International Journal of Advanced Trends in Computer Science and Engineering

Trends so far in Hydrogen Fuel Cell Technology: State of the art

Manish Kumar Singla[1], Amandeep Singh Oberoi [2*], Parag Nijhawan[3]

[1,2,3]Thapar Institue of Engineering and Technology Patiala, India

[1]msingla0509@gmail.com

[2*] oberoi@thapar.edu

[3]parag.nijhawan@rediffmail.com

ABSTRACT

Hydrogen is known to be the cleanest fuel due to its zero-emission capability. It's inherently immense energy content makes it the fuel for future but, it's economical, safe and efficient usage for power generation remains a challenge. Fuel cell is a chemical device that runs on hydrogen and oxygen gases to give out electricity and water that is capable of replacing the conventional fossil-fuels in various applications. This paper gives construction and functional details of various fuel cells that are commercially available. The reported types of fuel cell are categorized based on fuel oxidizer electrolyte, state of aggregation of the reactants, and electrolyte/operating temperatures. The operational parameters of each type are disclosed. Pros and cons of specific fuel cell types are listed along with their possible applications. Further, performance of typical fuel cells is analyzed with the help of a polarization curve and their respective efficiencies. The presented work summarizes the trends in hydrogen fuel cell market and throws light on the technology that probably would contribute towards sustainable development of society. The state of the art review on this promising technology would help better understanding the future directions of a sustainable energy development and its usage thereof.

Key words: hydrogen energy, clean fuel, fuel cell technology, fuel cell types, fuel cell efficiency

Nomenclature

ΔG	Gibbs free energy charge
ΔS	Change in entropy
ΔH	Change in enthalpy
T	The absolute temperature of the oxidation
E	Maximum EMF
F	Faraday value or constant
N	Number of faradays transferred in the course of the reaction
ΔV_T	Voltage gain with an increase in temperature
T_1 and T_2	Temperature

P_1 and P_2	Cell pressure
i_o	Exchange current density
I	Current through cell
R	Total cell resistance
i_1	Limiting current

1. INTRODUCTION

In the 21st century era, fuel cell has emerged as a clean power source on the earth. Fuel cell has many applications in different fields requiring portable or stationary power supply – be it automobile industry, defense industry or remote area power supply [1]. Fuel cell manufacturer like Ballard from Canada, Heliocentric and SFC energy from Germany are the leading producers of different types of fuel cell.

In 1802 Sir Humphrey Davy gave the concept of fuel cell and the associated chemical reactions but, failed to describe the operation of a carbon cell working at room temperature with nitric acid as an electrolyte. In 1839 [2], first hydrogen-oxygen cell was successfully operated by Sir William Grove, and the data was reported as a 'Gaseous Voltaic Battery' in his experiments. In this cell, the reaction between hydrogen and oxygen produced water and electric current. Sir William Grove finally published three important papers in 1842 [3], 1843 [4] and 1845 [5]. In 1842 article, Grove repeated his previous work and recognized a second phenomenon, i.e., 'Decomposition of water through its composition.' The fuel cell invented by Sir William Grove also proved the principle of regenerative. Fifty years later in 1889, L. Mond and C. Langer [6] justified Grove's work and established that Grove including later investigators overlooked the necessity of maintaining the activity of the catalyst unimpaired. They found that the most suitable absorbent for gas batteries is platinum black, when wet, it almost losses its condensing power. The problem is solved by using the quasi-solid foam as an electrolyte.

In 1921, the importance of kinetics in the development of a practical fuel cell was given [7]. The high-temperature cell was designed by the Baur et al. in which they used carbon as anode, molten alkaline carbonate as electrolyte and iron oxide as cathode. When they operated the cell at $1000^{\circ}C$,

they faced the problems with the materials and disposal of slag.

British scientist and engineers have done much of the pioneering work in basic and applied fuel cell research in the laboratory. F.T. Bacon, and J.C. Frost of Cambridge University developed, built and demonstrated in August 1959, a 6kW fuel cell power unit that drove a forklift truck, a circular saw and a welding machine. H.K. Ihrig of Allis-Chalmers, almost simultaneously in America, demonstrated in October 1959 to the press a 15kW fuel cell tractor. The effort made by the National Aeronautical and Space Agency (NASA) is remarkable for the application of fuel cells to meet auxiliary power requirements in some of the space projects.

2. WORKING OF HYDROGEN-OXYGEN FUEL CELL

The main features of a fuel cell [8-9] are shown in Figure1, and Figure 2 shows the working of a fuel cell. The figure includes a fuel electrode on anode, air electrode on cathode as oxidant and an electrolyte. The fuel and oxidizing agents are fed through the electrodes and are brought into contact with the electrolyte. Reaction between the oxidizing agent and fuel produces voltage at the electrodes. The positive terminal of the cell is the oxygen electrode, and the negative terminal of the battery is the fuel. The electrons with other ions are conducted through the electrolyte and travels from one electrode to another, completing the electrical circuit to satisfy the connected external load. The fuel cell continues to operate as the current flows through the load and the reactants (fuel and oxidant) are fed. The electromotive force (emf) of the fuel cell is in the order of 1V. In series, many cells are connected to provide a terminal voltage which is known as 'module.' Depending on the mode of operation, a fuel cell battery constitutes several modules connected either in series or parallel.
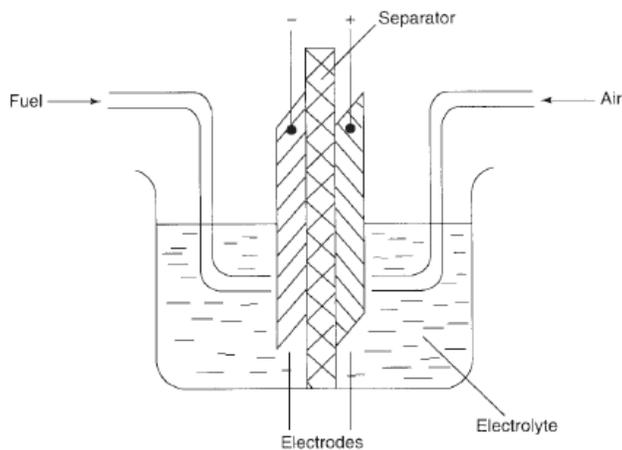
Figure 1: Schematic Diagram of Fuel Cell

The Gibbs free energy change, accompanying the oxidation of the fuel at the absolute temperature relates to the corresponding enthalpy and entropy changes given in equation 1.

$$\Delta G = \Delta H - T\Delta S \qquad (1)$$

The ΔG determines the maximum emf of the cell in terms of equation 2.

$$E = -\Delta G/nF \qquad (2)$$

The hydrogen-oxygen cell can be used to explain fuel cell principles. Two electrodes which are made up of platinum foil immersed in an electrolyte (solution which is of potassium hydroxide or sulphuric acid). In the fuel cell, the anode is fed with hydrogen gas, where it gets disassociated in the presence of catalyst forming H^+ ions and electrons, after that it passes to the electrolyte. The cathode is supplied with the oxygen gas which acquires electrons and reacts with water from the electrolyte (potassium hydroxide KoH solution) to form hydroxyl ions OH^-. In the electrolyte, the OH^- and the H^+ ions are in equilibrium with the water (H_2O). In [10-11] a DC power of 100 to 200 mA/cm^2 is applied at a voltage of about 1V which is typically on the electrical output of an individual cell. The overall reactions of hydrogen ions consumed at the oxygen electrode are replaced by the hydrogen electrode as given in equation 3.

