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Research Article

Polymer Exchange Membrane (PEM) Fuel Cell: A Review

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Abstract

The review paper includes introduction, working principle of the PEM fuel cell and Description of water management problem in PEM fuel cell. The discussions are based on elimination of water management problem by proper design of fuel cell. The paper shows the various types of efficiency, polarization characteristics and power characteristics. It also describes the various parameters (pressure, temperature, stoichiometry ratio and humidity) which affect the performance of fuel cell, its optimum range in which fuel cell operate safely and efficiently. This paper represents the recent work done for improvement of the performance of PEM fuel cell. Fuel cell performance is increased by proper water management on the membrane. Basic parameter which enhances the fuel cell performance is Relative humidity, Flow field design, Temperature, stoichiometric ratio. With the help of this studies, we observe that the fuel cell performance improve by Increasing the relative humidity, temperature, pressure , stoichiometric ratio and using the split serpentine flow field instead of single serpentine flow field. The objective of this study is to explore the research in the field of PEM fuel cell and to make it cost effective for sustainable power supply.

Keywords: *PEM fuel cell, Water management, affecting Parameters, Flow Field, Polarization curve, Efficiencies.*

1. Introduction

In 1989 the fuel cell discover by Sir William Grove. Proton exchange membrane fuel cells were first used by NASA in 1960's as part of the Gemini space program, and used on scale, expensive and not commercially affordable. This fuel cell used pure hydrogen and oxygen as a reactant gases. NASA interested to future development of Fuel cells because of the energy crisis in 1973.For investigate the performance of the fuel cell the fundamental model of polymer electrolyte membrane fuel cell was developed in 1990 by Springer.

In polymer electrolyte membrane fuel cell (PEMFC) ion exchange membrane (fluorinated sulfonic acid polymer) are used as a electrolyte, membrane has excellent proton conductor. Water management is the critical problem in PEM fuel cell because the conductivity of membrane is highly depend on the water content the membrane must be hydrate for efficient performance of fuel cell which depend on the reactant stream humidification , flow field of gas diffusion layer (GDL) and wetting property of GDL and polymer membrane.

1.1 Working of fuel cell

Fuel cell is electrochemical device which converts chemical energy of reaction into the electrical energy. It consists of an electrolyte with anode (negative electrode) and cathode (positive electrode) on either side, when H_2gas is fed to anode the H_2 is split into protons and electrons on anode catalyst layer the protons is allow to flow through the electrolyte to the cathode side but electrons are not allow to flow though the electrolyte so electrons are flow through the external circuit where electricity (discharge) are produced. When electrons and protons flow from anode to cathode simultaneously the O_2(from air) gas is fed to cathode after then electrons proton and O_2 react at cathode catalyst layer and produce water and heat as a byproduct. The fuel cell is work till the fuel is supplied continuously. Fig.1 shows the schematic diagram of PEM fuel cell

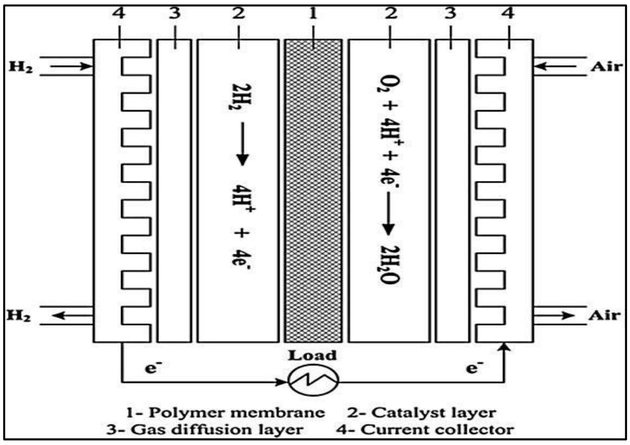

Fig.1 Schematic of PEM fuel cell

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1.2 Advantages of PEM fuel cell

- Highly efficient
- More electricity per unit of fuel is produce
- Low CO_2 emission
- Low operating temperature
- Quick startup

1.3Components of PEM fuel cell

(a) Electrolyte Membrane

Fuel cell membrane have relatively high proton conductivity, it provide a barrier to mixing of fuel and reactant gases. It is made of perfluorocarbon-sulfonic acid ionomer (PSA). The main property of the membrane is proton conductivity which is the function of water content and temperature.

