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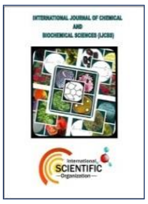

Advances in salt-based fuel cells technologies: A review

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Abstract

Fuel cells (FCs) offer the possibility of zero-emissions electricity generation and increased energy security. The most important features of FCs in comparison to other energy conversion devices are given as they are power generators which are able to directly change chemical energy of fuel into electrical energy with the efficiency higher than that of conventional coal or gas fired thermal power stations. Low pollutants are emitted and low level of noise is generated by FCs. FCs require low maintenance cost and less exchangeable parts. FCs can be classified on the basis of their operating temperatures. Therefore, present review is designed to study the different types of FCs such as high, medium and low temperature and type of electrolyte used like PEM (Polymer electrolyte membrane), AFC (Alkaline fuel cell), PAFC (Phosphoric acid fuel cell), MCFC (Molten carbonate fuel cell) and SOFC (Solid oxide fuel cell). Furthermore, some important components and working mechanisms of these FCs are discussed in detail. In order to move towards a sustainable existence in our critically energy dependent society, there is a continuing need to adopt environmentally sustainable methods for energy production, storage and conversion. Therefore, this review stresses and recommends using FCs in both stationary and mobile power applications as it offers significant advantages for the sustainable conversion of energy.

Key words: FCs, PEM, AFC, PAFC, MCFC, SOFC, sustainable energy

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1. Introduction

The production of chemicals and energy that is of high efficiency and non-pollutant to environment is a final destination for energy technologies and chemical reactor development that will soon help to sustainable development in the world. At the foreground of energy technologies, FCs are expecting to find various applications in the direct convertibility of chemical reactions into electrical energy with high efficiency and small pollutant since they generate much less pollutants than combustion process [1].

Today the world is going to find the several ways in the progress of energy generation and conversion which have the key factor to increase the economy of a nation and play a vital role in interaction between nature and society. Since yet, fossil fuels have the main lead to provide the energy resulting environmental pollution and greenhouse emission, especially toxic gasses, such as carbon dioxide and carbon monoxide cause the health hazard in urban areas. Hazards to health and environmental degradation due to pollutant air and dangerous non-treatable viruses have been encompassed both locally and globally. With the increasing energy demand of world, many global environmental issues are predicted due to the conventional technologies of production, transformation and use of energy [2].

Conventional energy conversion technologies like power plants that use the fossil fuels such as coal, oil and natural gas, are the major source of acid rain, global climate change, stratospheric ozone depletion, floods, land escaping and various other problems. These conventional energy conversion technologies are continuously increasing the global warming and health issues. The main reason in developed industrial countries is the environmental management mainly carbon dioxide which is causing all the environmental impacts. Acceptation of low emission carbon dioxide technologies and advancement in high efficiency energy technologies is dire need of the hour. In fact, the reduction of carbon monoxide, carbon dioxide and other toxic gasses ultimately decreases the thermodynamic efficiency of the energy conversion systems. Intensifying fossil fuel prices, strict environment legislation and continuing consumption of fossil fuels demand urgently a modern highly efficient energy conversion technology with the aim of low carbon emission, cost effectiveness, operated and decreasing greenhouse gases to improve the quality of environmental system. The adverse effects such as energy resources depletion, global warming and gradually increasing prices of fossil fuels now have been spurring to explore new beneficial and efficient energy resources to convert the chemical energy of fuels into electricity, building heating and cooling, thermal management of automotive and electronics [3].

Since yet, majority of energy conversion technologies are consuming the fossil fuels, however FCs has stood itself with a most advanced promising technology which avoid combustion of greenhouse gases, with due to directly converting the chemical energy of fuel into electricity through an electrochemical reaction resulting high efficiency, low emissions and clean operation. Additionally, operating on versatile range of fuels, higher power rate, capability to produce energy both locally and globally, easy installation and operation have made the FCs a promising clean, efficient and economical energy conversion technology. FCs, which is electrochemical device, has taken considerable attention in the sight of industrialist to replace the conventional fossil fuels driven energy conversion technologies towards FCs operated energy conversion technologies [4]**.**

FCs are efficient and clean devices to electrochemically convert the chemical energy of fuels such as hydrogen, natural gas, methanol, ethanol and hydrocarbons to electric energy with significantly high efficiency and much lower greenhouse-gas emission as compared to well-established internal combustion engine technologies. Thus, FCs are regarded as the most promising energy-conversion strategies for the sustainable energy development [5].

The first FC was invented in 1839 by Sir William Robert Grove [6]. He is known as father of the FCs. At the London Institution, where he was Professor of Physics (1840–1847), he used his platinum zinc batteries to produce electric light for one of his lectures. A FC is a device in which the energy of a fuel is converted directly into electricity direct current (DC) by an electrochemical reaction without resorting to a burning process, rather than to heat by a combustion reaction [7]. It produces electricity directly from the electrochemical reaction of hydrogen, from a hydrogen-containing fuel and oxygen from the air. Hydrogen is the ideal fuel for a FC, the infrastructure for producing and storing. Hydrogen is industrially produced by steam reformation of naphtha oil, methane and methanol. High purity hydrogen has been mainly used as a fuel for low temperature FCs such as polymer or alkaline electrolyte FCs [8].