$$H_2 \ + \frac{1}{2} O_2 \rightarrow H_2O \qquad (3)$$
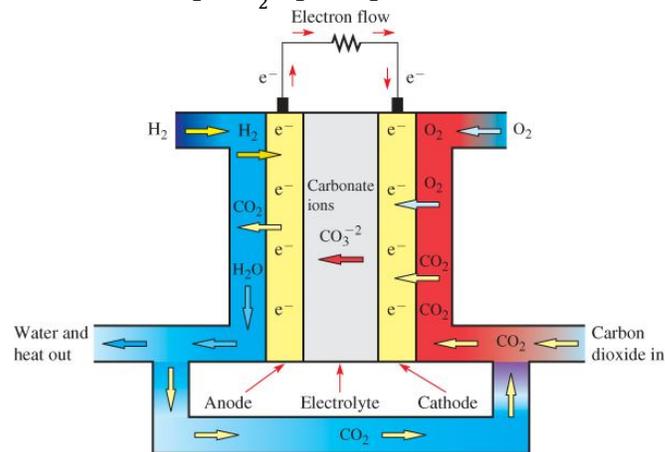
Figure 2 : Working of fuel cell

The reactants used in the fuel cell should be easily available and cheap. The heart of the fuel cell is the design and choice of the materials for the electrodes [12-13]. They are highly corrosive in the environment and must conduct electricity well. The electrodes are lightweight, thin, and the reactants are externally supplied through the electrodes. The most useful or conventional electrode catalysts in a fuel cell are made up of platinum or graphite [12]. In a fuel cell, many variables of electrolyte are used.

Fuels for fuel cell

The selection of fuel depends upon the volume, storage-ability, availability, transportability, and cost. The most important fuel is hydrogen because the combination of hydrogen and oxygen releases more energy as compared to the other fuels. However, hydrogen fuel is the most expensive fuel and its safe and efficient storage is a challenge. Hydrogen is present as a chemical compound (i.e. hydrocarbon) in almost all conventional fuels, for example Methane, Butene, Toluene, Ethane, Benzene, Butane, Kerosene, Decane, Octane, and many others. [9]. It is also

found chemically bonded with nitrogen in Ammonia and Hydrazine or in alcoholic groups like Methanol, etc. [9-15].

Pros and Cons of a hydrogen-oxygen fuel cell

The fuel cell has many pros compared to the conventional fossil fuels [16], but fewer cons. Some pros and cons are listed below:

- High Efficiency
- Low thermal emission
- Good fuel flexibility
- Non-polluting
- Low maintenance cost
- Low chemical emission

Based on lower heating value (LHV), the effectiveness of the fuel cell is 45 to 55%, and in hybrid, the effectiveness of the cell is 70%. The fuel cell is highly efficient in the peak load, but it is more efficient in the partial load [17]. The noise is also less in fuel cell because the moving part is only the fuel and the cooling system.

There are two cons i.e.

- The cost for the stationary electric generation is too high
- The hydrogen used in the fuel cell is quite expensive and its storage requires energy expenditure.

3. TYPES OF HYDROGEN-OXYGEN FUEL CELL

There are many different types of fuel cell based upon the fuel-oxidizer-electrolyte combination, temperature, and pressure at operation [9]. Fuel cells are also classified as regenerative, direct, and indirect fuel cells [9]. Direct fuel cells depend upon the temperature i.e., low temperature. Hydrogen-halogen, metal-oxygen, hydrogen-oxygen, and organic compound-oxygen fuel cells are in the category of the low temperature direct fuel cells. In the medium temperature category ammonia-oxygen, hydrogen-oxygen and organic compound-oxygen fuel cells are included. In the high temperature category, carbon-monoxide-oxygen and hydrogen-oxygen fuel cells are included. These three temperature-based fuel cells fall under the direct fuel cell category. On one side, reformer and bio-chemical fuel cells fall under the indirect fuel cell category; and on the other side, chemical, radioactive, electrical, photochemical and thermal fuel cell form a part of the regenerative fuel cells as shown in figure 3. The classification, according to the states of aggregation of the reactants, appears to be the most rational method. This method distinguishes most clearly between methods of construction and operation [12-15].

➤ Gaseous Fuel Cell: In the gaseous fuel cell new subdivision is classified depending upon the type of oxidizing agent used i.e., liquid oxidizing agent and gaseous oxidizing agent.

- Liquid oxidizing agent: In this oxidizing agent,, solution of bromine, hydrogen peroxide and chlorine are present as shown in equation 4.

$$H_2 + H_2O_2 \rightarrow 2H_2O \qquad (4)$$

- Gaseous oxidizing agent: In this oxidizing agent, solution of oxygen, chlorine, air, and mixture of many more gases are used as a fuel. The electrochemical reaction in terms of equation 5:

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O \qquad (5)$$

➤ Liquid Fuel Cell: The advantage of a liquid fuel cell is that it can be dissolved in the electrolyte easily because of the H₂O₂ (Liquid oxidant). Gaseous and liquid fuel-based fuel cells fall under the category of a direct fuel cell. The best known and highly developed direct fuel cell is hydrogen-oxygen cell. Among all the available direct fuel cells, "hydrazine cell" has reportedly been the best performer under the liquid fuel cell category [12]. The chemical reaction that takes place inside a liquid fuel cell is as shown in equation 6 below.

$$CH_3OH + 3H_2O_2 \rightarrow CO_2 + 5H_2O \qquad (6)$$
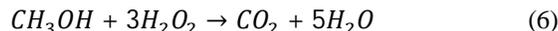
➤ Solid Fuel Cell: In this category, direct hydrocarbon fuel cell is less developed, but such cells are more efficient than the other conventional fuels that are being used in internal combustion engine. However, the disadvantage of this cell is its high cost. The associated chemical reaction that takes place in this solid fuel cell in terms of equation 7:

$$C + O_2 \rightarrow CO_2 \qquad (7)$$
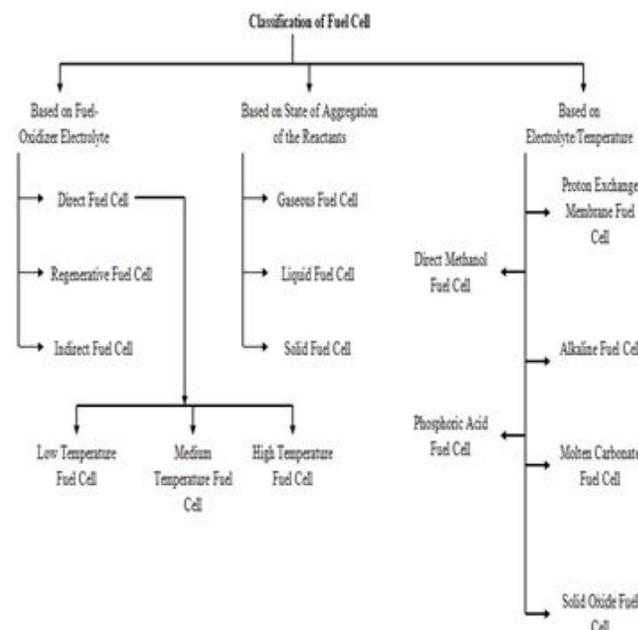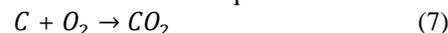
Figure 3: Classification of Fuel Cells

