Design and investigation of a fuel cell car prototype

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Abstract: A hydrogen vehicle is a vehicle that uses hydrogen as its on-board fuel for motive power. One of the ways to achieve it is by converting the chemical energy from the reaction between hydrogen and a fuel cell into electrical energy. The purpose of this work is to design and develop a fuel cell car model by implementing polymer electrolyte membrane (PEM) types of fuel cell as the source of power to propel the prototype car. This fuel cell has the capability to propel the electric motor by performing chemical reaction and converting chemical energy stored in hydrogen gas into useful electrical energy. In the developed fuel cell car prototype, the PEM fuel cell alone is used as the power source for the electric motor without the aid of any other power source such as a battery associated with it. Experimental investigations were carried out to investigate the characteristics of the fuel cell used and the performance of the fuel cell car prototype. The power it develops, voltage, current and speed it produces under different load conditions are among the parameters that were investigated.

Keywords: fuel cell; prototype; polymer electrolyte membrane; PEM; performance; hydrogen vehicle.

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1 Introduction

The automotive industry was the most rapidly developed industry in the last century. The latest technology in this industry is coming up and being introduced to catch up this faster growth so that the problems arising from its efficiency, cost, environmental and other matters related to automotive can be optimised. There are two major problems faced by current vehicles which are powered by the internal combustion engine which has as its energy source fossil fuels. The first problem is the limited amount of main source (petrol fuel) and sooner or later it will be depleted. According to the estimation by petroleum companies, the production of the most conveniently usable fossil fuels, petroleum and natural gas will peak sometime between 2015 and 2020 and then begin to decrease. This means that there will be reduced production of fluid fuels beginning around 2015 (Veziroglu, 2005). The second problem is the serious environmental damage caused by these fossil fuels such as global warming, climate change, acid rain, smog, odours and respiratory and other health hazards. Vehicles powered by fuel cell systems are one of the alternatives that can solve these two major problems. The objectives of this work are to design and develop a fuel cell car prototype which will be powered by the polymer electrolyte membrane (PEM) fuel cell and to investigate the performance of the car model powered by the PEM fuel cell.

2 Fuel cell

A fuel cell is in some aspects similar to a battery. It has electrolyte and negative and positive electrodes and it generates DC electricity through electrochemical reactions. However, unlike battery, a fuel cell requires a constant supply of fuel and oxidant. Also, unlike in battery the electrodes in fuel cell do not undergo chemical changes. Batteries generate electricity by the electrochemical reaction that involves the materials that are already in batteries. Because of this, battery may be discharged which happens when the materials that participate in the electrochemical reaction are depleted. Some batteries are rechargeable, which means that electrochemical reactions may be reversed when external electricity is applied – a process of recharging the battery. A fuel cell cannot be discharged as long as the reactants – fuel and oxidant – are supplied.

Advantages of fuel cell system include (O'Hayre et al., 2006):

- fuel cells have the potential for high operating efficiency that is not a strong function of system size
- highly scalable design
- numerous type of potential fuel source are available
- they produce zero or near-zero greenhouse emission.

Many types of fuel cell are currently being researched to make it commercialised. A few of them are polymer electrolyte membrane fuel cells (PEMFCs), alkaline fuel cells (AFCs), phosphoric acid fuel cells (PAFCs), solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs).

2.1 Fuel cells selection for automotive application

Thorough study of different fuel cells characteristics helped us to select the correct type of fuel cell. PEMFC shows the best characteristic to use in vehicle application (Thring, 2004). Instead of its pressure and temperature compatibility for vehicle usage, it also has other criteria that make it the best selection. The most important points or criteria that make PEMFC become the chosen fuel cell to be used in the prototype are (Barbir, 2005):

a *High chemical stability:* chemical stability is important in PEM because of the key role that the membrane plays. Chemical stack can take the form of peroxy radical, hydrogen ions, oxygen and even contaminants in the gas stream. If the polymer degrades, this will reduce the energy output of the fuel cell. If the membrane breaks, there will then be a path for the oxidant and the fuel to react directly.