(b) Electrode

Electrode is essentially made of a thin catalyst layer pressed between the ionomer membrane and a porous electrically conductive substrate. In this electrode catalyst layer electrochemical reaction take place.

(c) Gas diffusion layer (GDL)

GDL plays crucial role in PEM fuel cell, it distribute the reactant gases homogeneously from the flow field to the catalyst layer through it for the electrochemical reaction. It prevents local hotspot and catalyst flooding by removing heat and excess water from the electrode. It is made of carbon fiber material such as carbon fiber paper and woven cloths.

(d) Bipolar plates

The Bipolar separator/collector connect the cell electrically in series in fuel cell stack, it also separate the gases in adjacent cell. It is generally made of two families of material which are graphite composite and metallic.

2. Water management in PEM fuel cell

Water management play important role to obtain the good performance of PEM fuel cell. Water transport in the PEM cell done by three processes first is electro osmotic drag by which water molecules is transport from anode to cathode because of potential difference, second is back diffusion from cathode to anode because of concentration gradient and last one is because of pressure difference between anode and cathode. Proper management of water provide well humid membrane to achieve better proton conductivity simultaneously prevent the flooding at cathode side. Water management is improving by proper design of cell system which is described as follows. Fig.2 shows the schematic of detailed water behavior in a PEM fuel cell.

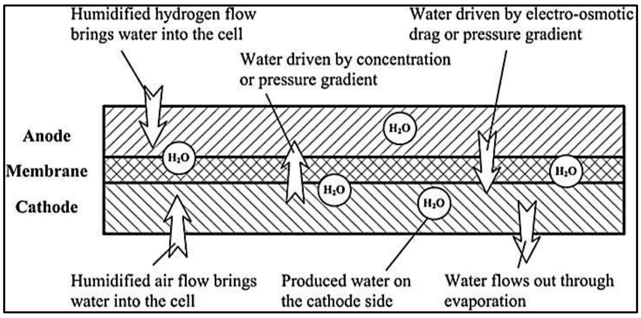

Fig.2 Schematic of detailed water behavior in a PEM fuel cell

2.1 Design of cell system

2.1.1Humidification of reactant gases

The proton conductivity of an electrolyte membrane can be maintained high when the membrane is fully humidified. Fully humid membrane offered low resistance to current flow and increase the efficiency of PEM fuel cell. There are three ways to increase the hydration level of the membrane which are internal humidification, external humidification and direct injection.

2.1.2 Design of flow field

Flow channel design is play important role in water management of fuel cell. It remove the water out of the cell which transport from the GDL by flow channels, There are three type of flow channel are used which are Conventional flow field, Serpentine flow field and Interdigitated. Fig 3 shows the schematic diagram of different type of flow field.

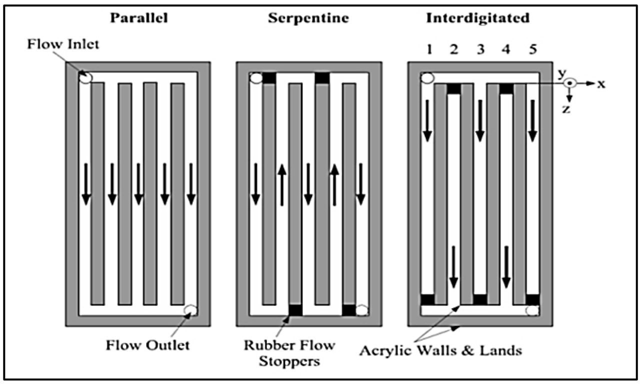

Fig.3 Schematic of three types of flow field

(a) Conventional flow field

In the conventional flow field transportation of the reactants and product is done by diffusion mechanism which reduces the transportation rate of the reactants because of this excessive accumulation of liquid water and finally arrive flooding problem.

(b) Serpentine flow field

The channel cross-section of serpentine flow field is small and the channel length is very long thus the pressure gradients are set up across the porous electrode resulting cross leakage flow between the adjacent channels. This cross leakage flow induce the strong convection in the electrode bringing the reactant gases to the catalyst layer for electrochemical reaction and simultaneously removing water from the reaction site and electrode. It is more efficient than conventional flow field, but it require higher pressure of reactant gases.

