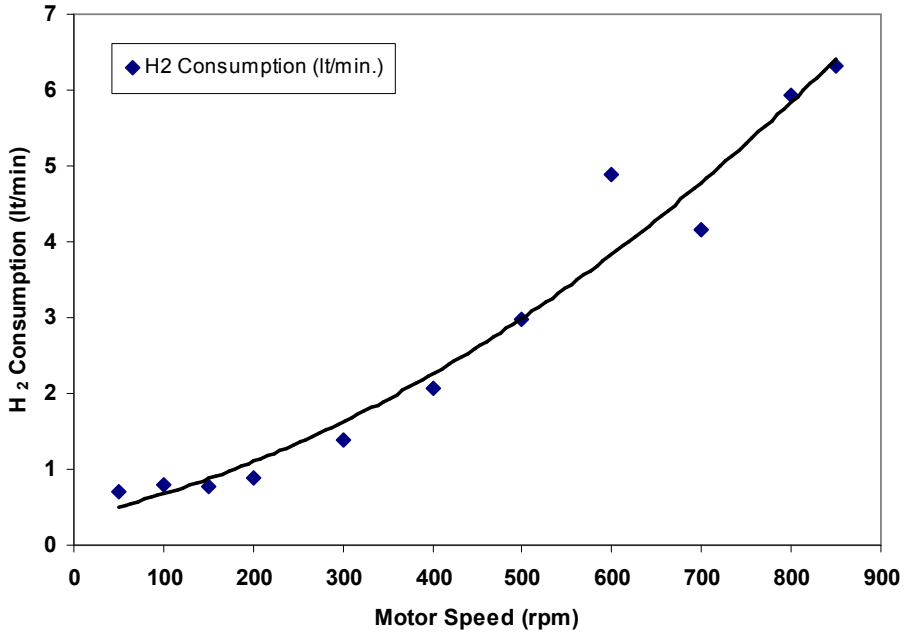


Figure 5.3. Motor speed-hydrogen consumption diagram

Increase in the hydrogen consumption is seen from Figure 5.3 when the rotation of the motor is accelerated. Since rotation rises up from 500 rpm to 600 rpm a sudden increase is seen on fuel consumption. Again this sudden change can be seen in Figure 5.1 for the current. There is a decrease between 600 and 700 rpm when rotation is increased. Down motion in this period would be appeared an experimental fault but also environmental conditions can cause this result between this range.

5.2. Test Result of 500W Electrical Motor in Laboratory Condition

Electrical motor of urban concept vehicle is established for the experiments. Different from the 2000 W motor, an extra DC-DC converted is not needed for this motor according to working voltage of 24 V which can be supplied directly by the Nexa power module. The results of the experiment are tabulated in Table 5.2.

Table5.2. Test results of 500 W electric motor without load

Revolution(rpm)	Current(A)	Stack Voltage(V)	Stack Temperature(°C)	H_2 Consumption (lt/min.)	H_2 Canister Pressure (Bar)
50	1,7	40,6	31,9	0,513	11,6
75	1,6	40,8	32,1	0,52	11,6
90	1,5	40,6	32,1	0,515	11,6
100	1,6	40,5	32,1	0,535	11,6
125	1,6	40,6	32,1	0,567	11,6
150	1,7	40,4	32,1	0,569	11,6
175	1,7	40,3	32,1	0,598	11,6
200	1,8	40,3	32,3	0,598	11,6
250	2	39,9	32,3	0,655	11,6
300	2,9	39,5	32,5	0,847	11,4
375	2,4	39,9	32,8	0,853	11,3
400	2,5	39,7	32,8	0,876	11,2

When data is analysed, below graphics are drawn as a result. As can be seen in Figure 5.4, current has a peak value at 300 rpm. This peak value is seen several time same and it can be commented as 500 W electrical motor needs a peak load at this rotation speed. On the other hand, to increase the speed of the electrical motor speed from 250 W to 300 W, much more loads are needed. The same comment can be made if rotation-voltage diagram is checked in Figure 5.5.