Regenerative Fuel Cell: The regenerative cell is similar to a rechargeable battery (Secondary) which means the reactants can be regenerated again and again. The main limitation of this cell is its mammoth cost due to recycling of the reactants. The regenerative fuel cell is used as chemical reactors. The chemical reaction associated to this cell is:

$$CH_3.CHOH.CH_3 + 2OH^- \rightarrow CH_3.CO.CH_3 + 2H_2O + 2e^-$$
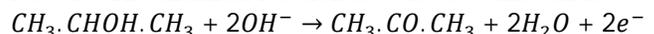
The fuel cell based on the classification of electrolyte or temperature:

(1). Phosphoric Acid Fuel Cell (PAFC)
(2). Alkaline Fuel Cell (AFC)
(3). Solid Oxide Fuel Cell (SOFC)
(4). Molten Carbonate Fuel Cell (MCFC)
(5). Direct Methanol Fuel Cell (DMFC)
(6). Proton Exchange Membrane Fuel Cell (PEMFC)

In [18], the detail of all the fuel cell that ever came into existence is discussed. The life of any typical fuel cell depends upon its operating temperature, thermo-mechanical, physio-chemical properties of materials used for fabrication of its components i.e., current collector, electrolyte, and electrodes, etc. Classification of fuel cell based upon the operating temperature involves low temperature and high temperature fuel cells. In a low-temperature fuel cell, charge carriers in the electrolyte are hydroxyl ions or protons. Various low temperature fuel cells are AFC, PAFC, PEFC, and DMFC, whereas high-temperature fuel cells are SOFC and MCFC. In high temperature fuel cells, charge carriers are mainly oxygen ions and carbonate ions. The characteristics of the various fuel cells are explained as below:

(1). Phosphoric Acid Fuel Cell: The evolution of this cell took place in 1965. As the name suggest, phosphoric acid with 100% concentration is used as an electrolyte in this type of cell. Its operating temperature is in the rage of 150 to 220°C. Reportedly, the electro catalyst used is generally platinum, on both anode and cathode sides [18]. Cathode catalyst, particularly in PAFC, is studied vigorously by many researchers using various electrochemical and physical methods [19 - 22]. The charge carrier in this fuel cell is H^+ ions. The primary cell component is made up of graphite and the primary fuel is enriched with the H_2 gas. Since, PAFC involves an external reforming of the fuel it takes hours to start operating. The power density of this cell is 55%, and the performance of this cell is lower than the alkaline fuel cell. It is the first conventional fuel cell that got commercialized. A typical PAFC-based power plant's capacity ranges from 50 to 200 kW, although some plants have a capacity ranging from 1MW to 5 MW. The 11 MW grid-connected is the largest reported plant in the world [20-21]. Figure 4 shows the schematic diagram of a PAFC. The electrochemical reactions incurred in a PAFC are as below:
The chemical reaction of the anode is:
$$H_2 \rightarrow 2H^+ + 2e^-$$
The chemical reaction of the cathode is:
$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$
The overall chemical reaction of this fuel cell in terms of equation 8:
$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{8}$$
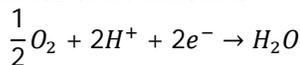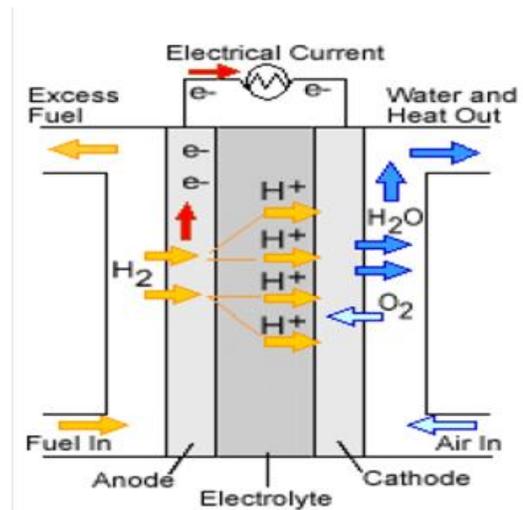
Figure 4: Phosphoric Acid Fuel Cell

The performance of cell depends mainly upon few parameters such as cell life, temperature and pressure. It should be noted that many problems could occur in a pressurized cell due to high current density [22].

•   Effect of temperature in the cell: Reduction of oxygen on the platinum improves the temperature of the cell. The operating temperature is reasonably valid in the range of 180 to 250°C as shown in equation 9.
$$\Delta V_T(mv) = 1.15(T_2 - T_1) \tag{9}$$

•   Effect of pressure in the cell: With the increase in the pressure the performance of cell is generally increased [23]. In the equation the theoretical change in the voltage as a function of pressure in terms of equation 10:
$$\Delta V_P = 146 \, Log \left(\frac{P_2}{P_1}\right) \tag{10}$$

The operating temperature range is 177 to 218°C and the pressure range is 0.1 to 1 Mpa. These ranges are based on the experimental data.

•   Effect of cell life: In a PAFC [24-26] the efficiency degrades over time. The below equation shows the overtime of cell degradation in terms of equation 11.
$$\Delta V = -3mv/1000h \tag{11}$$

Average working life of a typical PAFC is between 10,000h to 50,000h. The efficiency of the cell is 55% but the performance of this cell is lower than the alkaline cell because of slow oxygen reduction rate.

(2). Alkaline Fuel Cell: Generally, KOH is the electrolyte used in such type of cells. Usually, 85% concentration of KoH is used for high temperature operations whereas, 35 to 50% concentration is used for lower temperature operations. The schematic diagram of this cell is shown in Figure 5. A typical alkaline fuel cell could operate between the temperature ranges of 50 to 200°C. However, its usual lower operating temperature is 50°C and high operating temperature is 200°C. In this type of fuel cell, OH⁻ ions are the charge carrier and platinum-based material acts as a catalyst.
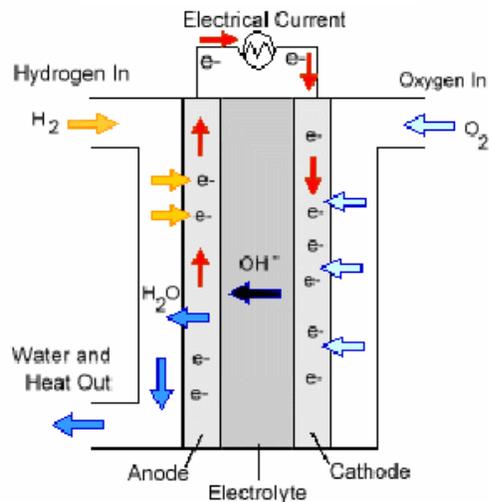
Figure 5: Alkaline Fuel Cell