(c) Interdigitated flow field

The flow channel design is a dead end mode, it force the gas to flow through the GDL and converting diffusion mechanism to force convection mechanism. The shear force developed from the flow gases flushing the liquid water out of the electrode thus reducing water flooding and improve the cell performance, but similar to the serpentine flow high pressure reactant gases are require.

2.1.3 Electroosmotic (EO) pumping

The operating principal of electroosmotic pumping is that water formed at cathode is forced out of the GDL by the hydrophobic forces where it coalesces in to droplets, these droplets absorb in to the hydrophilic porous glass structure of the EO pump. When the structure is fully saturated with the water EO pumping drives the water in to the integrated water reservoir. EO pumping prevent the water flooding thus improve the performance and stability of fuel cell.

3. PEM fuel cell performance

3.1 Efficiency

The fuel cell efficiency, defined as a ratio between the electricity produced and hydrogen consumed is directly proportional to its potential:

$$\eta=\frac{V}{1.482} \tag{1}$$

Where V is cell potential and 1.482 is the thermoneutral potential corresponding to hydrogen's higher heating value. Sometimes, the efficiency is expressed in terms of the lower heating value (LHV)

$$\eta_{LHV}=\frac{V}{1.254} \tag{2}$$

In addition, if some hydrogen is lost (i_{loss}) either due to hydrogen diffusion through the membrane, or due to combining with oxygen that diffused through the membrane or due to internal currents, hydrogen consumption will be higher than that corresponding to generated current, and consequently, the fuel cell efficiency would be somewhat lower than given by equation

$$\eta=\frac{V}{1.482}\frac{i}{(i+i_{loss})} \tag{3}$$

If hydrogen is supplied to the cell in excess of that required for the reaction stoichiometry, this excess will leave the fuel cell unused. In case of pure hydrogen this excess may be re-circulated back into the stack so it does not change the fuel cell efficiency (not accounting for the power needed for hydrogen recirculation pump), but if hydrogen is not pure (such as in reformate gas feed) unused hydrogen leaves the fuel cell and does not participate in the electrochemical reaction. The fuel cell efficiency is then

$$\eta=\frac{V}{1.482}\eta_{fu} \tag{4}$$

Where, η_{fu} is fuel utilization, which is equal to 1/SH2, where SH2 is the hydrogen stoichiometric ratio, *i.e.*, the ratio between the amount of hydrogen actually supplied to the fuel cell and that consumed in the electrochemical reaction.

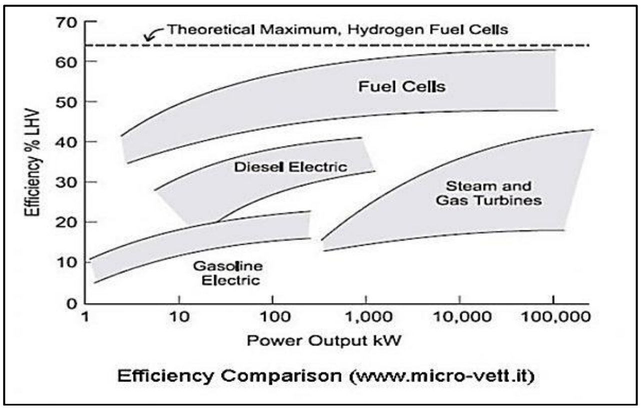

Fig.4 Efficiency comparison of fuel cell with conventional electricity generating unit

3.2 Polarization characteristics

The theoretical optimum fuel cell voltage of 1.23V would be realized at all operating current but the actual cell potential decrease from its optimum value because of irreversible losses. The losses which often called polarization over potential and overvoltage, these are arise from three sources. Fig.5 shows the polarization curve for PEM fuel cell.

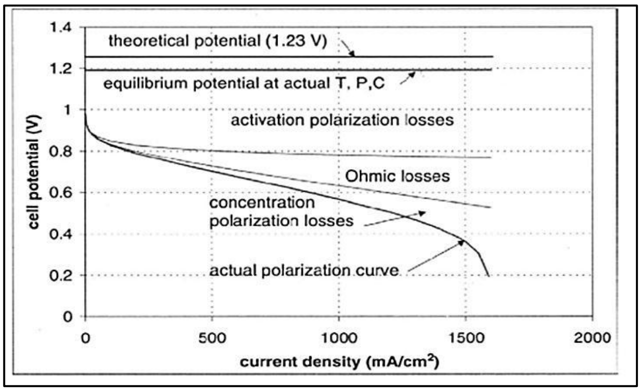

Fig.5 Polarization curve for PEM fuel cell

(a) Activation polarization

Activation polarization is present when the rate of an electrochemical reaction at an electrode surface is controlled by sluggish electrode kinetics. In other words, activation polarization is directly related to the rates of electrochemical reactions. There is a close similarity between electrochemical and chemical reactions in that both involve an activation barrier that must be overcome by the reacting species. In the case of an electrochemical reaction with $\eta_{act} > 50\text{-}100$ mV