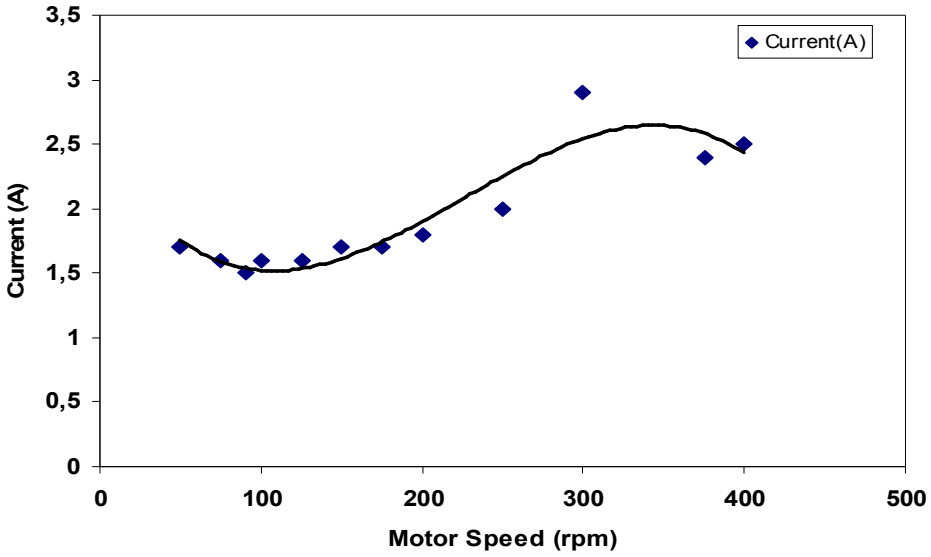


Figure 5.4. Motor speed-current diagram

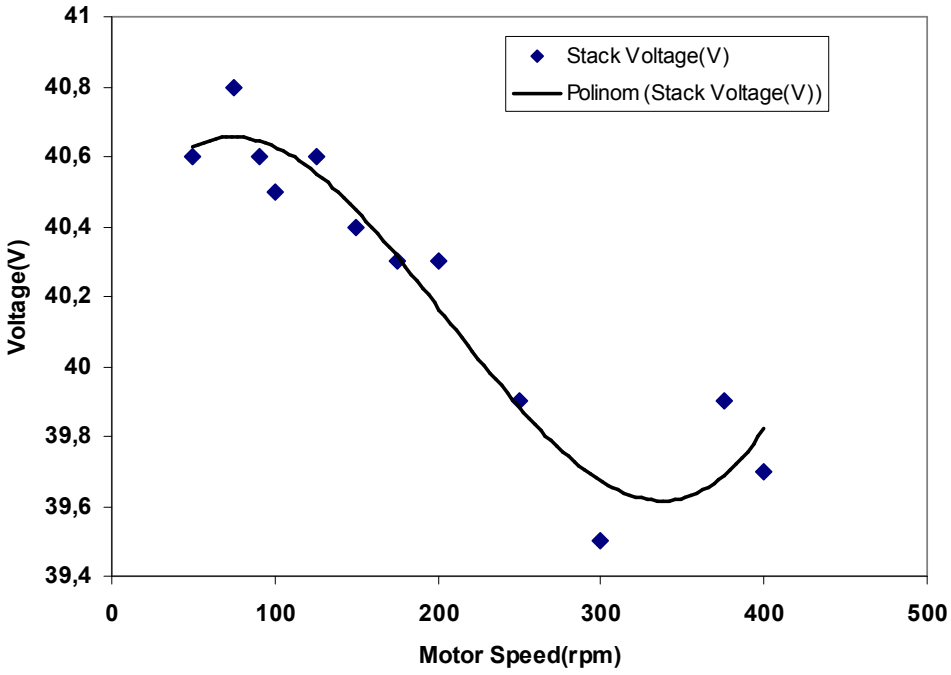


Figure 5.5. Motor speed-voltage diagram

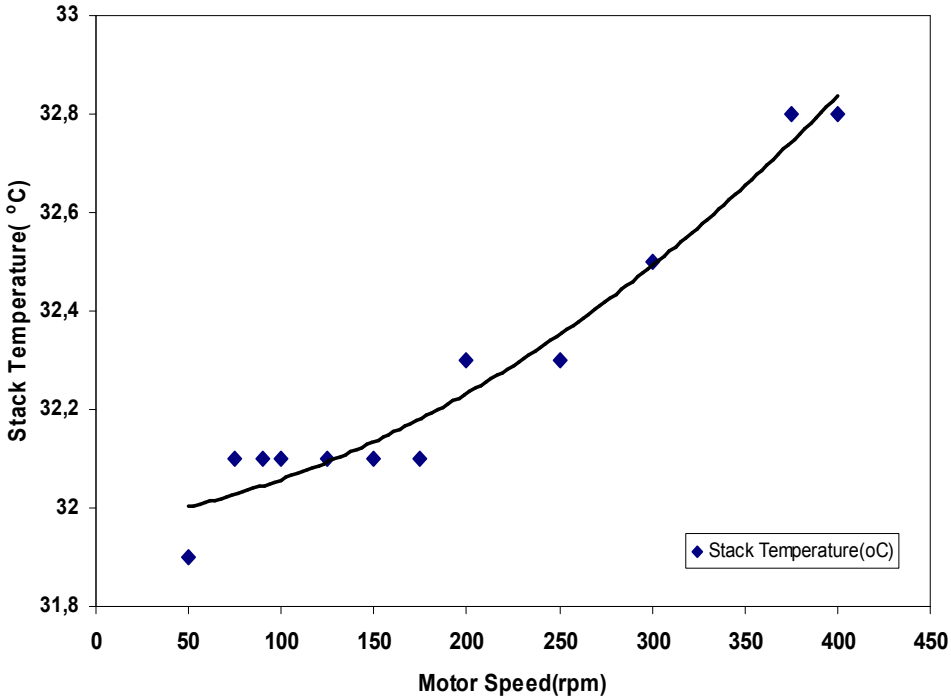


Figure 5.6 Motor speed-stack temperature diagram

When Figure 5.6 is examined, stack temperature is seen nearly constant or very low increase in temperature. If one compares it with the graph of 2000 W electrical motor it can be seen that there is big difference between 500 W and 2000 W electrical motors. This result can be lean on difference of power between motors. 