Parametric review on Fuel Cells and their Applications

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Abstract. This study aims to review the issues affecting the long term performance and the life span of the fuel cell in accordance with the various surveys of the currently available. According to current research, parameters such as temperature, pressure along with other issues such as fuel and oxidant starvation (stoichiometric effect), corrosion, poor water management, humidity, and uncontrolled chemical reactions are some of the reasons leading to poor performance in the fuel cell. Poor water management can either lead to flooding or dehydration, both of which are extremely detrimental for the longevity of the fuel cell since the former facilitates corrosion of electrodes, membrane and catalyst layers whereas the latter leads to shrinkage of the membrane. Also, contamination of fuel cell membranes due to corrosion products or any impurities from outside leads to the poisoning of the cell. The construction of fuel cells in the future taking into consideration all these issues and mechanisms can lead to a performance-enhanced and long-lasting fuel cell.

1. Introduction
The evolution pertaining to fuel cells date back to the 1800’s with Sir William Grove being recognized as the first one to develop the model. Various attempts were being made by scientists to develop various cells with different electrolytes and other variations in the parameters throughout the remainder of the century. Further developments also took place in the early 1900s which laid the foundation for the advancements in fuel cells. In 1959, Francis T. Bacon revealed the first fully operational fuel cell. NASA used proton exchange membrane fuel cells (PEMFC) as part of their Gemini space programs in 1960 for a few missions. At that time, hydrogen and oxygen were used as the two main reactant gases and were not a commercially viable option as the production of these gases was an extremely expensive process. Due to the energy crisis in 1973, there was a boost in the development of the fuel cell with NASA taking a particularly keen interest in researching it. The research has continued and many varieties of fuel cells have been successfully developed and are used in an extensive number of applications.

The fuel cell working is based on converting chemical energy into electrical energy. Due to the absence of any moving parts in this device, the efficiency of this device is much more than the conventional
engines such as the spark ignition and combustion ignition/Diesel engines. In spite of high system efficiencies and the benefits to the environment that come along with it due to its clean emission, it is very difficult to develop fuel cells which can be used as industrial products. They are not commercially viable yet and are still not ready to be used on mass scale. These problems arise due to its failure to compete with the existing technology due to the absence of appropriate materials and the manufacturing processes presently existing, thus increasing the cost of electricity per kWh [1].

Working of Fuel Cell:
A fuel cell comprises of four basic components, two electrodes namely the cathode and anode, an electrolyte as shown in figure 1. There is an external circuit which connects the anode and the cathode. Hydrogen is used as fuel for most of the fuel cells and sufficient oxygen must also be provided for the oxidation processes to occur. The hydrogen enters the fuel cell from anode side and at the cathode, it is divided into electron and proton, where the former are forced to travel through the external circuit, thus generating electricity on its way while the latter travels through the electrolyte towards the cathode. The external source may be connected to a bulb or any other load that requires electricity to operate. The electrons then recombine with the protons and oxygen to form water at the cathode. An attractive feature of fuel cells is its ability to produce less harmful products and generation of electricity with very less pollution and the formation of water as a byproduct.

![Figure 1. Schematic Diagram of a Fuel Cell](image)

Generally, a fuel cell stack is used because a single fuel cell produces very tiny amount of DC current by itself. The main intention of a fuel cell is to yield an electric current which can be used outside the fuel cell for doing any kind of work pertaining to electricity, such as illumination of a bulb or for providing power to an electric motor. This electricity eventually returns back to the fuel cell completing an electric circuit. The chemical reactions taking place at the cathode, anode and the overall chemical reactions are listed below.

At anode: \( \text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^- \)
At cathode: \((\frac{1}{2})\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2\text{O}\)
Overall reaction: \(\text{H}_2 + (\frac{1}{2})\text{O}_2 \rightarrow \text{H}_2\text{O}\)

Chemical energy is converted into electrical energy in galvanic cells. A fuel cell can also be considered as a galvanic cell, like a battery. The consumption rate of oxygen and hydrogen can be determined by the electric current load. But in an actuality, a variety of electrical loads are applied to the fuel cell [1].