$$\eta_{act} = \frac{RT}{\alpha nF} \ln\frac{i}{i_0} \qquad (5)$$

Where α is the electron transfer coefficient of the reaction at the electrode being addressed, and i_o is the exchange current density.

(b) Ohmic polarization

Ohmic losses occur because of resistance to the flow of ions in the electrolyte and resistance to flow of electrons through the electrode materials. The dominant Ohmic losses, through the electrolyte, are reduced by decreasing the electrode separation and enhancing the ionic conductivity of the electrolyte. Because both the electrolyte and fuel cell electrodes obey Ohm's law, the Ohmic losses can be expressed by the equation

$$\eta_{ohm} = iR \qquad (6)$$

Where i is the current flowing through the cell, and R is the total cell resistance, which includes Electronic, ionic, and contact resistance

(c) Concentration polarization

As a reactant is consumed at the electrode by electrochemical reaction, there is a loss of potential due to the inability of the surrounding material to maintain the initial concentration of the bulk fluid. That is, a concentration gradient is formed. Several processes may contribute to concentration polarization: slow diffusion in the gas phase in the electrode pores, solution/dissolution of reactants/products into/out of the electrolyte, or diffusion of reactants/products through the electrolyte to/from the electrochemical reaction site. At practical current densities, slow transport of reactants/products to/from the electrochemical reaction site is a major contributor to concentration polarization

$$\eta_{conc} = \frac{RT}{nF} \ln\left(1- \frac{i}{i_L}\right) \qquad (7)$$

Where, i_L is the limiting current

3.3 Power characteristic

It is a product of voltage and current (P=VI), the maximum power is obtain at approximate 0.5 to 0.6 V corresponding to relatively high current. At the peak point, the internal resistance of the cell is equal to the electrical resistance of the external circuit. Designer must be selected the desire operating range according to whether high efficiency or high power are require for application. It is never desirable to operate in the range beyond where the power curve drops off.Fig.6 shows the power characteristic curve with polarization curve for PEM fuel cell

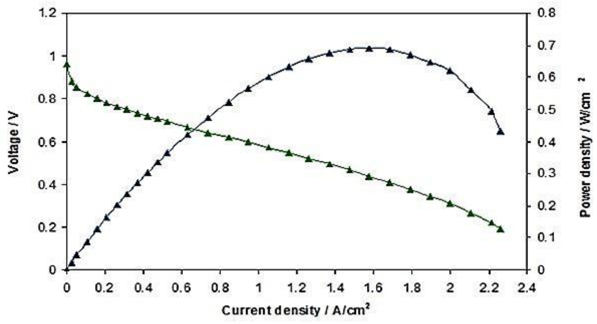

Fig.6 Power characteristic curve with polarization curve for PEM fuel cell

3.4 Process Parameters

There are various parameters which effect the performance of the fuel cell, by proper selection of range of these parameters can improve the performance of fuel cell which is

(a) Pressure

The rate of electrochemical reaction is proportional to the partial pressure of oxygen and hydrogen because the higher pressure forces the reactant gases in to contact with the electrolyte thus the polarization curve increase with increase the pressure of reactant gases and decreases with decreases with the pressure of reactant gases. But higher pressure require power to compress the reactant gases and create the problem of leakage, the optimum range of pressure is near the atmospheric pressure 1atm to 3atm.

(b) Temperature

Higher temperature improve the reaction rate because at higher temperature improve the mass transfer within the cell resulting decrease in cell resistance thus the polarization curve increase with increase in temperature and decrease with decrease in temperature. But the accumulation of water in oxidant stream limits the operating temperature bellow 100^{o}c i.e. at boiling temperature. At the boiling point of water the water boil and resulting steam severely reduce the partial pressure of oxygen thus reduces the cell performance due to oxygen starvation. The fuel cell voltage increase with increase the operating temperature until the temperature approaches the boiling point further increase in temperature result decrease the voltage. The optimum temperature is obtaining 80^oc where the two affect balance each other. Typically operating temperature is 70 to 90^oc with increases the boiling point of water by increasing the pressure.