2000 W electrical motor needs high current in high speeds but the 500 W electrical motor can not reach mentioned rotation speed.

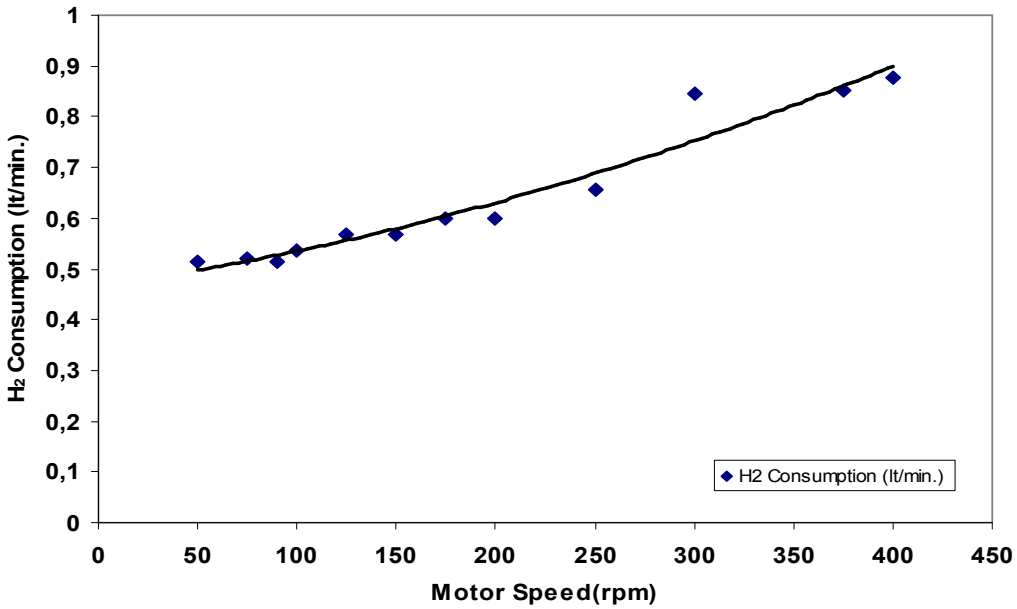


Figure 5.7. Motor speed-hydrogen consumption diagram

High rotation speed needs high current, high current needs high fuel consumption. This theory is verified by the experimental results and graphs which are based on these experimental results. And again, it can be said that high fuel consumption means high temperature exit.