There are various types of fuel cells available in market and they are mainly classified into two categories based on the temperature. The fuel cells operating on low temperature are proton exchange membrane, direct methanol, alkaline, phosphoric acid and biofuel cells. Molten carbonate fuel cells and solid oxide fuel cells have high operating temperatures. A regenerative fuel cell is a new type of fuel cell and still under development and also operates at high temperatures.
There are several parameters that affect the performance of the fuel cell and even the slightest change in these parameters lead to noticeable changes in the performance of the fuel cell. Parameters such as temperature, pressure, humidity among other parameters play a crucial role in the overall functioning of fuel cell. Also providing the fuel cells with suitable catalysts speeds up the reaction.

2. Types of Fuel cells

2.1. Proton Exchange Membrane Fuel Cell:

It is also called as Polymer electrolyte membrane as in figure 2, these fuel cell provides high power density and the advantages such as low weight and volume as compared to other types of fuel cells. These fuel cells also employ porous carbon electrodes containing a platinum catalyst and a solid polymer as the electrolyte. Hydrogen, water and oxygen from air are required in order for the polymer electrolyte membrane fuel cells to operate. Polymer electrolyte membrane fuel cells are usually fueled with pure hydrogen provided from onboard reformers or storage tanks. Polymer electrolyte membrane fuel cells are mainly used for transportation applications such as cars and buses and they operate at relatively low temperatures [2].

2.2. Direct Methanol Fuel Cell:

These fuel cells are powered by pure methanol. Since methanol has higher energy density than hydrogen but a lower density than fuels such as gasoline and diesel; methanol being similar liquid to gasoline, is also easier for transportation and stream to the public using existing infrastructure. The methanol used in this fuel cell is mixed with steam which is then fed directly to the fuel cell anode. Direct methanol fuel cell technology is comparatively novel as compared to other hydrogen fuel cells [3].

2.3. Alkaline Fuel Cell:

These fuel cells employ a large number of non-precious metals as a catalyst at the cathode and anode and a solution of potassium hydroxide in water as the electrolyte, thus they are also economical since they don’t need to use costly platinum catalysts. The reason for high performance of these fuel cells is due to the faster rate at which the chemical reactions take place inside the cell. However, they are
found to be easily poisoned by carbon dioxide; a small amount of carbon dioxide in the air can affect the operation of the fuel cell [4].

2.4. Phosphoric Acid Fuel Cell:
This fuel cell comprises of porous carbon electrodes containing a platinum catalyst and a liquid phosphoric acid, which is stored in a Teflon-bonded silicon carbide matrix as an electrolyte. These fuel cells have an efficiency up to 85 percent if they are used for the cogeneration. However, they are less efficient if they are used only for the generation of electricity. Since these fuel cells are very large and heavy, they are not as powerful as the other fuel cells. Phosphoric acid fuel cells are also more expensive since the fuel cells require an expensive platinum catalyst [5].

2.5. Molten Carbonate Fuel Cell:
These fuel cells use a molten carbonate salt mixture electrolyte which is suspended in a lithium aluminum oxide ceramic matrix which is porous and also chemically inert as shown in figure 3. These fuel cells operate at high temperatures of greater than 600ºC fuel cells that offer significant cost reductions over PAFC. They also offer significantly higher efficiency of about 60% when it is used to generate electricity than compared to phosphoric acid fuel cells. The major drawback of current molten carbonate fuel cell technology is its low durability and lifespan [6].

![Figure 3. Schematic Diagram of Molten Carbonate Fuel Cell [6]](image)

2.6. Solid oxide Fuel Cell:
These fuel cells use a hard and non-porous ceramic compound used as the electrolyte. An efficiency of about 50-60% can be expected when solid oxide fuel cells are used to convert fuel into electricity, but can be much greater if used for cogeneration. Since solid oxide fuel cells operate at very high temperatures of about 1000ºC, there is no need for using expensive catalysts made out of precious metals and as a result, the cost of these fuel cells is reduced [7,8].

2.7. Regenerative Fuel Cell:
Similar to other fuel cells, regenerative fuel cells produce electricity from oxygen and hydrogen and heat and water as by-products. Regenerative fuel cells can also be used solar power or other sources of electricity to split water produced as by-product into hydrogen and oxygen in a process referred to as electrolysis. These are comparatively new type of fuel cell technology which is currently under development by organizations such as NASA [9].