A unit cell of FCs system composes an electrolyte solution and porous electrode e.g. anode and cathode electrode on either side. In the typical FC, gaseous fuels (i.e. hydrogen) are supplied continuously to the anode electrode (negative electrode) and an oxidant (i.e. oxygen from air) is fed continuously to the cathode electrode (positive electrode); the electrochemical reactions suddenly occur at the electrodes surface and produce electricity with the by-products including heat and water. The most important features of FCs in comparison to other energy conversion devices are given as they are power generators which are able to directly change chemical energy of fuel (hydrogen, methane and naphtha) into electrical energy with the efficiency higher than conventional coal or gas fired thermal power stations. If the waste heat of FC is used in system, the fuel efficiencies are possible to go upto 90%. The efficiency of FCs can be increased by applying cogeneration of heat with high-temperature systems. For cogeneration of high temperature, waste heat is useful for many applications such as industrial processes or for additional electricity production [9].

2. Classification of Fuel Cell Technology

FCs can be classified based on their temperature of operation: high, medium and low temperature FCs or based on the type of electrolyte used. Primarily, the later method of classification is used for easier understanding and practical reasons and the six common types of FCs are: PEMFC, AFC, PAFC, MCFC and SOFC. The classification determines the chemical reactions that take place, type of catalysts required, operating temperature and fuel used. These factors in turn determine the most suitable applications for each type of FC [10]. Table 1 gives the comparison of different FCs (based on electrolyte type) in terms of their operating temperature, power, efficiency and applications.

2.1. Proton Exchange Membrane System

In proton exchange membrane fuel cell (PEMFC) ion exchange membrane (fluorinated sulfonic acid polymer) is used as an electrolyte, membrane has excellent proton conductor. Water management is the critical problem in PEMFC because the conductivity of membrane is highly depending on the water content. The membrane must be hydrated for efficient performance of FC which depend on the reactant stream humidification, flow field of gas diffusion layer (GDL) and wetting property of GDL and polymer membrane. It is shown in Fig.1.

2.1.1. Working of Fuel Cells

It consists of an electrolyte with anode (negative electrode) and cathode (positive electrode) on either side, when H_2 gas is fed to anode, the H_2 is split into protons and electrons on anode catalyst layer. The protons are allowed to flow through the electrolyte to the cathode side but electrons are not allowed to flow through the electrolyte so electrons flow through the external circuit where electricity (discharge) is produced. When electrons and protons flow from anode to cathode simultaneously the O_2 (from air) gas is fed to cathode after the electron, proton and O_2 react at cathode catalyst layer and produce water and heat as a by-product. The FCs work till the fuel is supplied continuously.

2.1.2. Components of Polymer Electrolyte Membrane Fuel Cells (PEMFCs)

Practically, the primary components of a PEMFC are the ion exchange membrane. There is a solid electrolyte, an electrically conductive, porous gas diffusion layer, an electro-catalyst (the electrodes) at the interface between the backing layer and the membrane. Cell interconnects and flow plates that are responsible to deliver the fuel and oxidant to reactive sites via flow channels and electrically connect the cells. Generally, the first three components are joined together to form a Membrane Electrode Assembly (MEA) which is the heart of the PEMFC [11]. Materials and manufacturing processes for PEMFC stacks is shown in the Table 2 [12].

2.1.2.1. Proton Conducting Membranes

The proton conducting membrane (PCM) is one of the vital components of the membrane electrode assembly (MEA) conducting only protons through it and acting as a barrier between the reactants and electrons and thereby making the PEMFC possible to attain high power densities. The desired properties for a membrane to be used as a proton conductor in a FC are: (i) high durability and low costs membranes (ii) no permeability to reactant species to maximize efficiency (iii) chemical properties compatible with the bonding requirements of membrane with the electrodes (iv) thermal and hydrolytic stability (v) elevated proton conductivity to support high currents with minimal resistive losses and zero electronic conductivity and (vi) good chemical, mechanical and electrochemical stability in FC operating conditions [13].

2.1.2.2. Electro Catalysts for PEMFC

Platinum is considered as the best catalyst for both anode and cathode FC reactions despite a large difference between the oxygen reduction reaction (ORR) and hydrogen oxidation reaction (HOR). The ORR at the cathode is a sluggish and complicated two/four electron reaction. However, even on pure Pt, the over potential for ORR is in excess of 300 mV. A great deal of effort has been made by many researchers toward developing appropriate catalyst materials, especially for the ORR. On the anode catalyst, most of the studies have focused on addressing the carbon monoxide poisoning issues of the Pt catalyst [13].

2.1.2.3. Anode Catalyst

Platinum is an excellent catalyst for the hydrogen oxidation reaction and has a very high exchange current density but is susceptible for carbon monoxide poisoning. Unfortunately, for many practical applications, the presence of trace levels of carbon monoxide impurities in the hydrogen-rich gas mixture produced by reforming of hydrocarbon fuels is inevitable. Carbon monoxide can strongly adsorb on the Pt catalyst and even mere traces (10 ppm) blocks the catalytically active area, thereby significantly decreasing its reactivity. This is termed as "carbon monoxide poisoning" of catalysts. The search for carbon monoxide-tolerant catalysts has been a challenging task in the successful development of more efficient PEMFC systems [14].