Electrolyte is the primary cell component, and H_2 is the primary fuel in a typical AFC. The average efficiency of the AFC is 50 to 60 % of the combined cycle. In 1960, the first AFC was developed and was used for running the vehicle as well as the Apollo space vehicle [27-28]. While operating on O_2 and H_2 an AFC performs better than other fuel cells. The electrochemical reactions of this fuel cell are:
The chemical reaction of anode:

$$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$$
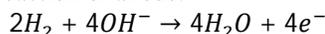
The chemical reaction of cathode:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$
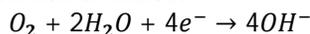
The overall electrochemical reaction of this fuel cell in terms of equation 12:

$$2H_2 + O_2 \rightarrow 2H_2O \qquad (12)$$

The alkaline electrolytes have advantages over the acid electrolytes to their lower over potential. Therefore, in such cells KOH is chosen as the preferred electrolyte over NaOH on the cathode side [27-28]. In 1980s, the development of AFCs reached its peak [29] due to more favorable oxygen reduction [30-31] and fuel oxidation-reduction [32-34] in alkaline condition. In [35], comparison of AFC with PEFC is reported whereas, in [36-42], different types of fuel cell are discussed that are used as AFCs.

(3). Direct Methanol Fuel Cell: This fuel cell is also known as Direct Methanol Proton Exchange Fuel Cell (DMPEFC). It is a special type of low-temperature fuel cell that operates on the principle of a PEMFC, as shown in Figure 6. Various components of a DMFC are two bi-polar end plates that act as anode and cathode, catalysts, and an electrolyte membrane. In 1960s, Murray and Grimet [43] have reported an impressive work of stacking 40 DMFC together which operates at 50°C. In this type of fuel cell, H^+ ions are the charge carrier and platinum-based material acts as a catalyst.
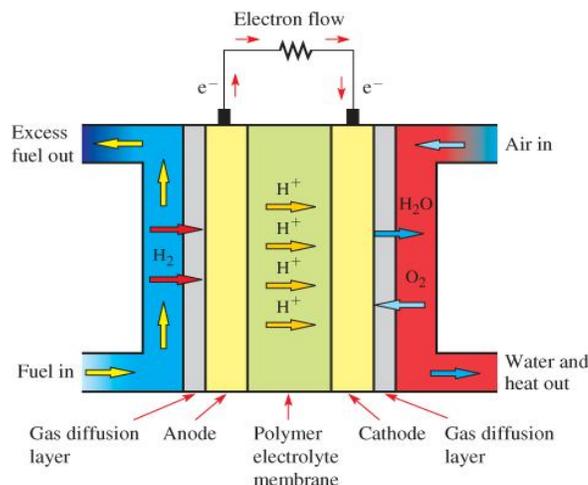
Figure 6: Direct Methanol Fuel Cell

The primary fuel in a typical DMFC is methanol and average cell efficiency is up to 30 to 40%. From 1960 to the early 1980s, the trend of using conventional electrolytes got changed [44] and in 1990s, polymer-based electrolytes were introduced in DMFC [45]. The chemical reaction of this cell is:
The chemical reaction of the anode is:
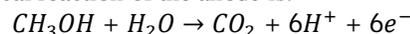
$$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$$

The chemical reaction of the cathode is:

$$\frac{3}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$$
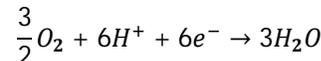
The overall electrochemical reaction of this cell in terms of equation 13:

$$CH_3OH + \frac{3}{2}O_2 \rightarrow CO_2 + 2H_2O \qquad (13)$$
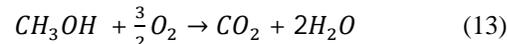
It is revealed through research that when the ceramic type electrolyte is used, then the operating temperature of the DMFC could reach between 450°C to 500°C [46-47]. The main disadvantage of this fuel cell is the slow startup. It takes more time to start compared to other fuel cells because of its high operating temperature. This cell has two major applications [48-53] - portable power generation, and power source for civil and military environments. It has low weight and that is why it is suitable for substituting batteries.

(4). Molten Carbonate Fuel Cell: This cell got introduced in 1960s. Combination of an alkali carbonate is generally used as an electrolyte in this cell and hence, the name of cell MCFC. The operating temperature of this cell is between 600°C and 700°C. Carbonate ions (CO_3^-) are the charge carriers in the cell and nickel serves as a catalyst. End plates of this fuel cell are made from stainless steel to avoid corrosion and the fuels used are CH_4, H_2, and CO_2. Efficiency of a MCFC ranges from 55 to 65% which is higher than other fuel cells. Figure 7 shows the schematic diagram of a MCFC.
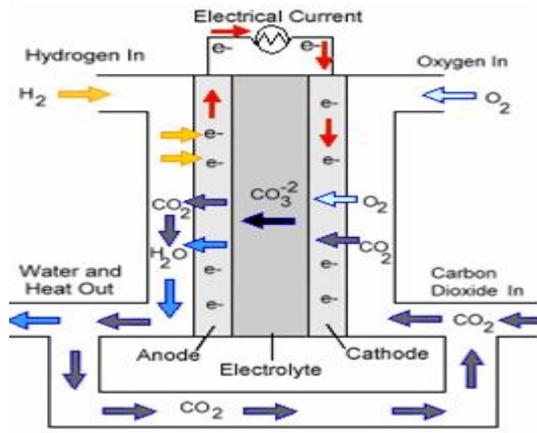
Figure 7: Molten Carbonate Fuel Cell

The in-situ fuel conversion concept is termed as the 'Direct Fuel Cell' (DFC). In [54] review of DFC is discussed, the efficiency of this cell is 70% [55]. The electrochemical reaction of this cell is:
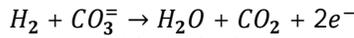
The chemical reaction of the anode is:

$$H_2 + CO_3^= \rightarrow H_2O + CO_2 + 2e^-$$

The chemical reaction of the cathode is:

$$\frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^=$$
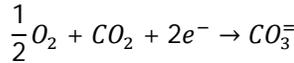
The overall electrochemical reaction of this cell in terms of equation 14:

$$H_2 + \frac{1}{2}O_2 + CO_2 \rightarrow H_2O + CO_2 \quad (14)$$
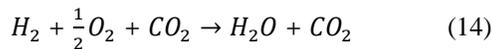
The MCFC is the second generation fuel cell after PAFC because it is also used for commercial purposes. [56-61] report on the various cell component used in fabrication of a MCFC. [60-61] critically discuss the design of a MCFC. The MCFC cell is mainly used in marine applications or the automobile applications [62-65].