2.8. Biofuel Cell:
A biofuel cell uses living organisms to produce electricity. Cells of this type use biological moieties such as enzymes of living cells to directly generate power from the chemical energy contained within
various organic or inorganic species. In this fuel cell, two electrodes which are separated by a semi permeable membrane are kept in a solution as displayed in figure 4. Any biological species such as microbes or enzymes can be placed in the solution. Once a suitable fuel is introduced, usually hydrogen, then the partial or complete oxidation process takes place at the anode and the electrons released by this process are used to reduce oxygen at the cathode. There are two types of biofuel cells, an Enzyme based and a microbial fuel cell. An Enzyme based biofuel cell is a specific type of fuel cell that uses enzyme as a catalyst to oxidise its fuel, rather than precious metals. They are a popular focus for research due to the high turnover rates associated with the enzymes leading to a high catalysis rate. One of the main issues associated with this type of fuel cell is that although the biological moieties will readily produce a supply of electrons, they cannot be used unless they can be transferred to the cathode. A microbial fuel cell is a bio-electrochemical system that drives the electric current by using bacteria and mimicking bacterial interactions found in nature. Microbes offer some major advantage over enzymes as they are able to catalyse a more thorough oxidation of many biofuels and can be less susceptible to poisoning, which makes them a better option for use in biofuel cells [10].

3. Parameters affecting fuel cell performance

3.1. Fuel Cell System Efficiency:-
It tells us about the overall performance of a system/power plant installed with fuel cells. The fuel cell stack functions properly only if it is provided with properly pressurized air and hydrogen and then cooled by a coolant. It is observed that additional equipments for regulation of gas/fluid streams, managing the output electricity, providing lubrication, operating other auxiliary equipment and control the process in actual fuel cell systems. Some system comprises of reformers for processing fuel. All of these multiple equipments bring about losses and collectively reduce the total efficiency of the system thus deviating from its ideal. While drawing comparisons between fuel cells and other systems generating power, it is crucial that each of the system must be defined in a similar way. While comparisons are made between an IC engine and a fuel cell power plant for an automotive application, they both can be defined in a similar way as device that delivers mechanical output power to the shaft by taking in fuel and air. In both cases, the fuel is stored in a tank after refining/reforming and other processing and drawn from the tank in either a gaseous or liquid form. A similarity between the two is the compression action; while the IC engine uses the piston action to do so, the fuel cell power plant accomplishes this by using an external compressor. The fuel cell power plant uses an inverter and electric motor to deliver power to the driveshaft while the IC engine delivers the mechanical power directly to the driveshaft. Heat is rejected to the surroundings in a similar way in both systems, i.e. using a radiator, a coolant pump and other heat management equipment. The overall efficiency of an IC engine is between 15 to 25%. The output obtained at the output of the flywheel ranges between 30 to 35% and are even higher for Diesel engines. A fuel cell power plant that operates on hydrogen, the efficiency breakdown at flywheel output is as follows:
Fuel cell efficiency: 40 to 50%
Air compression: 85% (uses 15% of gross power)
Inverter efficiency: 95%
Electric motor efficiency: 97%
An overall efficiency of 30 to 39% is yielded when all these values are multiplied. The overall efficiency is further reduced if a reformer is used and the overall efficiency drops to about 20 to 29%. Also, fuel system systems are heavier than IC engines of comparable power and range, thereby using more power on an ongoing basis [11].

3.2. *Polarization curves*:
A theoretical operating voltage of 1.2 V is realized at all operating currents ideally. But in practical use, fuel cells reach their uppermost output voltage in an open circuit and the voltage drops with increase in current. This is known as Polarization and is represented by Polarization curve as shown in figure 5. Batteries and fuel cells have similar polarization curves. Both of them have extremely good performances at partial loads since the voltage increases as the load decreases. The IC engines on the other hand perform excellently at full load conditions but fail to do so at partial load conditions. Polarization is mainly caused due to various chemical and physical factors related with different elements of the fuel cell [11-12].

