Fuel Cell Electric Vehicles as Alternative to Battery Powered Electric Vehicles

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***Abstract-** There is an increase in demand of converting the automobile industry to electro automobile industry due to various reasons like increase in environmental pollution and the raise in cost of the fuels for internal combustion engines. With the conversion into electrical vehicles various problems arises some of them were high charging time for the battery in battery powered electric vehicles, limitations to the range of vehicle per charge etc., To overcome these drawbacks, the fuel cell electric vehicle which is powered by the electrical power produced from the fuel cell. In this fuel cell electric vehicle there is no limitation for the range of electric vehicle. It is very high just like conventional internal combustion engines and there is no need to charge the vehicle since power is directly produced in the vehicle which is similar to ICE vehicles. This paper deals with the introduction to fuel cells, types of fuel cells and fuels used in them and it also gives clear calculation of energy from the fuel cell so that it meets the energy demand of electric vehicle by calculating the energy requires by the electric vehicle. Further, it states the main pros of fuel cell electric vehicles when compared with the battery packed electric vehicles*

***Indexed Terms-** Fuel cell electric vehicles, Conventional ICE vehicles, Battery powered vehicles, Environmental pollution, Range of electric vehicles*

I. INTRODUCTION

A fuel cell is an electrochemical cell that directly converts the chemical energy from the cells like H_2, methanol, methane biogas, carbon etc., into the electrical energy with the heat as the bi-product.

The efficiency of fuel cell in terms of electricity is given as ratio of electrical power generated by fuel cell to the chemical energy required by the fuel cell.

$$\eta_{fc} = p_{chem/}\ p_{elect}$$

Let us take the e.g. of hydrogen fuel for clear explanation. The base equation for a fuel cell is given by

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

With LHV = -483.84 KJ/MOL

HHV= -570.9KJ

LHV = HHV – (W * 9 latent heat of water vapour)

At anode: $2H_2 \rightarrow 4H^+ + 4e^-$

At cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

In the fuel cell, the anode is supplied with the fuel (H_2) and in the cathode (O_2) or air given, hence with the help of catalyst i.e., platinum the above reactions occur yielding $4e^-$, these are taken out from fuel cell through an external circuit and fed to battery (or) electric motor

Fuel cell history: The invention of fuel cell concept dates back to the 18th century.

- In 1830's, William grove found out that generation of electricity can be done by hydrolysis in constant experiments later.
- In 1889, two scientists Charles long court and ehu Xinhua mode, both created the term fuel cell through research. The first fuel cell based on air and gas.
- In 1932, francis bacon developed the world's first fuel cell equipment, which is now used as hydrogen fuel cell.
- In 1952, NASA conducted research on fuel cells after scientists and they developed fuel technology projects successfully and participated in several US space missions. In the US space program the fuel cell technology has played an irreplaceable role.

- Over the past decade, the vast majority of world's largest car manufacture have been involved in the research and manufacture of new fuel cell technology which has made a new source of power for electrical vehicle.

Fuel cell construction and working:
The fuel cell construction is given below. Here it is PEMFC (polymer electrical membrane fuel cell).

At anode, the fuel hydrogen (H_2) is pumped in and it is passed through the gas diffusion layer and at G.D.L, the catalyst (here pt) is present which activates the chemical reaction thus liberates the free electrons ($4e^-$) and the remaining ($4H^+$) passes through the proton exchange membrane which only allows the protons at cathode, the oxidant O_2 or air is pumped in, it passes through the gas diffusion layer and reacts with the $4H^+$ products of reaction at anode thus yielding stream ($2H_2O$) and heat energy (HHV & LHV).

The electrons are liberated and used at anode and cathode respectively. It is externally connected to an electric load thus producing the electrical power.

Functions of individual parts in FC:

- Anode & Cathode: also called as bipolar plates made up of graphites and used to called h_2 at anode and O_2 at cathode.
- Gas diffusion layer: These are made up of torry paper, porous carbon cloth with hydrophobic coating, gas diffusion and it is conductive material.

  In the gas diffusion layer where it consists of catalyst, the anode reaction happens and resulting free electrons are generated, since it is a conductive element the free electrons travel through an external circuit and protons (H^+) travels through proton exchange membrane.
- Membrane electrode with catalyst: It is also attached to G.D.L, it consists of catalyst platinum in the size of (nm) on carbon particles (µm size).
- Proton exchange membrane: The main function of the PEM is to only allow the positively charged particles (here only H^+) and the remaining electrons are blocked in proton exchange membrane.