5.3. Test Result of 1000W Electrical Motor in Laboratory Condition

1000 W power of electrical motor of urban concept vehicle is established to the magnetic breaker for the experiments. Because of 24 V operating voltage value, DC-DC converter is not needed again to assemble the system. Experiment results can be seen in Table 5.3.

Table 5.3. Test results of 1000 W electric motor

Rev.(rpm)	Torque (Nm)	Current (A)	Stack Voltage(V)	Stack Temp. (T°C)	Fuel Consump. (L/min.)	Canaster Pressure(Bar)
1010	0	3,70	39,10	27,79	1,216	8,70
975	0,46	4,86	38,17	28,18	1,579	8,35
966	0,84	5,9	37,7	29,43	1,976	7,69
935	1,4	7,5	37	30,52	2,443	7,32
908	2	9,1	36,5	31	2,760	7,01
860	3,125	12,4	35,75	32,1	4,057	6,49
845	4	14,48	35,55	34,19	4,762	5,55
840	4,2	15	35,4	33,89	5,102	5,15
839	4,6	16	35,31	34,62	5,396	4,87
820	5	17	34,82	35,81	5,747	4,63
808	5,6	18,88	34,58	37,46	6,237	4,37
799	6	19,8	34,37	39,27	6,536	4,06
785	6,4	20,8	34,1	40,1	7,229	3,8
764	7	22,26	33,53	38,6	7,326	3,54
750	7,4	23,6	33,44	40,82	7,576	3,28
716	8	24,9	32,3	32,86	8,264	3,2
711	8,6	26,4	32,2	37,2	8,621	2,95
705	9	27,5	32,2	40,37	8,772	2,73
695	9,4	28,3	31,9	40,76	9,188	2,41

Using of above data in Table 5.3, below graphs are drawn as a result to see the relationship between different parameters.

First graph below shows us torque variation according to the change in revolution of electrical motor speed. Change in torque is so close the linear fit curve in Figure 5.8. Naturally, it is expected a decrease in of electric motor speed when torque is increased. Revolution is decreased from nearly 1000 rpm when applied no load to 695 rpm when it is applied 9,4 Nm torque or nearly under 1 kg load.

On the second graph in Figure 5.9 fuel cell stack current is increased when electrical motor torque increased. When electrical motor is loaded more current is supplied by the fuel cell. And again potential of electrical motor is decreased with increasing of torque in Figure 5.10. It is anticipatory result, because current and voltage has inverse proportion with each other and graph 5.11 shows this result us easily.