b *High proton conductivity:* in the fuel cell the hydrogen ions must be able to easily reach the cathode and complete the electrochemical circuit. Further, resistance (Ohmic) polarisation is a major contribution to voltage loss in the typical range of operating current densities. Most of this resistance is due to resistance to ion flow in the membrane. Acceptable proton conductivities are above 10^{-2} S/cm in the membranes currently used, the conductivity of a membrane is a function of the water content as well as the ion exchange capacity.

c *Low cost:* apart from bi-polar plate material costs, Nafion^{TM} cost reduction is a major requirement of PEMFC market penetration. It has been estimated that Nafion^{TM} will make up as much as 18% of the total cost of the cell. Thus the lower cost material is desirable.

d *Thermal stability:* it is referred to have a polymer membrane that is stable at higher temperature. If the polymer does not degrade at higher temperatures it will then become possible to operate the fuel cell at higher temperatures. Currently PEMFCs operate at 80°C. At higher temperatures Nafion^{TM} becomes dehydrated and conductivity drops. A higher temperature would aid the kinetics of the cathode reaction (which are current limiting), as well as reduce carbon monoxide (CO) poisoning of the anode catalyst.

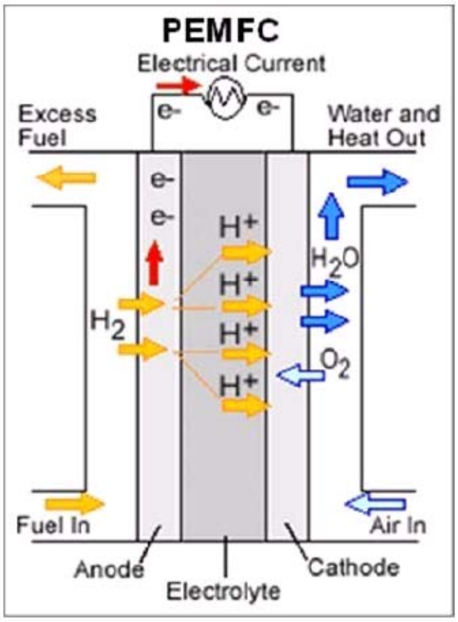
e *Durability:* apart from chemical and thermal stability, the membrane must be durable. A very strong material can allow for thinner membranes to be developed, which improve ion conductivity. More durable materials will also last longer. A criterion presented by reference sets the durability at ten years for the PEM. A separate durability criterion by the USDOE looks for durability of 5,000 h for 50 kW system used in a car.

f *Low expansion:* with water uptake there is an inevitable expansion of the membrane. Too much expansion of the pressure on the bi-polar plates (which may consequently crack) and the plate may also buckle off which is detrimental for the fuel cell.

2.2 Fuel cell basic operation

Figure 1 shows the basic operation of a fuel cell. Hydrogen is channeled through field flow plates to the anode on one side of the fuel cell, while oxxygen on the other side of the cell. At the anode, a platinum catalyst causes the hydrogen to split into positive hydrogen ions (protons) and negatively charged (electrons). The PEM allows only positively charged ions to pass through it to the cathode. The negatively charged electrons must travel along external circuit (load) to the cathode, creating an electrical current. At the cathode, the electrons and positively charged hydrogen ions combine with oxygen to form water which flows out of the cell (Li, 2006).

Figure 1 Fuel cell basic operation (see online version for colours)



There are four basic components in a single cell of PEMFC and they are:

- *Anode*. The anode, the negative side of the fuel cell has several jobs. It conducts the electrons that are freed from the hydrogen molecules so they can be used in an external circuit. Channels etched into the anode disperse the hydrogen gas equally over the surface of the catalyst.
- *Cathode*. The cathode, the positive side of the fuel cell also contains channels that distribute the oxygen to the surface of the catalyst. It conducts the electrons back from the external circuit to the catalyst where they can recombine with the hydrogen ions and oxygen to form water.
- *Polymer electrolyte membrane*. The PEM, a specially treated material that looks something like ordinary kitchen plastic wrap, only conduct positively charged ions and blocks the electrons. The PEM is the key to the fuel cell technology. It must permit only the necessary ions to pass between the anode and cathode. Other substances passing through the electrolyte would disrupt the chemical reaction.
- *Catalyst*. All electrochemical reactions in a fuel cell consist of two separate reactions: an oxidation half-reaction at the anode and a reduction half-reaction at the cathode. Normally, the two half-reactions would occur very slowly at the low operating temperature of the PEM fuel cell. Each of the electrodes is coated on one side with a catalyst layer that speeds up the reaction of oxygen and hydrogen. It is usually made of platinum powder, very thinly coated onto carbon paper or cloth. The catalyst is rough and porous so that the maximum surface area of the platinum can be exposed to the hydrogen or oxygen.