It is made by nafion 115, its thickness is 100 µm with water content 34% and conductivity is around 0.059s/cm

Fuel cell types:
Depending upon the type of electrolyte used in fuel cell, they are classified into 5 categories. They are shown below. Depending on the type, the operating temperature, materials used are different.

- Polymer electrolyte membrane (PEMFC).
- Phosphoric acid (PAFC).
- Molten carbonate (MCFC).
- Solid oxide (SOFC).
- Direct carbon (DCFC).

The fuel cells described above are formed into stacks in desired series and parallel order to get the required power output.

The cooling of the fuel cell stack formed is the main problem as more heat is developed due to more number of fuel cells together and the other main concerning issue in the fuel cell electric vehicle is the storage of hydrogen since it is the simplest and lightest element (it is lighter than helium, Hydrogen is 3.2 times less energy dense than natural gas and 2700 times less energy than gasoline).

The two main established technology of storing the hydrogen are

- Compressed hydrogen: It is a storage form where by hydrogen gas is kept under pressure to increase the storage density. Compressed hydrogen in hydrogen tanks at 350 bar and 700 bars is used in hydrogen tank as a storage in electrical vehicle.
- Liquefied hydrogen: It is a storage form in which hydrogen gas is liquefied by reducing its temperature to -253®c just like the liquefied natural gas (LNG) to -162®c.

  By this liquification by reducing the temperature results in potential efficiency loss of 12.79% i.e., (4.26kwb/kg out of 33.3kwb/kg).

II. ENERGY CONSUMPTION CALCULATION FOR ELECTRIC VEHICLE

The total energy consumed by an E- vehicle is the sum of the energy required to power the power train starting from the battery to wheels and the energy required to power up the auxiliary devices such as head lamps, Air conditioners, Sensors etc.., in the vehicle. So, this can be mathematically explained as follows

Etotal = E powertrain +E auxiliary

Firstly, we shall calculate the energy required by the power train. This can be calculated as follows

Ept = ∫ Ppt dt

Ppt = Fpt * vehicle speed

Fpt = Fi + Frs + Ff + Fa

Where

Ept = Energy consumed by the power train

Ppt = Power required by the vehicle

Fpt = Total force required by the vehicle

Fi = Inertial force of vehicle

Frs = Road slope force

Ff = Frictional Force of the vehicle

Fa = Aerodynamic drag force

Mathematically each of the force can be explained as the following

1. inertial force:

The inertial force of the vehicle is given by the following formulae

Fi = Mv * Av

Where

Mv = Mass of the vehicle

Av = Acceleration of the vehicle

2. Road slope force:

The road slope force is given by the following formulae

Frs = Mv * g * sin (α)

Where

g = Gravitational force constant

α = Road slope angle

3. Frictional force:

The frictional force of the road is given by the following formulae

Ff = Mv * g * Rr * cos (α)

Where

Rr = Coefficient of the road rolling resistance

α = Road slope angle

4. Aerodynamic force:

The aerodynamic drag force of the vehicle is given by the following formulae

Fa = ½ * Da * C * Af* V^2

Where

Da = Air density

C = Air drag coefficient

Af = Frontal area of the vehicle

V = Vehicle speed

Hence the total force required by the vehicle is given by

Fpt = Fi + Frs + Ff + Fa

And the power for the power train is given by

Ppt = Fpt * vehicle speed

Thus the energy consumed by the power train of E-vehicle is given by

Ept = ∫ Ppt dt

For example: consider the following terms to calculate the approximate energy required for an E-vehicle

Let ,Mass of the vehicle Mv= 1780 kg, Acceleration Av=1.66 m/sec^2 , slope of the road α= 0 (plane road),Rolling resistance = 0.00231 , Air density at 30degrees is 1.164 , air drag co efficient of air c = 0.14 , the vehicle average speed V = 30kmph , vehicle frontal area Af = 3.34 m^2

By assuming the above values the energy consumed by E vehicle is calculated as 227 Wh/km and thus, the energy consumed by the auxillary devices in the vehicle can be assumed as 0.01 percent of total energy consumed .Hence the total energy consumed by e vehicle can be 229.27 Wh/km.