(5). Solid Oxide Fuel Cell: The electrolyte used in this cell is solid, non-porous metal oxide. Its operating temperature is between 700°C to 1000°C. This cell has the highest operating temperature amongst all fuel cells. The $O^=$ ions are the charge carriers, and the catalysts used in this cell is made up of Perovskite (a calcium titanium oxide mineral composed of calcium titanate) as shown in Figure 8. The primary cell components of the cell are of ceramic. The efficiency of this cell is similar to a MCFC, and the power density of this cell is 1.5 to 2.6 (kW/m³).
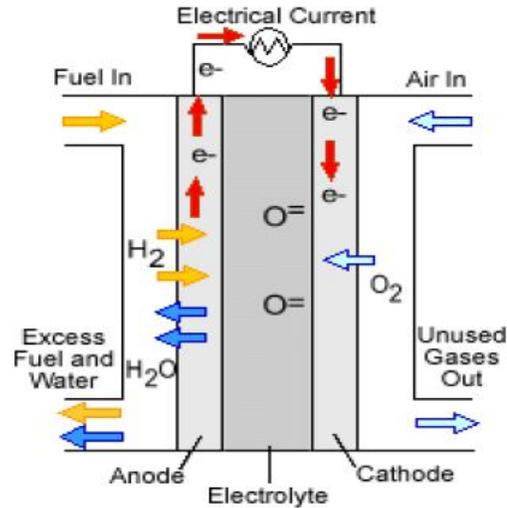
Figure 8: Solid Oxide Fuel Cell

Tabular and flat are the two different configurations of the SOFC. SOFC was developed in 1950s, but it was in 2000s when its mechanical characteristics were improved [66-70]. The electrochemical reaction of this fuel is:

The chemical reaction of the anode is:

$$H_2 + O^= \rightarrow H_2O + 2e^-$$

The chemical reaction of the cathode is:

$$\frac{1}{2}O_2 + 2e^- \rightarrow O^=$$
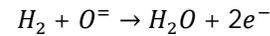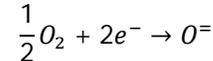
The overall electrochemical response of this cell in terms of equation 15:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad (15)$$

This cell has high flexibility to a vast variety of fuels, including coal gas [71], biomass-derived gas [72], and landfill gas [73].

(6). Polymer Electrolyte Membrane Fuel Cell: This cell is also known as Proton Exchange Membrane Fuel Cell (PEMFC). This cell is a solid polymer fuel cell. The operating temperature of this fuel cell is between 50° to 100°C. This cell falls in the category of low-temperature fuel cells. Charge in a typical PEMFC is carried by H^+ ions, platinum serves as an electro-catalyst, and nafion membrane as a proton exchange medium between anode and cathode as shown in Figure 9. The efficiency of this cell is similar to the AFC, and the power density of this cell is 3.8 to 6.5 (kW/m³). This cell is suitable for vehicle power [74-75].

The first organic cation exchange polymer membrane in the fuel cell was given in 1959 [76-77]. The review on the electrodes of this cell is discussed by Lister [78]. The electrochemical reactions associated with a PEMFC are:

The chemical reaction of the anode is:
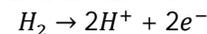
$$H_2 \rightarrow 2H^+ + 2e^-$$

The chemical reaction of the cathode is:

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$
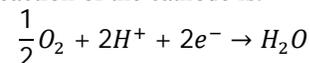
The overall chemical reaction of this fuel cell in terms of equation 16:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad (16)$$
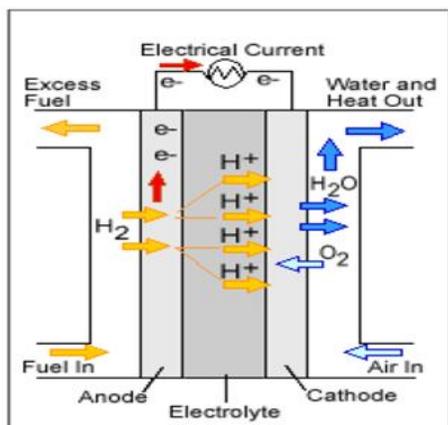
Figure 9: Polymer Electrolyte Fuel Cell

PEMFC can generate power from watts to kilowatts. That's why this cell is almost used in every application where electricity generation is needed [79-80]. This cell is already used in an electric vehicle, scooters, submarine, an automobile, etc. In the distributed power generation, this cell is also tested for homes, buildings, and shops [19-20]. PEMFC up to 70kW power is used in transportation industry, 500kW power for stationary applications and more than 500kW is used for portable power applications.

4.FUEL CELL PERFORMANCE

Fuel cell performance differs in real practical operation than a theoretical model working under ideal conditions. It is important to gauge both the performances for better understanding of the fuel cell system [81].

(1). Ideal Fuel Cell Performance: This performance depends upon the electrochemical reactions that occur with oxygen and different fuels within a working fuel cell. In a low-temperature fuel cell, generally metal catalysts help to achieve possible reaction and where commonly used fuel is H_2. In a high-temperature fuel cell, the most commonly used catalysts are nickel and non-noble metal, common fuel used is H_2.
The Nernst equation is defined in the ideal performance of a fuel cell, which is represented as cell voltage. The ideal standard potential across a typical fuel cell running on liquid water product is 1.229V whereas; it drops below 1.229 V when fuel cell utilizes gaseous water products.

(2). Actual Performance: In the actual performance, when the useful amount of electrical energy is obtained from a cell, then its equilibrium potential decreases because of irreversible losses. The polarization losses consist of activation, concentration, and ohmic losses. At low current density, the activation loss is dominant, and ohmic loss varies directly with current, as shown in Figure 10.
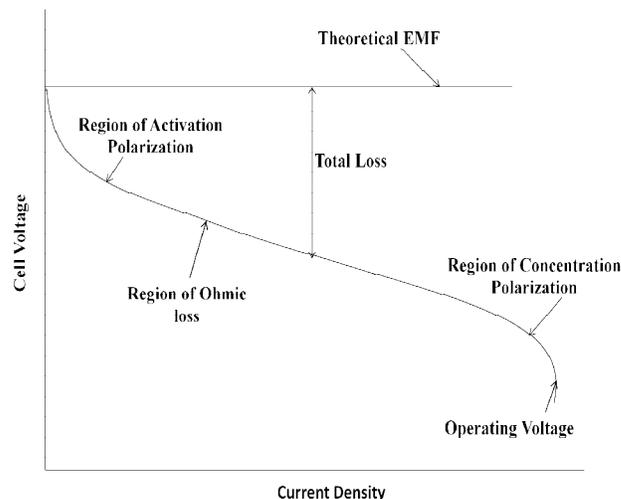
Figure 10: Voltage/Current Characteristics of Ideal and Actual Cell

- Activation Polarization Loss: It is directly related to the rates of electrochemical reaction for 50 to100 mV. The general form of the equation in terms of equation 17:

$$\cap = \frac{RT}{\alpha nF} \ln \frac{i}{i_o} \qquad (17)$$

- Ohmic Loss: The ohmic polarization loss is because of the flow of ions in the electrolyte and flow of electrons through the electron material as shown in equation 18.

$$\cap = i.R \qquad (18)$$

- Concentration Loss: These losses are associated with the purity of the reactant gases i.e. hydrogen and oxygen. Generally, concentration of the reactants is directly proportional to the operational efficiency of any fuel cell. The general form of the equation of concentration of loss in terms of equation 19.