2.1.2.4. Carbon Monoxide Tolerant Catalyst

The development of an anode catalyst with significantly lower affinity for carbon monoxide, either under steady state operation or under conditions of high carbon monoxide transient content is the challenge for low temperature PEMFC systems. Platinum-ruthenium catalysts appear to tolerate carbon monoxide better than platinum catalysts and an increase in cell temperature improves tolerance. Carbon monoxide tolerant catalyst research, as from its name, is based on improving the carbon monoxide tolerance of Platinum catalysts by incorporating secondary metals, which might either reduce the Pt-CO bond strength or to supply hydroxyl ions easily to the Pt surface and aid oxidation of carbon monoxide [15].

2.1.2.5. Cathode Catalyst

The cathode accounts for about one third of the performance losses in a PEMFC, mainly due to the limitations of the ORR catalyst. The ORR is a challenging reaction to catalyze, in the sense that the catalyst material must be (a) stable under the extremely corrosive conditions at a PEMFC cathode (b) chemically active to be able to activate oxygen and (c) noble enough to be able to release the oxygen from the surface in the form of water. Oxygen activation typically involves the adsorption of oxygen on the catalytically active sites through a proton and electron transfer to form adsorbed OOH before the O–O bond is broken; hence the catalyst must be able to stabilize OOH moderately. After dissociation, adsorbed O and OH are formed on the catalyst surface and the catalyst must not bind these species too strongly in order for water desorption to be fast [16].

Both noble and non-noble metal-based electrodes were studied for oxygen reduction, however, platinum seems to be the best single metal catalyst. In the case of noble metal catalysts, the activity of palladium-based materials appears to close to that of platinum, whereas in the case of non-noble metal electro-catalysts, transition metal chalcogenides and pyrolyzed macrocyclic compounds have been widely studied [17].

2.1.2.6. Catalyst Support

Carbon is the typical catalyst support material for FC applications due to its large surface area, high electrical conductivity and well-developed pore structure. However, the carbon support, especially at the cathode, is subjected to severe corrosion in the presence of water, according to the following reaction:

$$\mathbf{C + 2H_2O \rightarrow CO_2 + 4H^+ + 4e^-}$$

Agglomeration of Pt catalyst on the carbon surface is inevitable as carbon corrosion becomes more severe. This effect causes the performance of catalysts to degrade quickly, resulting in short lifetime of PEMFC which is not adequate for most of its projected applications. Therefore, highly stable catalyst supports are required to enhance catalyst lifetime. Some of the alternative supports studied include conducting metal oxides and conducting polymers. Vulcan has been extensively studied and used as supports for FC catalysts. Apart from Vulcan, several carbon materials have been investigated as catalyst supports for PEMFCs. Carbon nanotubes (CNTs) have been employed to improve catalyst durability, where Pt/CNTs showed a lower electrochemical surface area loss, a higher ORR activity and better corrosion resistance as compared to Pt/C [18].

2.1.2.7. Gas Diffusion Layer

The GDLs are directly adjacent to the bipolar plates and typically consist of two layers, the micro-porous substrate layer and a micro-porous layer (MPL). The porous gas diffusion layer in PEM FCs ensures that reactants effectively diffuse to the catalyst layer and minimize mass transport over potential. Typically, gas diffusion layers are constructed from porous carbon paper, or carbon cloth, with a thickness in the range of 100–300 µm. The GDLs are gas permeable and help distribute gases to the catalyst layer, conduct electrical current, and also provide a network of paths for liquid water to move from the MEA to the flow channel. The gas diffusion layer also assists in water management by allowing an appropriate amount of water to reach, and be held at, the membrane for hydration. In addition, gas diffusion layers are typically wet-proofed with a PTFE (Teflon) coating to ensure that the pores of the gas diffusion layer do not become congested with liquid water [19].

2.1.2.8. Membrane Electrode Assembly (MEA)

Membrane electrode assembly (MEA), as termed, is the assembly of the membrane and electrodes. As all the reactions within the FC occur in the MEA, it is widely referred as the heart of the FC. The MEA consists of a proton exchange membrane, catalyst layers and gas diffusion layers (GDL). Typically, these components are fabricated individually and then pressed together at high temperatures and pressures. Hence, the design and fabrication method of MEA is highly critical as it directly affects performance of the PEMFC. There are two general modes of MEA assembly. The most common and widely used mode is (i) application of the catalyst layer (CL) to the GDL, termed as the catalyst coated substrate (CCS), followed by membrane addition (ii) other mode is to directly apply the CL to the membrane, catalyst coated membrane (CCM), followed by GDL addition [20].

2.1.2.9. High Temperature-PEMFC

Recently, there has been an increased interest globally on PEMFCs that operate above 120°C and are termed as high temperature PEMFCs (HT-PEMFCs). The advantages of HTPEMFC over the traditional PEMFCs are high tolerance to carbon monoxide impurities, improved reaction kinetics due to increase in the operating temperature, minimum water management issues as the membrane does not require hydration, useful heat which can be used in co-generation applications, small cooling unit is sufficient due to larger temperature difference between the stack and the atmosphere, overall minimize the balance of plant requirements.