III. ENERGY CALCULATION OF FUEL CELL E- VEHICLE

For easy calculation of energy, let us assume the fuel cell to be PEMFC (Polymer Electrolyte Membrane Fuel Cell). The basic equation of PEMFC is given by

$$2H_2 + O_2 \rightarrow 2H_2O$$, LHV = -483.84 KJ/mol

HHV = -570.9 KJ/mol

At anode: $2H_2 \rightarrow 4H^+ + 4e^-$

At cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

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

$\Delta G = \Delta H - T\Delta S$, ΔG is Gibbs free energy, ΔH is the Enthalpy, ΔS is the Entropy and their values are given by ΔG = -237.13, ΔH = -237.83, ΔS = -48.7 kJ/mol

The efficiency of any fuel cell can be calculated by ŋ = $\Delta G/\Delta H$ = -237.13 / 285.83 = 0.8296 = 83 % at 25°C and 1 atm pressure

The EMF of cell (PEMFC) can be calculated by $2H_2 + O_2 \rightarrow 2H_2O$, EMF = $-\Delta G/ ZF$ where Z is the number of protons or positively charged particles and F is the faraday's constant

$$\Delta G = \Sigma (\Delta G_{products} - \Delta G_{reactants})$$
$$= \Sigma (2* (-237.13) - (2*0))$$
$$= -474.26 \text{ KJ/mol}$$

EMF = $-\Delta G$ / ZF = -474.26 / 4* 9.6485 * 10^4

=- 1.23 V at room temperature and pressure .

However, the calculated voltage of the fuel cell is the ideal voltage of the cell and it is different in practical that will be approximately 0.7 V

The power generated by single fuel cell can be calculated by

$$P_{ele} = P_{chem} - P_{ther}$$
$$P_{ele} = V_{out} * I_{out}$$
$$V_{out} = V_o - V_{AP} - R_i I_{out}$$
$$P_{ele} = (V_o - V_{AP} - R_i I_{out})*I_{out}$$

Here, P_{ele} is the electrical power generated by the fuel cell, P_{chem} is the chemical power in the fuel and P_{ther} is the thermal energy generated by the fuel cell.

The power produced by the fuel cell depends on several factors , they are the fuel cell type, size of the cell, the temperature at which it operates. A single cell in a stack barely produces the power of voltage 1V or less , this power is barely enough for the smallest applications. To increase the voltage thus increasing the power produced , the individual fuel cells are connected in series to form a stack. Depending on the requirement the number of fuel cells in a fuel cell stack changes. The power for the n cells in a stack can be known by

$$P_{ele} = V_O * I_O * N$$

By knowing the power produced by the fuel cell, it is also vital to know the amount of oxidant or air with 21% of O_2 , the amount of fuel H_2 consumed by the fuel cell and the water produced is also calculated for a fuel cell.

- Oxidant usage: firstly the usage of pure oxygen is calculated and then the air which contains 21% of oxygen is calculated

The oxygen usage by a single fuel cell is given by

O_2 usage = I / 4 F ; where I is the electric current of fuel cell and F is the faraday's constant and 4 is the number of protons or positively charged hydrogen atoms. The O_2 usage for a fuel cell stack which consists of n number of fuel cells is given by

O_2 usage = I * n / 4*F

Since $P_{ele} = V_O * I * n$

O_2 usage = P_{ele} / 4* V_o * F mole/sec

For clear understanding the moles/sec is changed into kg/sec

O_2 usage = 32*10^{-3} * P_{ele} / 4*V_o * F

= 8.29 * 10^{-8} * P_{ele} / V_o Kg/ sec

If the fuel cell is supplied with the air which consists of 21% of oxygen , then the amount of air consumed by the fuel cell is given by

Air usage = O_2 usage / 21% mole/sec

= molar mass of air * O_2 usage/ 21%

= 28.97*10^{-3} * O_2 usage / 0.21

= 3.57*10^{-7}*

Air usage is the consumption of air as oxidant instead of oxygen by fuel cell to produce the P_{ele} power

- Fuel (hydrogen) usage: The usage of hydrogen by fuel cell to produce power P_{ele} is calculated similar to calculation of O_2 usage in the fuel cell

H_2 usage = I / 2 *F moles/ sec

Where 2 is the amount of exchanged electrons per mole H_2 for hydrogen oxidation . the hydrogen usage for n number of cells in a fuel cell stack is given by

H_2 usage =I * n / 2*F moles/sec

For clear understanding the moles/sec is converted into the Kg/sec

H_2 usage = molar mass* H_2 usage Kg/sec

= 2.02 * 10^{-3} *Pele / 2 V_o* F

= 1.05*10^{-8} * (P_{ele} / V_o) Kg/sec

H_2 usage is the amount of fuel consumed by the fuel cell to produce P_{ele} power.