$$\cap = \frac{RT}{\cap F} \ln \left(1 - \frac{i}{i_L} \right) \qquad (19)$$

5.Conclusions and future scope

The state of art review presented on the currently prevailing trends in hydrogen fuel cell technology summarizes the types, construction, working, and key operation parameters that plays a significant role to achieve the optimum efficiency. Categorization of fuel cells on the basis of reactants gives a broad spectrum of sources of hydrogen gas available for usage in the field of alternate power generation. From the given chemical reactions of the individual type of fuel cell, the role of electrolytes as well as charge carriers is clearly defined. Since current trends in fuel cells involve usage of compressed hydrogen and oxygen gases (produced by expenditure of energy) as reactants, it cannot be considered as a sustainable solution to the global power needs. The intermediate steps involve losses across each system and the efficiency from energy in (while compressing the gases) to energy out (in form of electricity generation), what we have named as round-the-trip efficiency, drops significantly. The future directions in the fuel cell technology seek development of reversible cells that could run both as electrolyser and fuel cell thereby, reducing the incurred losses and hence improving the overall

efficiency. Also, fuel cells have clearly a long way to go contributing towards a sustainable development and no single alternate power generation system could fulfill the world's energy demand. Renewable energy harnessing systems in combination with fuel cell technology as a hybrid system could be foreseen as a tangible solution to the problem. More research, therefore, is required in system integration of both renewable and fuel cell technology in order to achieve the set targets of energy production from alternate energy sources, which could make the hydrogen fuel cell technology commercially and technically viable for society.

REFERENCES

[1]. EG&G Services Inc. **"Fuel Cell Handbook",** 5th ed., U.S. Department of Energy Office of Fossil Energy National Energy Technology Laboratory Inc.: Morgantown, West Virginia, USA, (2000).

[2]. Grove, W.R. **"On Voltaic Series and the Combination of Gases by Platinum"**, Philos. Mag. J. Sci., Vol. 16, pp. 127-130, (1839).
https://doi.org/10.1080/14786443908649684

[3]. Grove, W.R. **"On a Gaseous Voltaic Battery"**, Philos. Mag. J. Sci., Vol. 21, pp. 417-420, (1842).
https://doi.org/10.1080/14786444208621600

[4]. Grove, W.R. Proceedings of Royal Society, Vol. 4, pp. 463, (1843).

[5]. Grove, W.R. Proceedings of Royal Society, Vol. 5, pp. 557, (1945).
https://doi.org/10.1098/rspl.1843.0049

[6]. Mond, L., and Langer, C. **"V. A new form of gas battery."** Proceedings of the Royal Society of London, Vol. 46(280-285), pp. 296-304, (1890).
https://doi.org/10.1098/rspl.1889.0036

[7]. Bagotsky, V., **"Fuel Cell Problems and Solutions"**, New York, Willy. ISBN- 978-1-118-08756-5.

[8]. Borup, R., Jeremy, M., Bryan, P., Yu, S.K., Rangachary, M., Nancy, G., Deborah, M., et al. **"Scientific aspects of polymer electrolyte fuel cell durability and degradation"**, Chemical reviews, Vol. 107(10), pp. 3904-3951, (2007).

[9]. Bockris, J. O'M., and Srinivasan, S. **"Fuel Cells: Their Electrochemistry"**, McGraw-Hill Book Co., New York, Vol. 167(515-627), pp. 18-33, (1969).

[10]. Ascoli, A., Pandya, J.D., and Redaelli, G., **"Electrical characterization of a 2.5 kW phosphoric acid fuel cell stack operating on simulated reformed biogas."** Energy, Vol. 14(12), pp. 875-878, (1989).
https://doi.org/10.1016/0360-5442(89)90042-X

[11]. Barak, M., **"Primary and secondary batteries: fuel cells and metal-air cells"**, Electrochemical Power Sources: Primary and Secondary Batteries, Vol. 1, pp. 1, (1980).
https://doi.org/10.1049/PBEN001E

[12]. Steele, B.C.H., **"Materials for IT-SOFC stacks: 35 years R&D: the inevitability of gradualness"**, Solid state ionics, Vol. 134(1-2), pp. 3-20, (2000).
https://doi.org/10.1016/S0167-2738(00)00709-8

[13]. Aurbach, Doron., **"Characterization of batteries by electrochemical and non-electrochemical techniques"**, In Industrial applications of batteries, pp. 119-201, Elsevier, (2007).
https://doi.org/10.1016/B978-044452160-6/50004-8

[14]. Barak, M., **"Fuel cells—present position and outstanding problems",** Advanced Energy Conversion, Vol. 6(1), pp. 29-55, (1966).
https://doi.org/10.1016/0365-1789(66)90011-7

[15]. Sandstede, Gerd., **"From electrocatalysis to fuel cells."** (1972).
https://doi.org/10.1149/1.2403821

[16]. Energy Center of Winsconsin., **"Fuel Cells for Distributed Generation- A Technology and Marketing Summary"**, Energy Center of Winsconsin Inc.: Winsconsin, USA, (2000).

[17]. Mattey, J., **" The Fuel Cell Industry Review"**, Fuel Cell Today Limited: Roystone, Uk, (2012).

[18]. Appleby, A. J., and Foulkes, F. R., **"Fuel Cell Handbook"**, Van Norstand Reinhold, New York, NY, (1989). Republished by Krieger Publishing Company, Melborne, FL (1993).

[19]. Maoka, T., Kitai, T., Segawa, N. and Ueno, M., **"Changes in cathode catalyst structure and activity in phosphoric acid fuel cell operation"**, Journal of applied electrochemistry, Vol. 26(12), pp.1267-1272 (1996).
https://doi.org/10.1007/BF00249929

[20]. Hirschenhofer, J.H., **"Latest progress in fuel cell technology"**, IEEE Aerospace and Electronic Systems Magazine, Vol. 7(11), pp.18-23 (1992).
https://doi.org/10.1109/62.166861

[21]. Hirschenhofer, J. H. **"Status of fuel cell commercialization efforts."** In Proceedings of the American Power Conference, vol. 55, pp. 578-578, (1993).

[22]. Bloomfield, D.P., and Cohen, R., **"Pressurized fuel cell power plant"**, US Patent No. 3,972,731, (2000).

[23]. McBreen, J., W. E. Ograny, and R. Richter. **"Rotating disk electrode apparatus for the study of fuel cell reactions at elevated temperatures and pressures"**, J. Electrochem. Soc.US, pp. 131, (1984).
https://doi.org/10.1149/1.2115782

[24]. Ross, P.N., **"Anomalous current ratios in phosphoric acid fuel cell cathodes"**, LBL-13955; submitted to J. Electrochem. Soc., (1986).

[25]. Stonehart, P., and Philip N.R.J., **"The use of porous electrodes to obtain kinetic rate constants for rapid reactions and adsorption isotherms of poisons."** Electrochimica Acta, Vol. 21(6), pp. 441-445, (1976).
https://doi.org/10.1016/0013-4686(76)85123-7

[26]. Harasawa, K., Kanno, I., and Masuda, I., **"Fuel Cell R&D and Demonstration Programs at Electric Utilities in Japan"**, In Fuel Cell Seminar Abstracts, Tucson, AZ. (1992).