The performance of PEMFC will be enhanced by operating above 120°C through improved kinetics of the cathode and anode reactions. The operating temperature will also increase the tolerance towards poisoning species such as carbon monoxide. Although considerable effort has been expended to develop liquid-fueled PEMFC for transportation applications, most practitioners believe that onboard storage of hydrogen will be necessary for practical vehicles. HT PEMFCs can be ideal in this case which minimizes the system complexity with improved cooling system and reduced balance of plant components.

Based on a review of the literature as well as our understanding, we would like to suggest several future research topics for high-temperature catalyst development: (a) Development of highly durable catalyst supports, such as carbon with more graphitic components, ceramic and carbon-ceramic composite materials, which could survive in a high-temperature environment (b) Enhancement of the interaction between supports and catalysts to stabilize Pt nanoparticles and improve catalytic activity (c) Development of new catalysts such as highly durable non-noble catalysts. For long-term sustainable PEMFC commercialization, non-noble catalysts are the solution because of the limited supply and high cost of Pt (d) Optimization of HT-PEMFC catalyst and catalyst layer composition and structure through innovative design, evaluation, as well as fundamental understanding (e) Improved GDL structure and GDL materials, taking into account of higher operating temperature and non-humidified gases (f) Membranes with better conductivity and stability and (g) Better phosphoric acid distribution in the membrane and the electrode to improve the performance.

A number of potential improvements are foreseen for both manufacturing and materials in PEMFC stacks. These include the reduction of the catalyst loading down to 0:04 mg=cm^2 through improved deposition techniques, different nanostructure catalyst supports, the use of carbon composite materials and stamped metal sheets for the low plates and the reduction of the MEA thickness [21].

2.2. Alkaline Fuel Cell (AFC)

AFC was the first FC technology applied to practical power generators. They were introduced in 1960s, with great success in the Apollo missions [22]. Today, they are still serving as power suppliers for space shuttles and drinking water supplier for astronauts. However, due to carbon dioxide poisoning, AFC was considered not suitable for terrestrial transportation applications, as the ambient carbon dioxide concentration far exceeds the acceptable level for an AFC. As a result, in early 1990s, research and development works on AFC in many companies and institutions were drastically reduced, or even terminated [23]. For comparison, PEMFC emerged as a potential technology for transportation application and attracted increasingly more attention. Since several methods have been developed to successfully resolve the AFC, carbon dioxide poisoning problem in recent years, AFC re-emerged as a possible low temperature, moderate power generator for terrestrial applications. It is well known that oxygen reduction reaction kinetics is much faster in alkaline environment than in acidic environment; therefore, cheap nickel and silver, instead of expensive platinum, can be used as catalyst materials in AFC [24].

Much progress has been made, but many people may not be aware of it because other FC types have publicly prevailed. Recently AFCs have received attention because they are very efficient and basically of low-cost [25]. The AFC was the first FC technology to be put into practical service and make the generation of electricity from hydrogen feasible. Starting with applications in space, the alkaline cell provided high-energy conversion efficiency with no moving parts and high reliability. AFCs were used as the basis for the first experiments with vehicular applications of FCs, starting with a farm tractor in the late 1950s equipped with an Allis Chalmers AFC [26].

This was followed by the now famous Austin A40 operated by Karl Kordesch in the early 1970s [27] and continuing today with the commercialization activities of the ZEVCO company [28]. It is shown in Fig.2.

2.2.1. Working Principle of Alkaline Fuel Cell

Procedure in this type of systems is that the electrolyte flows between the anodes. In addition to ion transfer and electric current; its circulation leads the excess heat of system to the outside and before re-entry into the system shall pass within a heat exchanger for cooling. Electrolyte needs pumping system to keep circulating [29]. AFCs use an aqueous solution of potassium hydroxide as the electrolyte, with typical concentrations of about 30%. The overall chemical reactions are given by following equations:

$$\mathbf{2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-} \ldots\ldots\ldots (\textbf{Anode Reaction})$$

$$\mathbf{O_2 + 2H_2O + 4e^- \rightarrow 4OH^-} \ldots\ldots\ldots\ (\textbf{Cathode Reaction})$$

$$\mathbf{2H_2 + O_2 \rightarrow 2H_2O + Electrical\ Energy + Heat} \ldots\ldots\ldots (\textbf{Overall Cell Reaction})$$

By-product water and heat have to be removed. This is usually achieved by recirculating the electrolyte and using it as the coolant liquid, while water is removed by evaporation [30].

2.2.2. Stack Materials for Alkaline Fuel Cells

Table 3 enlists the materials currently used in the various AFCs and systems discussed in the literature. Potential improvements in the AFC stack materials include the reduction of the catalyst loadings, as well as development of cobalt oxide-based catalysts and replacement of the nickel mesh current collectors with a cheaper metal mesh [21].

The direct use of a liquid fuel in a FC has always attracted potential users because of the advantages in terms of logistics as compared to gaseous fuels. However, in conjunction with alkaline cells, which usually use a KOH solution as their electrolyte, the chemical reaction of the KOH with some fuels make that approach impossible, and a fuel processing step before the FC becomes a necessity. The most well-known example of such a liquid fuel is methanol. A liquid fuel that appeared to be more compatible with an alkaline electrolyte is hydrazine (N_2H_4). It can be considered as liquid storage of hydrogen, since it decomposes easily into hydrogen and nitrogen at the anodes. Work on hydrazine in FCs has been carried out intensively since 1950s to 1960s. Depending on the projects, air, pure oxygen, or H_2O_2 were used as the oxidant. Major disadvantages include the highly poisonous nature and the high cost of the hydrazine, as well as material problems, brought work on hydrazine FCs to an end by the beginning of the 1970s, and it does not seem likely that these developments will be started up again in the near future. The focus instead is on the use of hydrogen itself [31].