It is also important to know the amount of water produced from the fuel cell in advance which is very advantageous for vehicle design.

- Water output: In the fuel cell, the water is produced at the rate of one mole for every two electrons

  So, the water output = P_{ele} / 2 * V_o*F moles / sec

For clear understanding ,converting the moles/sec to Kg/sec so that

Water output = molecular mass * water output
The molecular mass of water is 18.02* 10^{-3} Kg/ mole
water output = 9.34*10^{-8}* (P_{ele} / V_o) Kg/sec

Thus by having the approximate values of inputs to the fuel cell that is oxidant consumption and hydrogen consumption and output of fuel cell that is water output, we can design the fuel cell stack required for the vehicle and heat management system

IV. DESIGN OF FUEL CELL STACK

The fuel cell is the main part in the fuel cell electric vehicle it serves as the source of energy which is required by the vehicle to operate . a typical fuel cell (PEMFC) has a rated voltage 1.23V . however the rated voltage cannot be obtained in practical application. The practical operational voltage of PEM fuel cell is estimated to be 0.7V. as this voltage is very less to meet the requirement of vehicle the fuel cells are connected either in parallel or in series. When the cells are connected in series the voltage will be multiplied by the number of cells that are connected in the fuel cell stack .the fuel cell stack is formed by number of individual cells either connected in series or parallel. Similarly when the cells are connected in parallel the current magnitude is multiplied with the number of cells connected. In general the fuel cells are connected in series such that voltage gets multiplied since the operational voltage is very small for an individual cell in the stack. The amount of fuel H_2 consumed, the amount of oxygen consumed and the water by product are calculated for an famous fuel cell electric vehicle Toyota mirai. It has the following specifications.

The power produced by fuel cell stack is 114 KW.

The number of individual fuel cells in stack are 370. The fuel cells in the stack are connected in series such that voltage of fuel cell stack would be

Voltage V_o = number of cells * voltage of each cell
= 370 * 0.7 V ; here the voltage of PEM fuel cell is considered to be 0.7V since it is the operational voltage

V_o = 259 V

The current of fuel cell in a stack is I = P_{ele} / V_o ; since the vehicle has 114 kw stack = 114*10^3 / 0.7
= 162.87 KA

If the fuel cells are connected in series in a fuel cell stack then,

I = 162.87 / number of cells = 162.87/30
= 0.44 KA

- Fuel consumption: the amount of fuel required by the fuel cell to produce the P_{ele} power is calculated by

  H_2 consumed = 1.05 *10^{-8} * I
  = 1.05 * 10^{-8}* 0.44KA
  = 1.05 * 10^{-5}* 0.44 KA
  = 0.462 * 10^{-5} Kg/sec

For clear understanding ,the Kg/sec is converted into Kg/hr

= 0.462 * 10^{-5} * 3600 Kg/hr
= 0.016632 Kg/hr

Since the fuel cell stack has 370 individual fuel cells for Toyota mirai , the hydrogen consumed will be

H_2 consumed = 0.016632 * 370 Kg/hr
= 6.15 Kg/hr

In practical , the 80% of the fuel is used by fuel cell to convert it into power, hence hydrogen consumed will be = 6.15 * 0.80 = 5 kg/hr

So to produce 114 Kw of electrical power , the fuel H_2 consumed by Toyota mirai car will be approximately 5 kg.

From the calculation of energy required by the electric vehicle from previous section per KM is given by E = 229.27 Wh/Km

For the 114 Kw of electrical power, the range would be

Range of vehicle = 114 * 1000 W / 228.29
= 500 KM

And the fuel consumed by the car would approximately be 5 Kg of hydrogen.

- Oxidant consumption: the amount of oxidant consumption (here O_2) is mainly taken from the air in the environment. Hence the amount of air usage of fuel cell can be calculated by

Air usage (O_2) = $3.57 * 10^{-7} *(P_{ele}/V_o)$
$= 3.57 * 10^{-7} * 0.44$ KA
$= 1.5708 * 10^{-4}$ Kg/sec

For clear understanding , the air usage is converted into Kg/hr

$= 1.5708 * 60* 60 * 10^{-4}$ Kg/hr
$= 0.005654$ Kg/hr

Similarly , the air used by entire fuel cell stack consisting of 370 fuel cells would be

Air usage = 370 * 0.005654 Kg/hr
= 2.10 Kg/hr

So the amount of oxygen from air used by fuel cell to produce 114 KW electrical power is approximately 2.10 KG.