The voltage resulting from the reaction of the fuel and oxygen varies with the load and ranges from 0.8 V at no load to about 0.4 V for full load. Owing to their low output voltage it becomes necessary to stack many cells in series to realise a practical system. For low power applications, the number of cells that needs to be connected in series is small but as power increases the number of cells that are required in the stack increases rapidly. For example, 100 V fuel cell stack consists of 250 cells in series and to produce 300 V at full load requires 750 cells stacked in series.

2.3 Stack design

There are many parameters that must be considered when designing a fuel cell. A very important design consideration is the overall stack design and configuration. The most commonly used stack configuration is the bipolar configuration (Collen, 2007). In designing a fuel cell stack, following parameters should be considered:

1. size
2. volume
3. desired power output
4. preferred stack voltage
5. desired efficiency.

Stack power output, $W = V_{st} I$

where V_{st} = stack voltage potential (volt) and I = stack current (ampere)

Stack voltage potential, V_{st} = sum of individual cell voltage = (average individual cell voltage) × (number of cells in stack)

$$V_{st} = \sum_{i=0}^{N\,cell} V_i = \overline{V}_{cell} N_{cell}$$

Current, $I = iA_{cell}$:

where i = current density (A/cm^2) and A_{cell}: = cell area (cm^2).

The cell potential and the current density are related by the polarization curve:

$$V_{cell} = f(i)$$

Approximate fuel cell stack efficiency,

$$= \frac{V_{cell}}{1.482}$$

The principle of designing fuel cell stack is:

a Small number of cells with large active area would result in high current, low voltage combination and large number of cells with very small active area would be difficult to align and assemble.

b Larger active area is more difficult to achieve uniform condition. More typically, active area is between 50 and 300 cm^2 depending on application.

c Maximum number of cells in stack is limited by compression forces, structural rigidity and pressure drop through long manifolds.

3 Design and model development

In this project we have designed and developed a fuel cell car prototype by implementing an PEMFC type of fuel cell as the source of propulsion power. It has the capability to propel the electric motor by performing chemical reaction and converting chemical energy stored in hydrogen gas into useful electrical energy. In this fuel cell car prototype, the PEMFC fuel cell alone is used as the power source to run the electric motor without any other power source.

3.1 Car prototype selection

The first step in developing the product was determining the type of the car. In our case, we have chosen a remote control (RC) car model as our product. Its movement can be controlled freely. There are different components in a RC car. The components are: chassis, suspension, drive train, tyres, engine/motor and bearings.

3.2 Electric motor selection

This is an important part in developing the fuel cell car. The electric motor acts as an engine of the car substituting the internal combustion engine. There are several motors available in the market. To select the motor best suited for a RC car, it is important to know the size of the model and amount of cells planned to be used. Size of the RC vehicle will determine the size of motor needed to push the weight. For motors this is often best represented by the weight of the motor itself. Cell count will determine the winding or more specifically the KV of motor needed. It's also necessary to know the number of teeth for the gearing in the transmission. This will help to determine the exact motor cell count. In this project, the RS-540SH-6527 motor of capacity range 7–9 volts was chosen because it can propel the car with high speed and also can carry heavy load up to 4 kg.

3.3 Fuel cell stack selection

We selected the H-30 FCS-B30 PEM fuel cell to power the car model for its earlier mentioned advantages. The range of voltage it produces must be equal to or lower than that of the electric motor chosen to make the motor work in optimum performance and also to avoid overheating. If the voltage produced by fuel cell is lower than that needed by the motor, the motor will run slowly and not uniformly. This PEM fuel cell (Figure 2) can only stand for 0.5 bar. But hydrogen tank storage supplies the hydrogen at a pressure up to 10 bars. So to reduce this high pressure from hydrogen storage tank, a pressure regulator is used (Figure 2).