2.2.3. Manufacturing Techniques and Materials

2.2.3.1. Electrode and Catalyst

Even limiting the discussion to alkaline cells, electrodes and catalysts could fill a book on their own, given the impressive amount of work carried out until now not only by industrial companies but also at universities and research centers. Within the present scope, only a short review will be presented, and in the selection of examples the focus has been on those electrodes currently used in alkaline FC programs. The type and manufacturing of anodes as well as cathodes are linked to the catalysts chosen. Unlike phosphoric acid FCs, alkaline FCs offers the possibility to use not only precious metal catalysts, but also nonprecious ones. The latter are most commonly based on Raney nickel powders for the anodes and silver-based catalyst powders for the cathodes whereas platinum or platinum alloy catalysts are either based on the use of precious metal particles deposited on carbon supports or are part of metallic electrodes, generally based on nickel substrates.

It is clear that there are some general requirements for all types of electrodes: (a) good electronic conductivity, in order to reduce ohmic losses (b) adequate mechanical stability and suitable porosity (c) chemical stability in the alkaline electrolyte environment (d) electro-chemical stability with time, which means stability of the catalysts as such and stability of the way they are incorporated in the electrodes.

Another important characteristic is the hydrophobic or hydrophilic nature of electrodes. The latter usually are metallic electrodes. The former is only partly wetted, generally because of the presence of hydrophobic PTFE (poly tetra-fluoro-ethylene) in carbon-based electrodes. It is important for the long life of hydrophobic electrodes that their hydrophobicity be adequately preserved by an appropriate structure of the PTFE-containing catalytic layer. Usually, electrodes consist of several layers with different porosities, so as to organize within and through the electrodes the respective flows of liquid electrolyte and gaseous fuel (hydrogen) or oxidant (air or oxygen). Widely different techniques can be used for manufacturing such electrodes or some of their layers. Usually powders are mixed and then pressed or calendared into layers. Sedimentation as well as spraying techniques can be used, and in many cases high-temperature sintering operations are used to ensure good mechanical stability [32].

2.3. Phosphoric Acid Fuel Cell (PAFC)

FCs which use phosphoric acid solution as the electrolyte, are called PAFCs. The phosphoric acid in aqueous solution dissociates into phosphate ions and hydrogen ions; the hydrogen ions (H^+) act as the charge carrier.

$$\mathbf{H_3PO_4 \rightarrow H^+ + H_2PO_4}$$

Phosphoric acid is chemically stable, and is easy to handle. It also has an extremely low vapor pressure even at an operating temperature of 200°C (473 K). This implies that phosphoric acid in the electrolyte layer cannot be easily discharged from the FC together with the cell exhaust gas, although even such minute discharge, results in the degradation of cell performance in the long term. It is shown in Fig.3.

2.3.1. Working Principle of Fuel Cell

At the fuel electrode, pure hydrogen or reformate fuel gases the principal component being hydrogen is supplied, and air is supplied at the air electrode; the resulting electrochemical reaction yields an electric power output. At the fuel electrode, hydrogen reacts at the electrode surface to become hydrogen ions and electrons, and the hydrogen ions migrate toward the air electrode within the electrolyte [33].

$$\mathbf{H_2 \rightarrow 2H^+ + 2e^- \ldots\ldots\ldots \text{Fuel Electrode}}$$

At the air electrode, the hydrogen ions, which have migrated from the fuel electrode; electrons, which have passed through the external circuit, and oxygen supplied from outside, combine to produce water in the following reaction:

$$\mathbf{\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \ldots\ldots\ldots \text{Air Electrode}}$$

Hence the net FC reaction produces water as follows:

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

2.3.2. Cell Structure

The PAFC itself consists of a pair of porous electrodes (the fuel electrode and air electrode) formed from mainly carbon material, between which is placed an electrolyte layer consisting of a matrix impregnated with highly concentrated phosphoric acid solution. The catalytic layer of the electrodes where reactions take place consists of the carbon material, minute metal catalyst particles, and water repellant material, in a construction such that the reaction gas is supplied and the electrolyte retained effectively. The voltage obtained from a single FC is from 0.6 to 0.8 V or so; in actual power plants several hundred cells are stacked and connected in series, forming a sub unit called a "cell stack". Heat is generated due to energy losses in the course of the electrochemical reaction of hydrogen with oxygen, and so cooling plates are inserted at regular intervals between FCs, and cooling water is passed through them to maintain a cell operating temperature of about 200°C (473 K) [34].

2.3.3. Features of Phosphoric Acid Fuel Cells

The PAFC do not suffer the carbon dioxide-induced electrolyte degeneration seen in alkaline FCs, and so can use reformed gas derived from fossil fuels, though expensive platinum catalyst is necessary in order to promote the electrode reactions. Thus, it can make use of city gas (natural gas-based) and other existing fuel infrastructure. However, when carbon monoxide exists at high concentrations, as in coal-gasified gas, the platinum catalyst used in electrodes is poisoned, leading to performance degradation, so that use of such fuels is impractical without effective means of eliminating carbon monoxide. This gives an additional constraint. The operating temperature is about 200°C (473 K). Consequently, if the cell is designed such that it does not make direct contact with the phosphoric acid, copper, iron and other metals can be used. Also, in order to endow the electrode catalyst layer with water-repelling properties, a fluoride resin (PTFE) or other highly heat-resistant organic material may also be used. In order to remove the heat generated by the electrode reactions, the FC is itself water-cooled as mentioned above [35].