[27]. Koscher, G.A., and kordesch, K., **"Handbook of Fuel Cells- Fundamentals, Technology and Applications"**, John Wiley and Sons, England, Vol. 4, pp. 1125-1129, (2003).

[28]. Carrett, L., Friedrich, K.A., and Stimming, U., **"Fuel Cells- fundamentals and applications"**, Fuel Cells, Vol. 1, pp. 5-39, (2001).

https://doi.org/10.1002/1615-6854(200105)1:1<5::AID-FUCE5>3.0.CO;2-G

[29]. Schulze, m., and Gulzow, E., **"Degradation of nickel anodes in alkaline fuel cells",** J. Power Sources, Vol. 127, pp. 252-263, (2004).
https://doi.org/10.1016/j.jpowsour.2003.09.021

[30]. Burchardt, T., Gouerec, P., Sanchez-Cortezen, E., Karichev, Z., and Miners, J.H., **"Alkaline fuel cells: contemporary advancement and limitations",** Fuels, Vol. 81, pp. 2151-2155, (2002).
https://doi.org/10.1016/S0016-2361(02)00163-1

[31]. Yu, E.H., and Scott, K., **"Development of direct methanol alkaline fuel cells using anion exchange membranes",** J. Power sources, Vol. 137, pp. 248-256, (2004).
https://doi.org/10.1016/j.jpowsour.2004.06.004

[32]. Wang, Y., Li, L., Hu, L., Zhuang, L., Lu, J., and Xu, B., **"A feasibility analysis for alkaline membrane direct methanol fuel cell: thermodynamics disadvantages versus kinetic advantages",** Electrochem. Commun., Vol. 5, pp. 662-666, (2003).
https://doi.org/10.1016/S1388-2481(03)00148-6

[33]. Rahim, M.A.A., Hameed, R.M.A., and Khalil, M.W., **"Nickel as a catalyst for the electro-oxidation of methanol in alkaline medium",** J. power Sources, Vol. 134, pp. 160-169, (2004).
https://doi.org/10.1016/j.jpowsour.2004.02.034

[34]. Cifrain, M., and Kordesch, K., **"Hydrogen/oxygen (air) fuel cells with alkaline electrolytes",** John Wiley and Sons, England, Vol. 1, pp. 267-280, (2003).

[35]. McLean, G.F., Neit, T., Prince-Richard, S., and Djilali, N., **"An assessment of alkaline fuel cell technology",** Int. J. Hydrogen Energy, Vol. 27, pp. 507-526, (2002).
https://doi.org/10.1016/S0360-3199(01)00181-1

[36]. Lee, S., Kim, J., Lee, P., and Lee, J., **"The characterization of an alkaline fuel cell that uses hydrogen storage alloys",** J. Electrochem, Soc., Vol. 149, pp. 603-606, (2002).
https://doi.org/10.1149/1.1467365

[37]. Verma, A., Jha, A.K., and basu, S., **"Manganese dioxide as a cathode catalyst for a direct alcohol or sodium borohydride fuel cell with a flowing alkaline electrolyte",** J. Power Sources, Vol. 141, pp. 30-34, (2005).
https://doi.org/10.1016/j.jpowsour.2004.09.005

[38]. Verma, A., and basu, S., **" Direct use of alcohols and sodium borohydride as fuel in an alkaline fuel cell",** J. Power Sources, Vol. 145, pp. 234-237, (2005).
https://doi.org/10.1016/j.jpowsour.2004.11.071

[39]. Verma, A., Jha, A.K., and basu, S., **"Evaluation of an alkaline fuel cell for multi-fuel system",** J. Fuel Cell Science and Technology, Vol. 2, pp. 234-237, (2005).
https://doi.org/10.1115/1.2039955

[40]. Parsons, R., and VanderNott, T., **"The oxidation of small organic molecules",** J. Electroanal. Chem, Vol. 257, pp. 9-45, (1988).
https://doi.org/10.1016/0022-0728(88)87028-1

[41]. Morris, J.H., Gysling, H.J., and Reed, D., **"Electrochemistry of boron compounds",** Chem. Rev., Vol. 85, pp. 51-76, (1985).
https://doi.org/10.1021/cr00065a003

[42]. Verma, A., and basu, S., "Direct alcohol and borohydride alkaline fuel cells", Recent Trends in Fuel Cell Science and Technology, Springer, pp. 157-187, (2007).
https://doi.org/10.1007/978-0-387-68815-2_7

[43]. Murray, J.N., and Grimes, P.G., **"Fuel Cell Handbook",** 4th ed., U.S. In Fuel Cells, American Institute of Chemical Engineers, New York, pp. 57, (1963).

[44]. Arico, A.S., Baglio, V., Antonucci, V., **"Direct Methanol Fuel Cells: History, Status and Prespectives",** Wiley-VCH: Weinheim, pp. 1-78, (2009).
https://doi.org/10.1002/9783527627707.ch1

[45]. Hacquard, A., **"Improving and understanding direct methanol fuel cell performance",** Thesis, Worcester Polytechnic Institute, (2005).

[46]. Naryan, S.R., Valdez, T.I., **"High-Energy Portable Fuel Cell Power sources",** John Wiley& Sons: New York, (2008).

[47]. Rayment, C., Sherwin, S., **"Introduction to Fuel Cell Technology",** Department of Aerospace and Mechanical Engineering University of Notre Dame, USA, (2003).

[48]. Ni, M., Leung, M.K.H., Leung, D.Y.C., "**Technological development and prospect of alkaline fuel cells",** In: Proceedings of 16th World Hydrogen Energy Conference, pp. 33-39, (2006).

[49]. Li, C., Shi, Y., Cai, N., **"Effect of contact type between anode and carbonaceous fuels on direct carbon fuel cell reaction characteristics",** J. Power Sources, Vol. 196(10), pp. 4588−4593, (2011).
https://doi.org/10.1016/j.jpowsour.2011.01.039

[50]. Jiang, C., Irvine, J.T.S., **"Catalysis and oxidation of carbon in a hybrid direct carbon fuel cell",** J. Power Sources, Vol. 196 (17), pp. 7318− 7322, (2011).
https://doi.org/10.1016/j.jpowsour.2010.11.066

[51]. Huppmann, G., **" Fuel cells-Molten carbonate fuel cells Systems",** In Encyclopedia of Electrochemical Power Sources; Elsevier: Amsterdam, The Netherlands, pp. 479−496, (2009).
https://doi.org/10.1016/B978-044452745-5.00271-9

[52]. Turco, M., Ausiello, A., and Micoli, L., **"Fuel Cells Operating and Structural Features of MCFCs and SOFCs",** Springer International Publishing, pp. 31–76, (2016).
https://doi.org/10.1007/978-3-319-03215-3_2

[53]. Joghee, P., Malik, J.N., Pylypenko, S., and O'Hayre, R., **"A review on direct methanol fuel cells- in the perspective of energy and sustainability",** MRS Energy Sustainability, Vol. 2, pp. 1-31, (2015).
https://doi.org/10.1557/mre.2015.4

[54]. Ermete, A., **"The stability of molten carbonate fuel cell electrodes: A review of recent improvements",** Appl. Energy, Vol. 88, pp. 4274-4293, (2012).
https://doi.org/10.1016/j.apenergy.2011.07.009

[55]. Sharaf, O.Z., Orhan, M.F., **"An overview of fuel cell technology: Fundamentals and applications",** Renewable and Sustainable Energy Reviews, Vol. 32, pp. 810-853, (2014).
https://doi.org/10.1016/j.rser.2014.01.012

[56]. Garche. J., and Jorissen, L., **"Applications of fuel cell technology: status and perspectives",** Electrochem. Soc. Interface, Vol. 24(2), pp. 39-43, (2015).

https://doi.org/10.1149/2.F02152if

[57]. Farooque, M., Katikaneni, S., and Maru, H.C., **"The direct carbonate fuel cell technology and products review",** Carbonate Fuel Cell Technology V, Electrochemical Society Proceedings, Vol. 99(20), pp. 47-65, (1990).