Figure 2 H-30 FCS-B30 PEM fuel cell and pressure regulator (see online version for colours)

3.4 Hydrogen storage tank selection

In the development of fuel cell vehicles, hydrogen storage is the biggest remaining research problem according to the Office of Science and Technology Policy, Executive Office of the US President (January 2003). Current hydrogen storage systems are inadequate to meet the needs of consumers in a fuel cell vehicle. Existing and proposed technologies for hydrogen storage include:

1 physical storage: pressurised tanks for gaseous hydrogen and pressurised cryo-tanks for liquid hydrogen

2 reversible hydrogen uptake in various metal-based compounds including hydrides, nitrides and imides

3 chemical storage in irreversible hydrogen carriers such as methanol

4 cryo-adsorption with activated carbon as the most common adsorbent

5 advanced carbon materials absorption including carbon nanotubes, alkali-doped carbon nanotubes and graphite nanofibres.

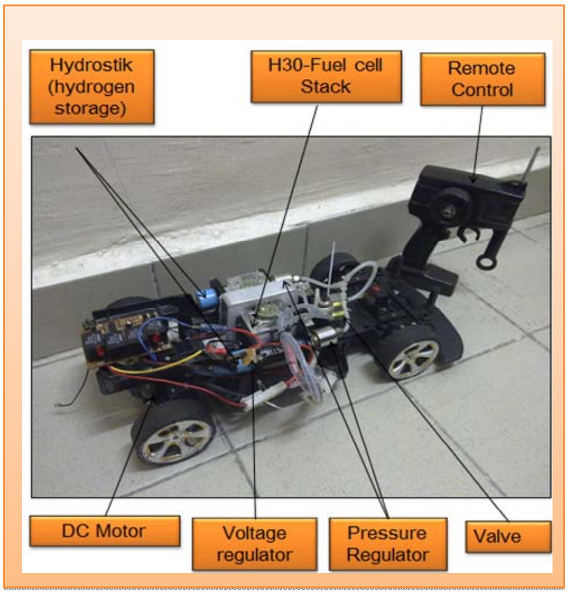
In this project, a metal hydride hydrogen storage tank is used which is manufactured by Horizon company and called Hydrostik^{TM} (Figure 3). This tank is a container loaded with hydrogen storage alloy powder, heat exchange parts and gas transport components. The container body materials are generally aluminium alloy or stainless steel. Hydrogen being stored at low pressure in the vessel, they provide a safe and reliable energy storage particularly for portable applications, in-house and in-board storage. The weight is also low just 90g and the tank can store about 10 L of compressed hydrogen gas.

Figure 3 Hydrostik^{tm} (see online version for colours)

4 Overall fuel cell car prototype assembly

Figure 4 shows the model assembly based on material selection as mentioned.

Figure 4 Final product, PEM fuel cell car prototype (see online version for colours)



5 Result and discussion

5.1 PEMFC performance experiment

Experiment was conducted to determine the performance of H30 PEMFC. We tried to operate until it reached its maximum output before putting it into the fuel cell car prototype. Besides that, we have measured the flowrate of hydrogen to determine its consumption. We used programmable electronic load (e-Load) machine model ZVL300-150-40L to vary the load to the H30 PEMFC.

Result: $P = VI$

The power, P, in the above equation is a time-varying quantity and is called the instantaneous power. Thus the power absorbed or supplied by an element is the product of the voltage across element and the current through it. If the power has a + sign, power is being delivered to be absorbed by the element.

Ohm's law states that the voltage V across a resistor to be the resistance, R. (the resistance is a material property which can change if the internal or external conditions of the element are altered, e.g., if there are changes in the temperature). Thus, $V = IR$..

For the first experiment, we set the current as a variable. We changed the current from 1 A to 1.9 A. From the result, we got the highest power of 13.448 W. For the second experiment, we set the voltage as a variable. We changed the voltage from 9.4 V to 7.5 V. The PEMFC can supply until 9.4 V even though the theoretical value is 8.4 V. The graph of voltage versus current shows the voltage will drop according to the current increase (Figure 5). This current shows the load applied to the PEMFC. The capability of the PEMFC will drop if the load applied to it is increased (Figure 6).