**Figure 5. Polarization curves denoting active, ohmic and activation regions**

**Activation Polarization**: The energy barrier that must be overcome to initiate a chemical reaction between reactants is called Activation Polarization. The electron transfer rate is slow at low current draw and a portion of the electrode voltage is lost in order to reimburse for the lack of electro-catalytic activity.

**Ohmic Polarization**: Ohmic Polarization occurs due to resistive losses in the cell. These resistive losses occur within the electrolyte (ionic), in the electrodes (electronic and ionic), and in the terminal connections in the cell (electronic). Since the stack plates and electrolyte obey Ohm’s law (V=IR), the amount of voltage lost in order to force conduction varies linearly throughout this region.

**Concentration Polarization**: A Concentration polarization is usually encountered when the electrode reactions are hindered by mass transfer effects. In this region, the reactants are utilized at greater rates than they can be supplied while the product gathers at a greater rate than it can be removed. Eventually these effects hinder further reaction altogether and the cell voltage drops to zero.

3.3. *Power characteristics*:
The product of voltage and current is the electric power (P=VI). A fuel cell’s polarization curve denotes a relationship between current and voltage at any point of the curve. Hence this can be used to derive a corresponding power curve. The instantaneous power is represented graphically at any point as the
rectangular area that just touches the curve. As seen from the figure 6, the maximum power occurs when the voltage ranges from 0.5 to 0.6 V which corresponds to a high current. At this peak value, the electrical resistance of the external circuit is equal to the internal resistance of the cell. There is a tradeoff between high power and high efficiency since the efficiency drops with increasing voltage. The desired operating range must be selected based on whether the efficiency or the power is of more importance. Care should be taken to operate in the range before which the curve drops off [11].

3.4. Pressure and temperature:
Pressure and temperature of the stack play a crucial role in determining the shape of the polarization curves. To characterize the stack performance over the entire operating pressure and temperature, a family of polarization curves is drawn. Thus we can conclude that in general, any parameter that leads to the polarization curves increasing or going up is beneficial, since it results in higher electrochemical efficiency and greater power. The converse is also true.

With increasing operating pressure, the fuel cell polarization curves typically increase. Conversely, with decreasing operating pressure the polarization curves decrease as well. This is due to the rate of the chemical reaction being proportional to the partial pressures of the hydrogen and the oxygen. Higher pressures help to power the hydrogen and oxygen to come in contact with the electrolyte. The pressure sensitivity is greater at high currents. In spite of promoting electrochemical reactions, the increase in
pressure causes other problems. Fuel cell stack flow field plates exhibit smaller flow-induced pressure losses at low pressure and thus should be operated at low pressures. For higher pressure, a higher compression ratio is also required, which absorbs more gross power. The redesigning of a few fuel cell components has to be done which is not economical while also increasing the size. The fuel stack and overall system efficiency have negligible changes when operating pressure is increased. Owing to these reasons, the PEM fuel cells are operated near to the atmospheric pressure range. The fuel cell polarization curves typically increase, with increasing operating temperature. Conversely, the polarization curves decrease with decreasing operating temperature well. This happens because at higher temperatures, mass transfer within the fuel cells is improved and results in a net decrease in cell resistance. These effects improve the reaction rate altogether.

The operating temperatures are limited to below 100ºC due to the buildup of product water within the oxidant stream. The water boils and the resulting steam rigorously decreases the partial pressure of the oxygen at this temperature. The performance is then dramatically reduced due to lack of oxygen. This can potentially harm the fuel cells lifespan. Higher temperatures can be attained by operating at higher pressures since this increases the water boiling point accordingly but only to some extent. The fuel cell voltage increases with increasing temperature until it approaches the boiling point of water after which the voltage declines with increasing temperature. At 80ºC, an optimum temperature is obtained where the two effects balance each other out. Typically operating temperatures are between 70 to 90ºC [13].

3.5. *Humidity effects*:
An appropriate amount of humidification is important for PEM fuel cell operation since water molecules move with the hydrogen ions during the ion exchange reaction. Insufficient humidification can lead to dehydration of the membrane and cracks or holes in the membrane. This collectively results in a chemical short circuit, local gas mixing, hot spots, and also the possibility of fire. But it has also been observed that excess humidification leads to condensation and flooding within the flow field plates.