[58]. Ghezel, A.H., and Maru, H., **"Direct fuel cell/turbine system for ultra high frequency power generation",** Fuel Cell Seminar, Palm Spring, CA, (2002).

[59]. Yuh, C., Farooque, M., Maru, H., **"Advances in carbonate matrix and electrolyte",** Carbonate Fuel Cell Technology V, Electrochemical Society Proceedings, Vol. 99(20), pp. 189, (1999).

[60]. Tanaka, T., et al., **"Development of internal reforming molten carbonate fuel cell technology",** Proceedings of the 25th IECEC, American Institute of Chemical Engineers, New York, (1990).

[61]. Miyazaki, M., Okada, T., Idle, H., Matsumato, S., Shinoki, T., and Ohtsuki, J., **"Development of an indirect internal reforming molten carbonate fuel cell stack",** Proceedings of the 27th Intersociety Energy Conversion Engineering Conference Proceedings, San Diego, CA., Vol. 3, pp. 290, (1992).
https://doi.org/10.4271/929163

[62]. Pant, D., Van, B.G., Diels, L., Vanbroekhoven, K., **"A review of the substrates used in microbial fuel cells (MFCs) for sustainable energy production",** Bioresour. Technol, Vol. 101, pp. 1533-1543, (2010).
https://doi.org/10.1016/j.biortech.2009.10.017

[63]. Sun, H., Xu, S., Zhuang, G., Zhuang, X., **"Performance and recent improvement in microbial fuel cells for simultaneous carbon and nitrogen removal: A review",** J. Environ. Sci. Vol. 39, pp. 242-248, (2016).
https://doi.org/10.1016/j.jes.2015.12.006

[64]. Williams, M.C., Strakey, J.P., and Singhal, S.C., **"US distributed generation fuel cell power program",** Journal of Power Sources, Vol. 131, pp. 79-85, (2004).
https://doi.org/10.1016/j.jpowsour.2004.01.021

[65]. Lunghi, P., Bove, R., and Desideri, U., **"Analysis and optimization of hybrid MCFC gas turbine plants",** Journal of Power Sources, Vol. 118, pp. 108-117, (2003).
https://doi.org/10.1016/S0378-7753(03)00068-5

[66]. Bessette, N.M., and Wepfer, W.J., **"Prediction of on-design and off-design performance for a solid oxide fuel cell power module",** Energy Convers, Mgmt., Vol. 37(3), pp. 281-293, (1996).
https://doi.org/10.1016/0196-8904(95)00188-3

[67]. Patel. P., Maru, H.C., Borglum, B., Stokes, R.A., Petri, R.J., Sishtla, C., Krist, K., Armstrong, T., and Virkar, A., **"Thermally integrated power systems, high power density SOFC generator",** Proceedings of the Fuel Cell Seminar, San Antonio, TX, pp. 132-135, (2004).

[68]. Agnew, G., and Spangler, A., **"Reducing fuel cell system cost without lowering operating temperature",** Proceedings of the 2nd International Conference of Fuel Cell Engineering and Technology, Rochester, New York, (2004).

[69]. Menzler. N.H., Tietz, F., et.al, **"Materials and manufacturing technologies for solid oxide fuel cells",** Journal Material Science, Vol. 45, pp. 3109-3135, (2010).
https://doi.org/10.1007/s10853-010-4279-9

[70]. Kobayshi, Y., Tomida, K., et.al, **"Development of next-generation large-scale sofc toward realization of a hydrogen society",** Mitsubishi Heavy Ind. Tech. Rev., Vol. 52, pp. 111-116, (2015).

[71]. Ziock, H.j., Anthony, E.J., et.al. **"Technical progress in the development of zero emission coal technologies",** Proceedings of the 20th Annual International Pittsburgh Coal Conference, (2002).

[72]. Van, H.J., Membrez, Y., and Bucheli, O., **"Biogas as fuel source for SOFC co-generator",** Journal of Power Sources, Vol. 127, pp. 300-312, (2004).
https://doi.org/10.1016/j.jpowsour.2003.09.027

[73]. Pusz, J., Bove, R., and Sammes, N.M., **"Landfill gas energy recovery based on micro-tubular solid oxide fuel cells",** Proceedings of the 9th International Symposium on solid oxide fuel cells, Quebec City, Canada, (2005).
https://doi.org/10.1149/200507.0277PV

[74]. Rajasekar, N., et. al**., "Comparative study of PEM fuel cell parameter extraction using Genetic Algorithm",** A in Shams Engineering Journal, Vol. 6(4), pp. 1187-1194, (2015).
https://doi.org/10.1016/j.asej.2015.05.007

[75]. Hatti, M., "**Neural Network Power Controller for PEM Fuel Cells Systems",** IEEE International Conference on Mechatronics, pp. 1-6, (2015).

[76]. Rosli, R.E. et. al., **"A review of high-temperature proton exchange membrane fuel cell (HT-PEMFC) system",** International Journal of Hydrogen Energy, Vol. 30, pp. 1-22, (2016).

[77]. Shin, D.W., Guiver, M.D., Lee, Y.M., **"Hydrocarbon-based polymer electrolyte membranes: Importance of morphology on ion transport and membrane stability",** Chem. Rev., Vol. 117, pp. 4759-4805, (2017).
https://doi.org/10.1021/acs.chemrev.6b00586

[78]. Lister, S., and McLean, G., **"PEM fuel cell electrodes",** Journal Power Sources, Vol. 130, pp. 61-71, (2004).
https://doi.org/10.1016/j.jpowsour.2003.12.055

[79]. Yang, J.S., et.al, **"High Molecular Weight Polybenzimidazole Membranes for High temperature PEMFC",** Fuel Cells, Vol. 14(1), pp. 7-15, (2014).
https://doi.org/10.1002/fuce.201300070

[80]. Devrim. Y., Devrim, H., and Eroglu I., **"Polybenzimidazole/SiO2 hybrid membranes for high temperature proton exchange membrane fuel cells",** International Journal Hydrogen Energy, Vol. 41(23), pp. 10044-10052, (2016).
https://doi.org/10.1016/j.ijhydene.2016.02.043

[81]. Giri, N.K., "**Alternate Energy Sources, Applications and Technologies",** 1st edition, Khanna Publisher (2016). ISBN No. 978-81-7409-304-2.