Figure 5 Voltage vs current (see online version for colours)

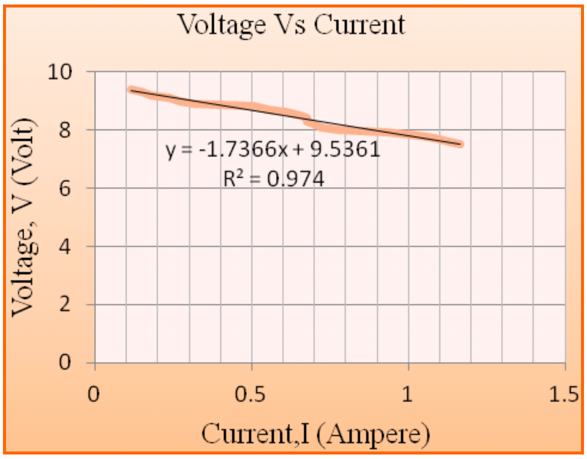


Figure 6 Power vs current (see online version for colours)

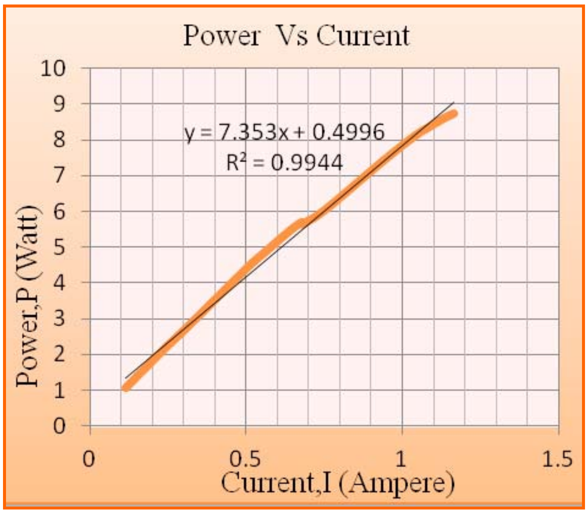


Figure 7 shows the assembly of the fuel cell flow rate measurement system. The system procedure is to connect the flow meter to the hydrogen supply system. The output of flow meter tube is connected to the fuel cell. Once the fuel cell is running, readings are obtained from the flow meter every one minute. The result was compared with the supplier specification. Figures 8 and 9 show that the flow rate of hydrogen gas does not change rapidly with the variation of voltage and time. In real world application, hydrogen still cannot be directly used as power source to the car's engine. It is difficult to control the volume of hydrogen flow under different car operating conditions: for example while you speed up or cruising. The proper control system is needed before we can implement the system which used hydrogen to propel the car's engine directly.

Figure 7 Fuel cell flow rate measurement system assembly (see online version for colours)

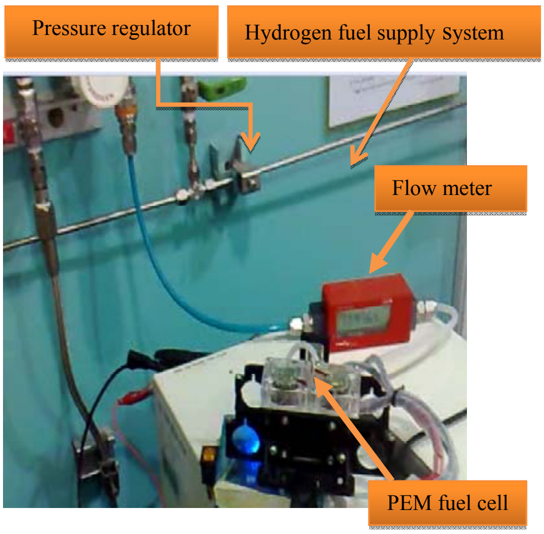


Figure 8 H_2 flow rate vs time (see online version for colours)