A phenomenon known as cell reversal occurs due to this where the affected cells produce a zero or negative voltage and if a large enough negative voltage occurs, the affected fuel cells start to act like an electrolyser. Excessive heat is produced which can potentially lead to the destruction of the cell. Cell reversal is detected by cell monitoring systems before cell damage occurs.

Humidity is usually measured by using the term “relative humidity”; the word is used since relative since it depends on the pressure and temperature of the gas. A gas is said to be saturated and has a relatively humidity of 100% when it has absorbed as much water as it is physically able to at a given pressure and temperature. The relative humidity drops if the saturated gas becomes hotter. But if the gas cools, the gas remains saturated at the new temperature due to the condensation of water [14].

Fuel cells are generally operated at or near saturated conditions at the fuel cell operating temperature so that the relative humidity is 100% or close to it. This provides the maximum amount of water possible while also preventing flooding due to excess water. Thus the use of water to provide humidification effectively limits fuel operating and storage temperature between 0 and 100ºC. Outside of these limits, the water freezes and boils respectively [14].

3.6. *Stoichiometric Effects*:

With increasing reactant gas stoichiometry, the fuel cell polarization curves increase and the polarization curves decreases with decreasing reactant gas stoichiometry. This effect occurs because higher stoichiometry increases the chance of hydrogen and oxygen molecules to sufficiently interact with the electrolyte. Insufficient stoichiometry starves the fuel cell stack of sufficient reactants for reaction and thus can cause permanent damage to the fuel cell. The fuel cell performance degrades and the cell voltage drops when starved from fuel or oxygen. Stoichiometry is defined as the ratio of the amount of gas present relative to the amount of that gas that is needed to complete the reaction. A stoichiometric ratio of 1.0 provides exactly the correct number of gas molecules to theoretically complete the reaction.
Stoichiometric ratios greater than 1.0 provide excess gas and ratios less than 1.0 provide insufficient gas. Thus it is always desirable to keep the stoichiometric ratio above 1.0 for the reactions to take place sufficiently [15].

3.7. Fuel Cell Flooding:-
Flooding is the buildup of excess water and it takes place at both the electrodes of the fuel cell membrane. As discussed in humidity effects, it is essential to keep the membrane humidified for high proton conductivity, because the membrane’s conductivity is directly related to its water content but it should be noted that accumulation of too much water also impacts performance and lifespan of the fuel cell. Reactant starvation occurs due to excess water blocking the flow channels and the pores of the gas diffusion layer (GDL), thus instantly leading to reactant starvation. The transport rate of the reactants to the electro catalyst sites is significantly reduced i.e. flooding leads to an instant increase in the mass transport losses, particularly at the cathode. Water blocks the pores of the GDL which creates a sterical (caused by the spatial arrangement of atoms in a molecule) hindrance which prevents the reactants to reach the catalysts eventually leading to gas starvation and an immediate drop in cell potential. The voltage can be recovered relatively fast by purification of the cathode and anode. The pore size may be reduced due to water layer present on the GDL surface[2,16].

3.8. Contamination of the Cell:-
PEM fuel cells contamination can also have adverse effects on the performance and lifespan. Contamination of the fuel cell is the process when impurities pollute and penetrate into cell components slowing down the actual reactions that take place in a cell by initiating a chemical attack. These contamination products originate from components placed inside the cell and are transported into the cell via the reactants. Metal, alkaline metal and ammonium ions, silicon and catalyst particles along with gases such as carbon monoxide (CO), nitrogen oxides (NOx) or sulfur dioxide (SO2) can be present in the cell. Trace amount of impurities can also lead to considerable degradation of performance [2].