(c) Stoichiometry ratio

It is the ratio of the amount of gas present relative to the amount of that gas that is needed to exactly complete the reaction, thus stoichiometry ratio 1.0 provide exact amount of gas molecule for theoretically complete the reaction below this ratio provide insufficient gas for reaction and above this ratio provide excessive gas for reaction. Higher stochiometry ratio increases the chance that sufficient number of hydrogen and oxygen interact with electrolyte thus polarization curve increase with increase the stochiometry ratio and decrease with decrease in stochiometry ratio. The optimum value of stochiometry ratio is 1.4 for the hydrogen and 2 for the oxygen at rated load.

(d) Humidity

Humidity is typically measure as “Relative humidity”. When a gas has absorbed as much water as it is physically able at a given pressure and temperature, it is said to be saturated and has a relatively humidity of 100%. With increase the temperature of the saturated gases relative humidity drops (4% decrease in relative humidity with each degree Celsius of temperature). Humidification is essential for the operation of PEM fuel cell because the water molecule moves with the hydrogen ion during the ion exchange reaction. Insufficient humidification of the membrane leads the cracks and holes in the membrane resulting chemical short circuit, hot spot, local gas mixing and possibility of fire occur. Excessive humidification leads the condensation and flooding within the flow field resulting the phenomenon known as cell reversal where the affected cell produce zero or negative voltage. By proper humidification of reactant gases can improve the performance of fuel cell. Fig.7 to Fig-10 shows the effect of pressure, temperature, relative humidity and stoichiometric ratio on the performance of the fuel cell.