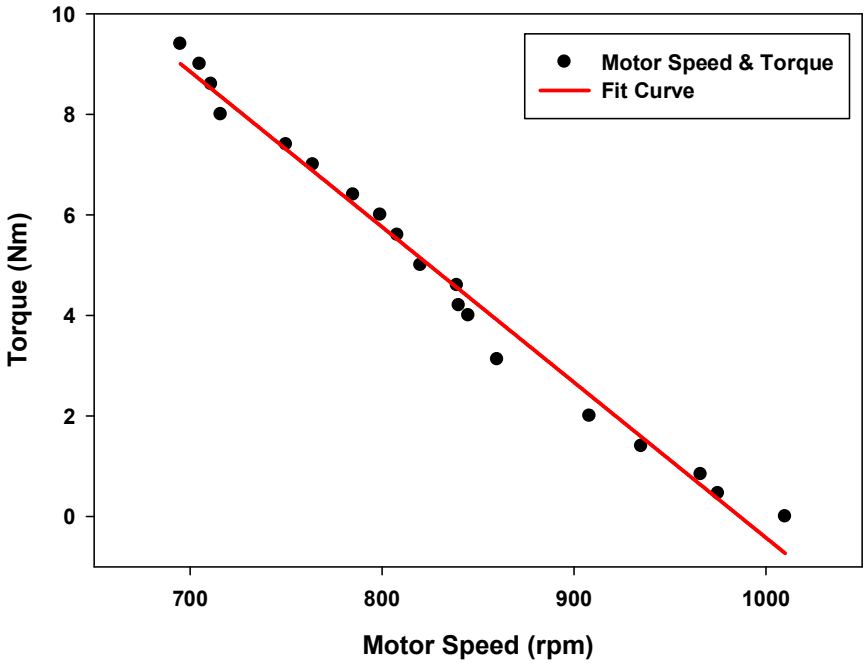


Figure 5.8. Torque variation according to motor speed

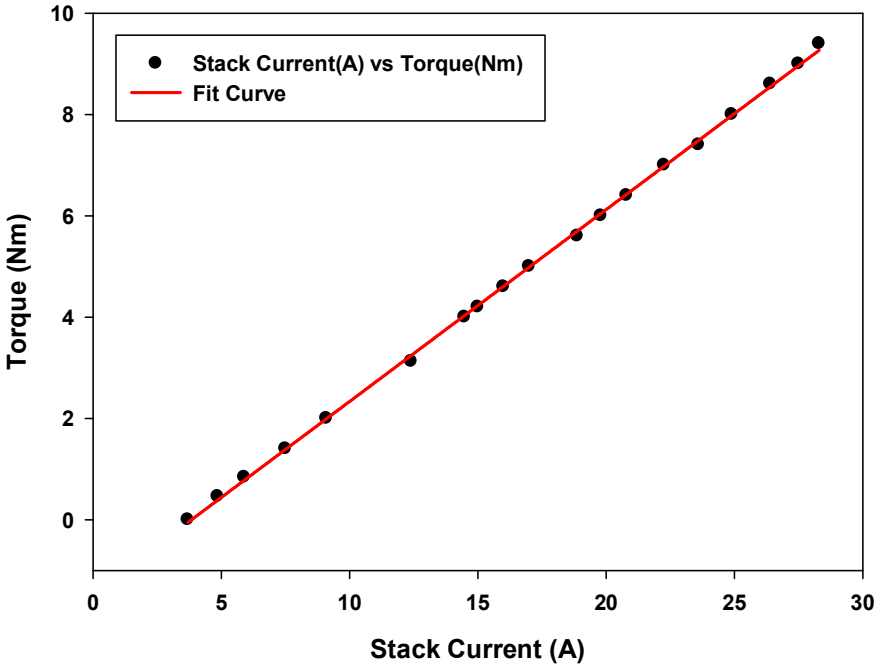


Figure 5.9. Stack current according to torque variation

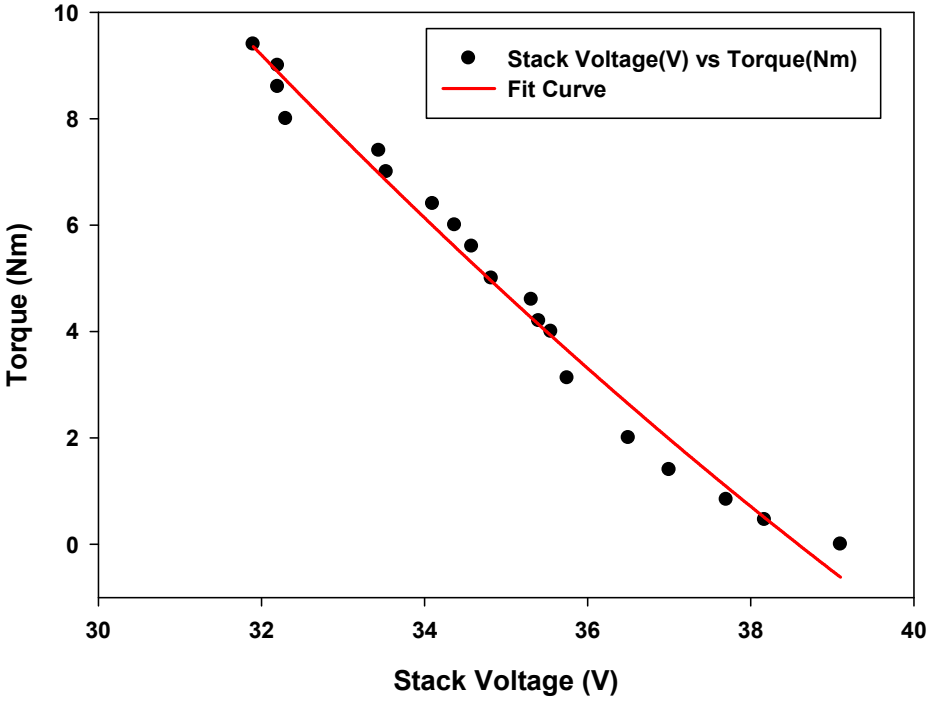


Figure 5.10. Stack voltage according to torque variation

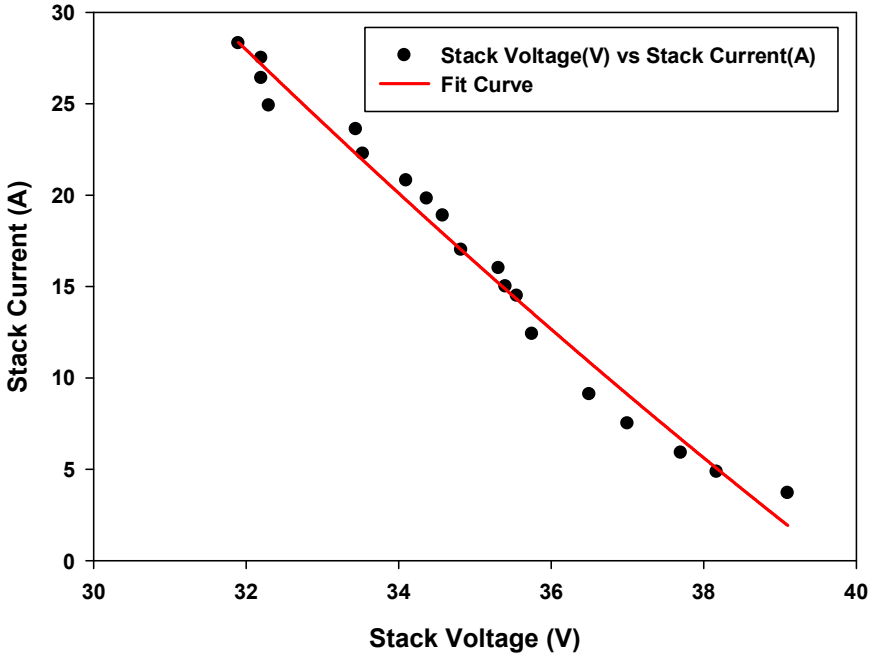


Figure 5.11. Change in stack voltage and current

It can be mentioned about power characteristic of electrical motor when using of formula;

$$P = V \times A$$

And also vehicle speed can be calculated with using wheel diameter and below formula;

$$\upsilon = 2 \times \Pi \times r_w \times \omega$$

When above formulas are used and necessary units are converted, the table below can be obtained.

Table 5.4. Calculated power and speed of urban vehicle

Rev.(rpm)	Torque(Nm)	Current(A)	Stack Voltage(V)	Power (W)	Speed(Km/h)
1010	0	3,70	39,10	144,67	83,77
975	0,46	4,86	38,17	185,51	80,86
966	0,84	5,9	37,7	222,43	80,12
935	1,4	7,5	37	277,50	77,55
908	2	9,1	36,5	332,15	75,31
860	3,125	12,4	35,75	443,30	71,33
845	4	14,48	35,55	514,76	70,08
840	4,2	15	35,4	531,00	69,67
839	4,6	16	35,31	564,96	69,59
820	5	17	34,82	591,94	68,01
808	5,6	18,88	34,58	652,87	67,01
799	6	19,8	34,37	680,53	66,27
785	6,4	20,8	34,1	709,28	65,11
764	7	22,26	33,53	746,38	63,36
750	7,4	23,6	33,44	789,18	62,20
716	8	24,9	32,3	804,27	59,38
711	8,6	26,4	32,2	850,08	58,97
705	9	27,5	32,2	885,50	58,47
695	9,4	28,3	31,9	902,77	57,64

It is seen that above table the maximum power of electrical motor is closed during the experiments. If it is drawn on a graph, one can see the linear increase in power with torque in Figure 5.12.