Waste heat at a temperature range below 200°C is available; which cannot just be used for space heating and water heating, but can also be extracted in part as steam and used as the heat source of refrigeration equipment for cooling. The electric power generation efficiency of PAFCs under atmospheric pressure operation is approximately 40% (LHV basis), which is superior, or at least competitive with existing gas turbine and gas engines. Properties of low NOx and low noise make them suitable for cogeneration systems for urban environmentally friendly power sources. Unlike the high temperature FC systems such as MCFCs and SOFCs, a combined cycle system with gas turbine or steam turbine generators to maximize the system efficiency is generally difficult for PAFCs, since the quality of plant exhaust heat is inadequate for such purposes. In pressurized PAFC systems, thought reformer exhaust gas at elevated pressure and temperature can be passed through an expanded to drive an air compressor or an electric power generator, the total power generation efficiency stays in a range of 44–46% [36].

2.4. Molten Carbonate Fuel Cell (MCFC)

This is a simple high-performance matrix-free biomass MCFC without carbon dioxide recirculation. In terms of energy sources, about 87% of the energy consumed in the world depends on fossil fuels [37] which is a major source of carbon dioxide emission. It is desirable to integrate more renewable energy sources with lower carbon footprints. Biomass from energy crops, agricultural residues, wastes and residues, and forestry is an important renewable energy source. It is estimated that global biomass potential is about 200 EJ (up to 600 EJ), which is about one-third of the world's total energy consumption [38]. Biomass energy is used to generate heat through combustion or to generate electricity by supplying steam for the same kind of steam-electric generators used to burn fossil fuels. FC technology is another type of technology that is used to convert the chemical energy in biomass into electricity. Biomass can be used to produce charcoal through pyrolysis. The charcoal produced is an ideal fuel for DCFCs [39]. Schematic diagram of MCFC is shown in Fig.4.

2.4.1. Carbon Dioxide Conversion into Useful Products

One technique that has been proposed to compromise between the pros and cons of fossil fuels is carbon capture and storage (CCS), in which carbon dioxide is captured, compressed and stored away from the atmosphere for protracted periods of time in geological formations. Alternative to storage, it would be highly desirable to convert the captured carbon dioxide to useful products such as hydrocarbons, methanol and other chemicals [40]. Electrochemical reduction of carbon dioxide in aqueous solutions is a proven technology and requires the use of appropriate electrolyte, electrode material, catalyst and operating conditions [41]. An alternative method of converting carbon dioxide to a useful product is to reduce it to solid carbon *via* electrolysis in molten alkali metal carbonates. In the 1960's, researchers established that carbon could be electro-deposited from molten salts containing carbonate and lithium ions ($CO_3^{2-}$and Li^+) [42].

More recently, a number of authors have suggested that this process could be utilized for the indirect conversion of carbon dioxide to carbon [43] through electro-reduction of CO_3^{2-} ions in the molten salt electrolyte to solid carbon and oxide ions. The oxide ions produced from the reaction can react with carbon dioxide present in the atmosphere above the molten salt to regenerate the CO_3^{2-} ions [44].

$$\mathbf{CO_3^{2-} + 4e^- \rightarrow C + 3O^{2-}}$$

$$\mathbf{CO_2 + 3O^{2-} \rightarrow CO_3^{2-}}$$

2.4.2. Fuel Processing

MCFCs have two types of fuel processing. One is an external reforming MCFC (MCFC-ER) that produces hydrogen at the outside of the MCFC stack. In this case, the stack temperature can be controlled by convection heat transfer only. Therefore, the external reforming adopts a pressurized operation to supply a high rate of cooling gas flow. The other type is an internal reforming MCFC that directly generates hydrogen in the MCFC stack. The stack temperature is controlled within the stack to remove the heat generated from the endothermic reforming reactions. Because the MCFC with internal reforming does not require a high flow rate, this FC can operate under atmospheric conditions [45]. Internal reforming processes can be further divided in direct (MCFC-DIR) and indirect (MCFC-IIR) one: in the first case, the reforming is made in the anode room itself, with benefit on thermal exchange efficiency, on the other hand, the internal reforming, can be also made just adjacent the anode. The two types can be also integrated in a two-step reforming of the anode inlet flow [46].