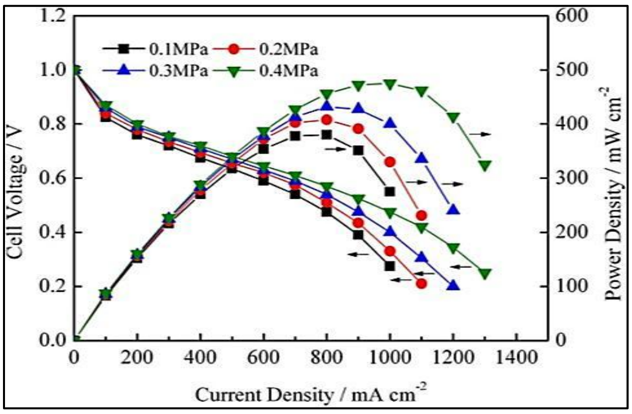

Fig.7 Effect of pressure on performance of fuel cell

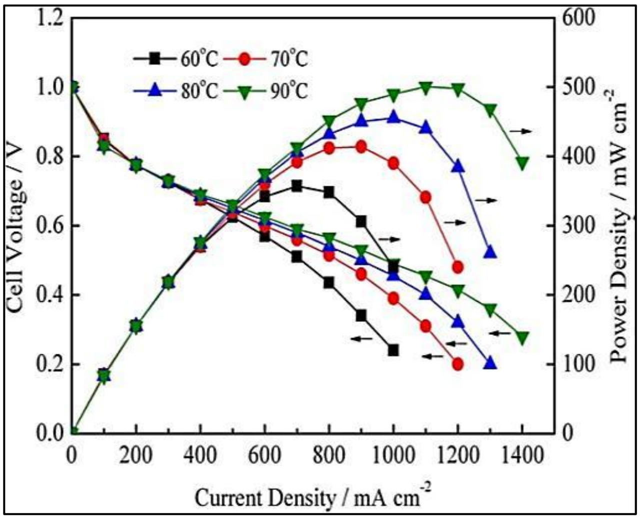

Fig.8 Effect of temperature on the performance of fuel cell

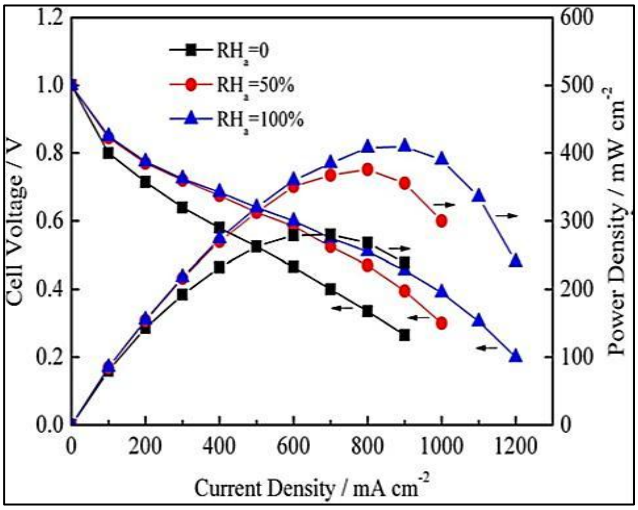

Fig.9 Effect of Relative humidity on the performance of fuel cell

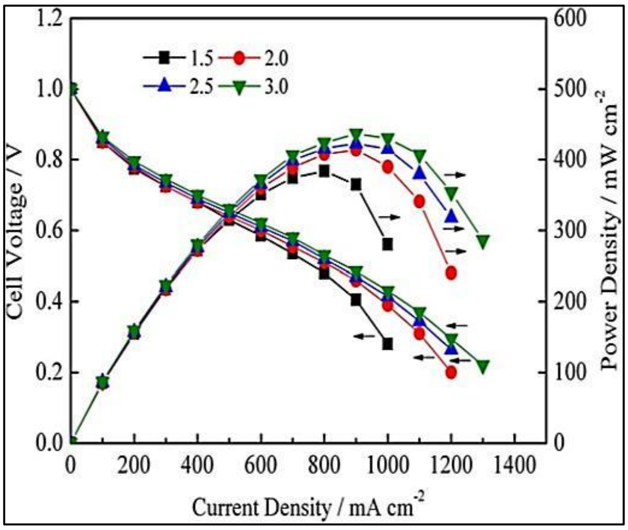

Fig.10 Effect of stoichiometric ratio on the performance of fuel cell

4. CFD Software used in analysis of PEM fuel cell

PEM fuel cell has the spatial dimensions so it is not possible to easily measured internal quantities. The use of the computational fluid dynamic (CFD) is one of the possible software for analysis of species concentration, Pressure distribution and Temperature gradient throughout each component of fuel cell. There are different types of CFD software use for analysis of fuel cell such as FLUENT, COSMOL multi-physics (FEMLAB), STAR-CD, NADigest FDEM and open FOAM.

5. Worldwide Installations

Table1 PEM Installation

Site	Total Power	Fuel	Country	Year
Met Office	Less than 1kw	Hydrogen	Germany	2011
Prime minister Residential Quarter	1kw to5kw	Natural gas	Japan	2005
Minister of land Infrastructure & Transport	1kw to 5kw		japan	2004
Nippol Oil, Yokohama Refinery	1kw to 5kw	Kerosene	Japan	2004
Spa bath	>5kw to 250 kw	Natural gas	Germany	2002
Hakkaido University Experiment house	1kw to 5kw	Natural gas	Japan	2001
Bewag fuel cell innovation Park	>5kw to 250kw	Natural gas	Germany	2000

Source- FUEL CELLS 2000 (www.fuelcells.org)

6. Project cost for PEM fuel cell

Factors such as durability and cost still remain as the major barriers to fuel cell commercialization. In the past two years, more than 35% cost reduction has been achieved in fuel cell fabrication; the current status of $61/kW (2009) for transportation fuel cell is still over 50% higher than the target of the US Department of Energy (DOE), i.e. $30/kW by 2015, in order to compete with the conventional technology of internal-combustion engines.

7. Literature Review

Jianlu Zhang et al (2007) In this paper the performance of the fuel cell investigated with dry hydrogen and air in the temperature range of 23°C to 120°C ,Relative humidity, temperature, pressure and reactant flow rate evaluated researchers found that the performance of the fuel cell was better with 100% relative humidity compared to the 0% relative humidity at inlet.