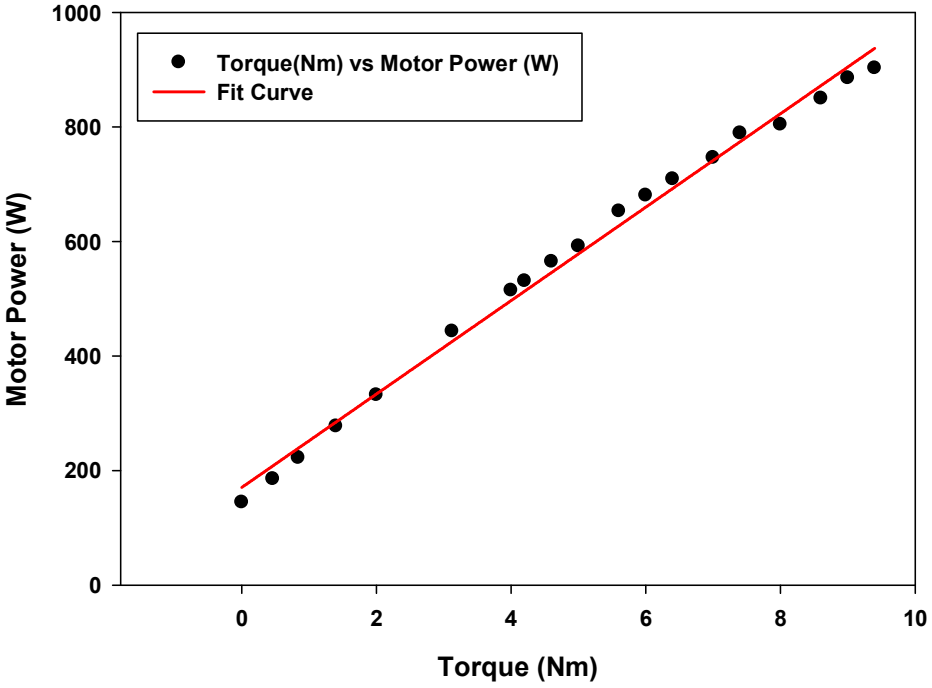


Figure 5.12. Change in power during electrical motor loaded.