2.4.3. Working Principle of FC

In new designed FC, air or oxygen was not bubbling into the molten carbonate electrolyte. The only possible direct chemical reaction between the fuel and oxygen is through dissolved molecular oxygen (O_2). It has been reported that, at a temperature of 600°C, the dissolved oxygen in 62 mole percent Li_2CO_3–38 mole percent K_2CO_3 and that in 52 mole percent Li_2CO_3–48 mole percent Na_2CO_3 are in charged forms, such as superoxide (O^{-2}) or per-carbonates (CO_4^{-2}) and the dissolved molecular oxygen (O_2) at high temperatures is negligible. [47]. In the reaction between charged oxygen species and the anode, there must be a loss of electrons to generate electricity. Under this circumstance, the charged dissolved oxygen is used as the charge carrier. The possible cathode reactions are:

$$\mathbf{O_2 + e^- \rightarrow O^{2-}}$$

$$\mathbf{CO_2 + O_2 + 2e^- \rightarrow CO_4^{2-}}$$

The formed anions will diffuse in the molten carbonate and react with the solid fuel at the anode. If carbon is used as the fuel, the reactions at the anode are:

$$\mathbf{C + O^{2-} \rightarrow CO_2 + e^-}$$

$$\mathbf{C + CO_4^{2-} \rightarrow 2CO_2 + 2e^-}$$

$$\mathbf{C + 2CO_3^{2-} \rightarrow 3CO_2 + 4e^-}$$

For reactions second and forth reaction, the charge carriers are O^{-2} ions; thus, carbon dioxide is not required for the reaction. Therefore, theoretically, an MCFC can work without flowing carbon dioxide. In high-temperature FC technology, fuel (usually natural gas), mixed with steam, can feed directly the anode of the FC stack. In MCFC, the reforming stage can be integrated within the FC in an indirect (IIR) or direct way (DIR). In the IIR case, a reforming unit is placed in the stack, converting natural gas and steam into a hydrogen-rich gas before entering into the cell anode. In MCFC-DIR, instead, the catalyst bed is located in the same chamber of the anode, providing better thermal and steam management. It is assumed that only hydrogen is directly converted in the cell electro-chemical reaction. Other components in the fuel, such as carbon monoxide, methane and higher hydrocarbons are converted through reforming processes and shift reactions: in IIR case, the fuel reaches an equilibrium in the integrated reformer at a specified temperature before it can be transmitted to the anode, while, when the DIR is considered this reforming temperature is the same of the FC one and the methane conversion is affected by mutual interaction of reforming and oxidation reactions at the anode side [48].

2.5. Solid Oxide Fuel Cell (SOFC)

A SOFC is a device that generates electricity directly from oxidizing a fuel (it generates energy based on a chemical relation) [49]. SOFC is shown in Fig.5.

2.5.1. Working Principle of Solid Oxide Fuel Cell

Hydrogen flows into the FC through the anode. Chemical reaction at anode separates the hydrogen atoms into protons and electrons. The electrons flow to the electric circuit generating electricity. Protons flow through electrolyte to the cathode. Oxygen flows into the FC through the cathode. Chemical reaction takes place at cathode, between the protons coming from the anode, electrons and oxygen to produce water and heat.

2.5.2. Components of Solid Oxide Fuel Cell

The main components of SOFC are: the anode, cathode and electrolyte.

2.5.2.1. Anode

The anode is where electrochemical oxidation of the fuel gas occurs as shown in this reaction

$$\mathbf{H_2 \rightarrow 2H^+ + 2e^-}$$

The anode should have many qualifications and the most important ones are high electrical conductivity and high porosity.

2.5.2.2. Cathode

The cathode is where electrochemical reduction of oxygen occurs as shown in this reaction**:**

$$\mathbf{1/2O_2 + 2H^+ + 2e^- \rightarrow 2H_2O}$$

The cathode should have many qualifications such as high electronic and oxygen ion conductivity, chemical stability at different operating temperatures, enough porosity and chemical compatibility with the electrolyte.

2.5.2.3. Electrolyte

The electrolyte is where component that allows the ion transportation between electrodes. The main qualifications of the electrolyte are high oxygen conductivity, high ion conductivity and no porosity. Generally, the reaction of the cell produces heat, water, and electrical work as shown in the equation:

$$\mathbf{1/2O_2 + 2H^+ + 2e^- \rightarrow 2H_2O + W_{Electricity} + Q_{Heat}}$$

The passage of O^{-2} ions is done through the electrolyte, as more or less hydrated. The electrons collected at the anode joining the cathode through the load is produced from hydrogen and oxygen, water, electricity and heat. This can be interpreted as the reverse reaction of the electrolysis of water. The electrodes are separated by a solid electrolyte whose role is to allow ion migration from one to the other, under the effect of the created electric field [50].

2.5.3. Energy Efficiency

Solid oxide FC technology attracts more attention than the other FCs technologies mainly because of the various advantages especially when it come the very low emissions and very high efficiency. We can clearly understand that the FCs electric efficiency is relatively higher than the combustion-based power plants. The efficiency of FCs is between 50% and 60% and if we combine SOFC with gas turbine hybrid systems we can get an efficiency that exceeds 70% [51].

2.5.4. Solid Oxide Fuel Cell Designs

There are two basic cell structure types for SOFC batteries: planar and tubular. Each design offers a different performance. Tubular technology is the simplest one to design. The Fig.6 shows the potential performance of SOFC operating at 1000°C. We can clearly see that the planar design provides a better performance than the tubular one. But the planar technology is difficult to setup with problems of leakage due to the expansion of materials in high temperatures.

The potential difference of a power source is an electrical pressure that triggers a current to flow in a circuit. It is the work performed per unit of charge when a charged object moves between two points in an electric field [52]. Performance of SOFC operating at 1000°C is shown in Table 4.