Table No. 1 Summary of different fuel cells

| Parameters | Efficiency | Electrolyte used | Ions in the electrolyte | Operation Temperature | Fuel | Catalyst used |
|------------|------------|------------------|------------------------|-----------------------|------|---------------|
| PEM        | Up to 40%  | Nafion membrane  | H⁺                    | 60 - 120°C            | Hydrogen      | Platinum or platinum/Ruthenium |
| DMFC       | Around 10% | Nafion membrane  | H⁺                    | 60 - 120°C            | Methanol      | Platinum or platinum/Ruthenium |
| AFC        | 60 – 70%   | Potassium hydroxide | OH⁻                 | > 100°C               | Hydrogen      | Nickel and Silver |
| PAFC       | 40 – 50%   | Phosphoric Acid  | H⁺                    | 160 – 200°C           | Hydrogen      | Platinum or platinum/Ruthenium |
| MCFC       | Up to 60%  | Carbonate salts of sodium & potassium | CO₃²⁻ | 600 – 800°C | Hydrogen as a fuel + CO₂ to replenish | Nickel chromium |
4. Applications of Fuel Cells

Various applications of fuel cells along with their parameters have been discussed in the above sections. One of the main reasons for using fuel cells instead of the conventional systems is due to its ability to produce clean power with highly reduced emissions and also due to its higher efficiency and overall performance as compared to other systems [13].

4.1. PEMFC:

PEMFC are capable of producing power up to hundreds of kW and thus can be used for a wide variety of applications where electricity generation is a requirement. They have wide range of applications such as vehicles, bicycles, aerospace and defence applications which may comprise of space shuttles and submarines. They are also utilized for distributed power generation inside individual homes, buildings or communities due to their modularity and excellent flexibility in power supply.

4.2. AFC:

Due to the high reactivity of OH- ions with carbon and its compounds, even the slightest quantity of carbon dioxide affects the efficiency considerably. Due to the lack of any carbon and its compounds in space this fuel cell can easily be used in space environments and they are still the main technology used in related applications. Also due to the production of extremely clean byproducts which in turn reduces pollution in the space environment these fuel cells are nearly irreplaceable with the current available technology.

4.3. MCFC & SOFC:

They demand very high operating temperature above 600 degrees and 1000 degrees Celsius respectively and mostly, all of the applications regarding these kinds of fuel cells are restricted to large and emission free power plants. The heat from these fuel cells can be used for cogeneration or can be used for other applications such as industrial processes or steam turbines in order to generate more electricity. Developments have been made for using MCFC as substitute power supply for ships. This will be cleaner and avoid the pollution of the marine Diesel engines. SOFC is used for tri-generation, which is a simultaneous process of cooling, heating and power generation from only one fuel point.

4.4. Biofuel Cell:

They can be used for power production which require only low power, but where replacing batteries may be unfeasible, such as wireless sensor networks. They can function as biosensors and microbial cells can measure the solute concentration of waste water, as the current generated from a microbial cell is directly proportional to the energy content of waste water used as fuel. A device constructed in 2010 was capable of producing electricity and reducing Cu2+ ions to copper metal. A first self-
powered and autonomous biochemical oxygen demand (BOD) biosensor has been developed and allows to detect organic contaminants in fresh water.

5. Conclusion
In this review article, development of the fuel cell with improved performance and various impelling parameters has been discussed. Overall efficiency of the fuel cell is affected by the interactions between different parameters. Also, it has adverse impact on fuel cell durability. Hence, to avoid any losses concerning to working parameters of the fuel cell, essential remedial actions should be incorporated to improve performance as well as life of fuel cells. It has been revealed that working performance and the life span of the fuel cell is most influenced by polarization, working temperature, operating pressure and humidity. Major conclusions are as follows

- With increase in temperature and pressure, polarization curve also increases which affects rate of reaction resulting into oxygen starvation. This in turn hampers durability of fuel cell.
- In order to achieve higher efficiency of the fuel cell, ideal stoichiometric ratio is found to be 1.4 for fuel (hydrogen) and 2.0 for air.
- Poor water management leads to humidity imbalance. This results into massive reduction of the electrochemical active surface area (ECSA) and affects gas diffusion layer (GDL).
- Corrosion of the electrode and membrane strongly influenced performance in long run and major difficulty in commercialization of fuel cell.
- Biofuel cell is one of the most dynamic areas towards power generating sources for prosthetic devices within humans as it has numerous benefits over present technologies.

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