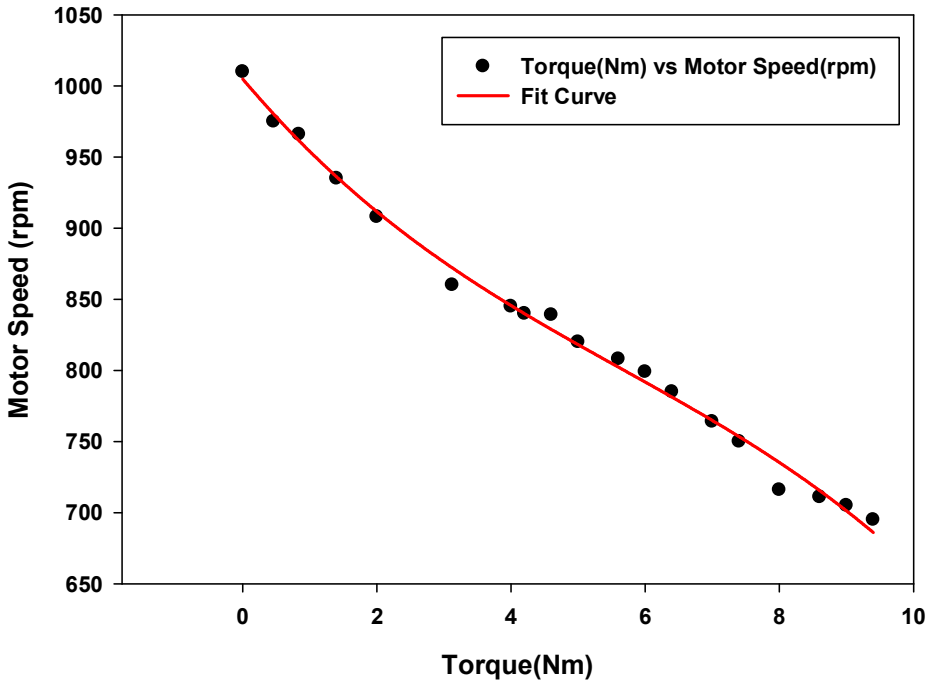


Figure 5.13. Fit a cubic curve for torque-speed graph.

Test results show that there is a problem to use of 1000W electrical motor on the vehicle if it is look for the torque value in Table 5.4. Because maximum power of electrical motor is really reached when only 1kg of load is applied to system. To see the maximum torque would be supplied by the motor, a cubic curve is drawn in Figure 5.12 between torque and motor speed parameters and this curve equation is:

$$y = -0{,}3127x^3 + 5{,}2842x^2 - 55{,}968x + 1005$$

"y" is used for the motor speed and "x" is used for torque above equation. If this equation is used to calculate the value, the maximum torque will be nearly 17,3 Nm supplied by the 1000 W electrical motor and this torque value is not good enough to move the vehicle from constant position.

5.4. Emission of Fuel Cell Power Module

During the experiments no harmful gasses are seen. This is again an expected result according to type and the reaction of the fuel. After the chemical reactions of the hydrogen and the oxygen water is formed. Water can not be in liquid form; according to temperature, produced water can be in gasified form. These emission conditions were also realized participants' vehicle in Tübitak and Shell competitions.

6. CONCLUSION

Fuel cells offer a technology which can dramatically reduce air pollutant emissions or both stationary and mobile applications. Since fuel cells directly convert chemical energy into electrical energy, they can also attain higher efficiencies than standard heat engines. Cost is still a major issue with regard to marketing fuel cells, as they are composed of expensive materials. Recent break-through has dramatically reduced the amount of platinum than fuel cells will require, however. Improving the energy density of fuel cells will be another important challenge for fuel cell researchers over the next decade. Given the potential of fuel cells for high efficiencies and zero emissions, fuel cell vehicles could meet transportation needs into the twenty-first century and beyond. Our current transportation system is responsible for a significant portion of urban air pollution, and our almost exclusive dependence on oil for transportation fuel requires large and increasing expenditures for foreign oil. Alternative fuels used in conventional engines can help alleviate these problems to some extent, but significant emissions of criteria pollutants and greenhouse gases will remain. What is needed are vehicles that are nonpolluting and that use renewable fuel; hydrogen fuel cell vehicles fill the bill.

Fuel cell systems have several advantages:

Fuel cells are clean devices that no pollution or greenhouse gases are produced by fuel cell running on hydrogen fuel. Fuel cell vehicles are zero-emission vehicles whose only output is water vapor.

Hydrogen systems have an enviable safety record; in many cases, hydrogen is safer than the fossil fuel it replaces. In addition to dissipating quickly into the upper atmosphere if it leaks. Hydrogen is completely non-toxic, unlike fossil fuels.

Though fuel cells not been in use long enough to give a definite lifespan so, fuel cells may have significantly longer life times than machines they replace.

Fuel cells may be any size small enough to fit in a suitcase or large enough to generate power for an entire community. Power systems to be upgraded as demand increases, reducing up front capital costs is allowed by this modularity.

Chemical energy is converted directly to electricity by the fuel cells. Less energy is lost with using fuel cells to waste heat and have efficiencies two or three times higher than internal-combustion engines.

Although some noise may be produced by the various vehicle auxiliary systems such as water pumps or air compressors, the fuel cell itself produces none. Overall, the vehicle is significantly quieter than conventional vehicles.

There are also disadvantages beside the advantages of fuel cell and fuel cell vehicles such as cost and optimizing the vehicle design. Fuel cells are still more expensive than conventional vehicle power sources. More work must be done to optimize the integration of the fuel cell and its auxiliary systems (water pumps, air compressors, reformers, electronic controls) into the vehicle.

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