Table 2 PEM fuel cell Cars

Automaker	Fuel cell size type/ Rang(mi per km)	Fuel Type	Commercial Introduction
BMW	5kw/180 mi 300 km	Gasoline/Liquid hydrogen	Munich Airport Hydrogen Vehicle Project
Ford Motor Company	85 kW / 180 mi per 290km	8.8 lb. (4kg) Compress. H2 @ 5,000 psi	3 year demonstration in Vancouver beginning late 2004. 30 fleet vehicles in Sacramento, Orlando and Detroit
Honda	100kw/354 mi 570 km	Compress hydrogen	Small scale production of 200 vehicles between 2008-2010. Leasing in Southern California and Japan.
Hyundai	80kw/185 mi 300 km	Compress. hydrogen @ 350 bar	Demonstrating 33 Hyundai Tucsons and Kia Sportage FCVs in the US between 2004-2009 and in Korea between 2006-2010
Daimler	90kw/239 mi 385 km	Compress. hydrogen	Small series production starts in 2009. 70 to be deployed in Los Angeles& San Francisco by2012

Source- FUEL CELLS 2000 (www.fuelcells.org)

D.H. Jeon et al. (2008)CFD simulations were performed for four 10cm^2 serpentine flow-fields single channel, double channel, cyclic-single channel, and symmetric-single channel patterns to investigated the effect of flow-field design. Researchers have taken two operating conditions with high relative humidity and low relative humidity and evaluated over potential, Current density distribution, water content at different cell voltage. It conclude that At high relative humidity double channel flow field give better performance and uniform current density distribution and at low relative humidity cyclic single channel and symmetrical single channel give better performance and uniform current distribution.

PilHyong Lee et al (2009) focused on numerical simulation of the effects of operating conditions, especially cathode humidity, with simple micro parallel flow channels. It evaluated water concentration, Oxygen concentration, Ion conductivity and concludes the maximum power density could be obtained under 60% humidified condition at the cathode where oxygen concentration was moderately high while maintaining high ion conductivity at a membrane

HyeYeon Park et al (2010) investigated the three-dimensional numerical computations have been carried out to investigate the dynamics inside proton exchange membrane fuel cell (PEMFC) and its performance. It evaluates Relative humidity, stoichiometric ratio at anode and cathode channels, and cell configuration. It find that higher cell performance obtain in the case of 3.0 stoichiometric ratio at cathode channel than 1.5 stoichiometric ratio. Cell voltage is a little more affected by humidity change at cathode in comparison to results at humidity change at anode. It also conclude that Serpentine flow channel gives better performance than single flow channel

Wei Yuan et al (2010) developed the 3D model to predict the effects of operating parameters on the performance of PEM fuel cells. It evaluates operating pressure, fuel cell temperature, relative humidity of reactant gases, and air stoichiometric ratio and find out that Cell performance improve with increase of operating pressure, temperature and stoichiometric ratio at RHa=100% the output of the fuel cell reaches maximum power density at RHc= 50% the fuel cell achieve the best performance

P.V. Suresh et al (2011) found a flow field design which is based on the improvement of the local cross-flow conditions in a split serpentine flow field and evaluates Velocity, Mass fraction of Oxygen and Water along the length of flow field, current density, Power. It observe that this flow field increase the cross flow, reduce the overall pressure drop , increase the stoichiometric ratio and gives higher current and power delivered compare to the single serpentine flow field.

Dong Hyup Jeon et al (2011) analyze the CFD simulations were performed on a 300-cm^2 serpentine flow-field configuration at various RHC (relative humidity at cathode) levels. It evaluates cell voltage, Over potential, Ohmic loss, average water content and average temperature and observed that the contribution of cathode over potential is dominant, whereas that of anode over potential is small The contribution of Ohmic loss is presented significant especially at high current density and dry RHC. The current density and water content distribution becomes uniform according to the increasing of RHC.

8. Conclusion

In PEM fuel cell water management is the critical problem which effects the performance of the fuel cell, various researches have done on this type of fuel cell, the water management is depend upon the flow field, relative humidity and wetting property of gas diffusion layer. Earlier Serpentine flow field of channels give better performance because it create high pressure drop compare to the parallel flow field which help in effective water draining inside the unit cell. Recently new split serpentine flow field with enhance the cross flow as well as reducing the accumulation of liquid because of this the problem of flooding at cathode reduce. Relative humidity of anode and cathode side also effect the performance of fuel cell for obtain the good performance of the fuel cell the reactant gases must be humid. By use of the split serpentine flow channel and external humidifier the performance of the fuel cell improve. The performance of fuel cell also improves by selecting the proper range of operating parameter (pressure, temperature, relative humidity and stoichiometric ratio).

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