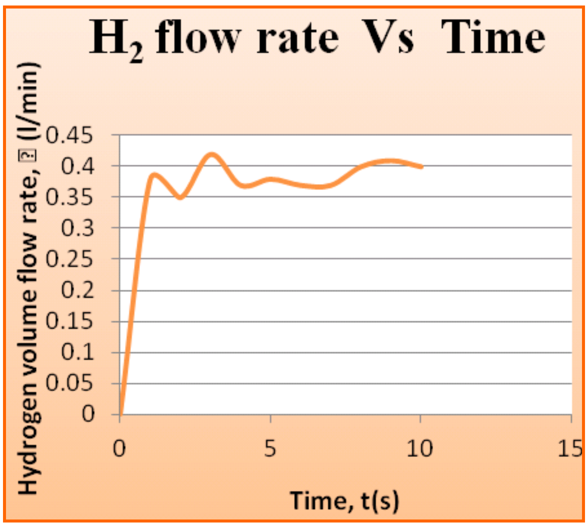
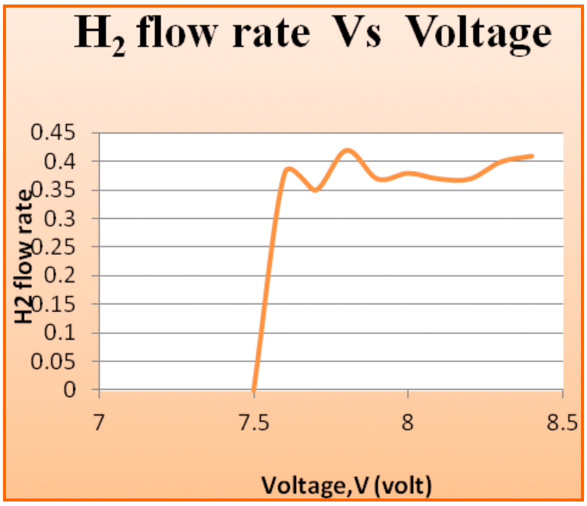


Figure 9 H_2 flow rate vs voltage (see online version for colours)



6 Conclusions and recommendations

6.1 Conclusions

Hydrogen-powered fuel cell vehicles could play a central role in future transportation systems. They produce only electricity, heat and water at the point of use. There has been great interest in hydrogen as a primary energy carrier, displacing petroleum-based fuels.

It is hoped that fuel cell vehicle will become the conventional vehicle in the future. It is because of their emission that will cause no harm to the environment. Nowdays, it is one of the most expensive cars, but if it is produced on a mass scale, the cost will go down. The government also should play an important role in the process of developing this zero emission vehicle.

Present work shows the development of a prototype car powered by fuel cell. It shows the possibility to replace the conventional internal combustion engine with fuel cell. It is not impossible to realise a fuel cell car in the real world. The performance of the fuel cell car prototype is a little bit interesting, even though it is not producing high performance but it produces zero emissions. Further research needs to be carried out to increase its performance.

6.2 Recommendations

In this project, the developed fuel cell car prototype used the current produced by fuel cell directly to the motor. The current supplied to the motor was not constant owing to the variation in the flow rate of hydrogen. It can cause harmful effect to the fuel cell and the fuel cell car prototype. One of the recommendations is to make the car a hybrid. The current produced by the fuel cell would be supplied to the batteries and the batteries would supply to the motor when necessary. It would be safer than the present design.

References

Barbir, F. (2005) *PEM Fuel Cells: Theory and Practice*, Academic Press, Amsterdam, The Netherlands.

Collen, S.S. (2007) *Designing and Building Fuel Cells*, 1st ed., McGraw Hill, New York.

Li, X. (2006) *Principal of Fuel Cells*, Taylor and Francis Group, New York.

O'Hayre, R., Cha, S., Colella, W. and Prinz, F.B. (2006) *Fuel Cell Fundamentals*, 6th ed., John Wiley and Sons, New Jersey, USA.

Thring, R.H. (2004) *Fuel Cells for Automotive Applications*, Professional Engineering Pub., Bury St Edmunds, UK.

Veziroglu, T.N. (2005) 'Ecohealth problems and climate change ii: permanent solution to environmental problems: hydrogen energy system', *IFSSH World Congress 'Health Challenges of the Third Millenium', Book of Invited Background Papers*, 21–27 August 2005, Istanbul, pp.315–335.