- Water output: The resulting by product of fuel cell reaction is water. The amount of water that is produced from the production of 114 KW electrical power would be

Water output = $9.34 * 10^{-8} * (P_{ele}/V_o)$ Kg /sec
$= 9.34 * 10^{-8} * 0.44$ KA Kg/sec
$= 4.1096 * 10^{-5}$ Kg/sec
$= 4.1096 * 10^{-5} * 3600$ Kg/hr
$= 0.01479$ Kg/hr

The water produced by the entire fuel cell stack consisting of 370 fuel cells would be

= 0.01479 * 370 = 5.47 Kg/hr

So , for the production of 114 KW electrical power, the amount of water produced from the fuel cell stack consisting of 370 fuell cells would be approximately 5.5 Kg

While designing a fuel cell stack, the cooling of the stack is the main criteria for design. The temperature of fuel cell stack should be kept normal in order to prevent them spoiling . the following methods are used for heat management system, they are

- Cooling by convection
- Cooling using condenser
- Cooling using heat spreaders
- Cooling by using cooling plates

In this Toyota mirai electric vehicle, the cooling by using condensation that is by condensing the water vapor from the exhaust and by internally circulating the condensed water is used such that the need for external cooling device is eliminated

V. COMPARISON OF FUEL CELL VEHICLES AND BATTERY POWERED VEHICLES

The fuel cell is an electro chemical cell which can efficiently convert the chemical energy in the fuel into direct electricity. Whereas the battery is also an electro chemical cell which can store the electrical energy and later supply the same. In the following section, we compare the hydrogen powered fuel cell stack electric vehicles with the battery powered electric vehicles in the following terms

- Vehicle weight
- Storage volume
- Green house gas pollution
- Cost
- Time for refueling

- Vehicle weight: the fuel cell electric vehicle with fuel cell stack has very low weight when compared with the battery powered electric vehicles. To produce 1KW electrical power the weight of the fuel required by the fuel cell stack would be 0.030 Kg where as the battery weight would be around 5 Kg compressed hydrogen and fuel cells can provide electricity to a vehicle traction motor with weights that are around 8 to 14 times less than battery weights.

- Storage volume: Despite the fact that storage of fuels like hydrogen is very much complicated and requires large volume, it can be said that the storage volume of fuel cell stack would be very much less than the storage volume required by the batteries in the battery powered electric vehicles.

- Green house gas pollution: The two electric vehicles fuel cell electric vehicles and battery electric vehicles do not produce green house gases but to charge the batteries in BEV electricity is used. Since on average 52% of electricity is produced from fossil fuel energy and from this kind of production, it would lead to green house gases emission resulting in climatic disorder. So the fuel cell electric vehicles are far more advantageous than the battery electric vehicles.

- Cost: According to kromer and heywood's MIT USA analysis, the advanced battery electric vehicles with 200 miles range would approximately cost 10,200 $ more than the conventional car in 2030. Whereas the fuel cell electric vehicle with 350 miles range would only cost 3600$ more than the conventional car in 2030. From this analysis we can conclude that fuel cell electric vehicles would cost less than the battery powered electric vehicles.

- Time for refueling: the fuel cell electric vehicle would only require 3 minutes to fill the fuel tank where as the battery powered vehicles would require 3-4 hours depending on the type of battery and chargers used , with this data we can say that fuelling time for fuel cell electric vehicle is an advantage. Generally the most drivers would not accept more than 15 to 20 minutes refueling time on long distance travel for electric vehicles.

CONCLUSION

The fuel cell stack in the fuel cell electric vehicles works like a mini power plant which converts chemical power in hydrogen into direct electricity that can run the vehicle. The driver's can fuel their vehicles almost as quickly as they can with conventional fossil fuel powered vehicles and it is also lighter than the power supply for a similar battery powered electric vehicle. But the main problem is it's implementation in the real world. The vehicle manufacturing companies don't want to invest in fuel powered electric vehicles unless they know there will be places to get the fuels like hydrogen filling stations and on the other hand fueling companies don't want to invest in filling stations if there are no vehicles on the road. But I believe the fuel cell electric vehicle is a better replacement for the conventional internal combustion engine vehicles and they are more beneficial than the battery powered electric vehicles.

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