2.5.4.1. Tubular Design

The components of the tubular design are manufactured in the form of a hollow tube. The cell is built in layers around a tubular cathode with air flowing through the inside of the tube and the fuel flowing around the exterior of the tube. Fig.6 explains the components of tubular solid oxide FCs.

2.5.4.2. Planar Design

The components of the planar design are manufactured in horizontal stacks, with air and fuel flowing through canals fabricated into the cathode and anode [50]. Fig.7 explains the parts of FC. The comparison between planar and tubular solid oxide fuel cell is shown in Table 5.

This table shows the comparison between some properties of Planar and Tubular SOFC

3. Characteristics and Applications of Fuel Cells

In order to move towards a sustainable existence in our critically energy dependent society, there is a continuing need to adopt environmentally sustainable methods for energy production, storage and conversion. The use of FCs in both stationary and mobile power applications can offer significant advantages for the sustainable conversion of energy. Benefits arising from the use of FCs include efficiency and reliability, as well as economy, unique operating characteristics and planning flexibility and future development potential. By integrating the application of FCs, in series with renewable energy storage and production methods, sustainable energy requirements may be realized. This technology is very interesting for a many different applications including micro power generators, auxiliary power generators, stationary power generators, distributed power generators and portable power generators for transportation, military projects and the automotive market. These are all applications that will be used in a large number of industries and environments on a worldwide scale [53].

3.1. PEMFC Advantages and Disadvantages

Advantages of the PEMFC are as follows: (i) power density of the cell stack is very high, particularly in pressurized systems (ii) operative pressure difference between the anode and the cathode can be very large due to the mechanical properties of the solid polymer electrolyte.

Therefore, operating with a pressurized system it is quite easy and (iii) a wide variety of cell component materials can be adopted on account of its low operating temperature (80°C). In particular, use of low-cost carbon materials may contribute to the cost reduction of cell stack. On the other hand, the PEMFC technology shows the disadvantages listed below: (a) PEMFC catalysts are susceptible to carbon monoxide poisoning due to their low operating temperature. Therefore, carbon monoxide concentration has to be reduced below 10 ppm with carbon monoxide removal if the reformate from hydrocarbons or alcohols is used as a fuel for the PEMFC (b) temperature of recovered waste heat is lower than that of other FCs. As a result, recovered heat can be utilized only as hot water and (c) water management of the membrane electrolyte is very important for the cell performance, because it secures the appropriate amount of water to show its sufficient ionic conductivity.

On account of these features, PEMFC development for electric vehicle and portable power applications still needs more time. The PEMFC technology is also promising for residential cogeneration systems if combined with small-scale natural gas fuel processors [54]. They are highly efficient in their operation. They are able to produce more electricity per unit of fuel. Low carbon dioxide emission occurs. Their operating temperature is also very low. They work on quick startup mechanism [55].

3.2. PEMFC Applications

PEMFCs can generate power from some volts to hundreds of kilovolts. Because of this, they may be used in almost every application where local electricity generation is needed. PEMFC are already being tested inside applications such as automobiles, buses, utility vehicles, scooters, bicycles, aerospace/military applications (e.g. Shuttle and submarines). PEMFC are also being tested for distributed power generation inside individual homes, buildings or communities due to their modularity and excellent flexibility in power supply [56]. PEMFC used for different applications have at the same time different configurations whose characteristics change in order to achieve the requirements needed by the different environments in which they are involved. Here we will now analyze the three most important application environments for PEMFCs which are the followings: (a) transportation (upto 70 kW) (b) stationary power applications (upto 500 kW) and (c) portable power applications (upto some kW).

3.2.1. Applications for Transportation and Automotive Sector

Transportation is a competitive and promising sector for PEMFC due to two factors: (a) the future expected deplete of fossil fuels and (b) the possibility to guarantee environment friendly vehicles. The development of a Fuel Cell Vehicle (FCV) requires the on-board integration of a fuel-cell system and electric energy storage devices with an appropriate energy management system. It is a fact that FCV systems equipped with direct conversion fuel processors (which is the most secure FCV technology since it does not imply the storage of hydrogen that can easily cause an explosion) can successfully compete with conventional Internal Combustion Engine (ICE) vehicles in all aspects except for the cost and maintenance. The main requirements that the automotive PEM stack technology still needs to fulfill in order to become a major technology on the market are: (i) a very short start-up time (fraction of a minute) (ii) small size and weight of the PEMFC systems and (iii) in operating life time which spans from 3000 to 5000 operational hours [57].

3.2.2. Stationary Applications for Distributed Power Generation

Distributed power generation is another sector in which PEMFC developments holds great interest. The high modularity, high efficiency and lower emission of PEMFC stacks allow their use for the expansion of the electric network. As a result, part of the loads of the network can be directly managed by many power systems which are distributed inside different types of buildings and structures, thus lowering the burden placed on the power plants. Stationary FCs for distributed generation could be used inside in many different places as the main power source in places not reached by the electric power grid (i) as supplemental power source working in parallel with the electric grid (ii) as complementary power source in power systems based on renewable energy like photovoltaic and wind turbines (thus generating power when these energy sources cannot meet the demand) and (iii) as emergency power generators to cover malfunctions of the electric grid. The requirements that these systems have to fulfill are: (a) a lower noise level since the power unit is usually installed indoor (b) short start-up time for emergency power systems (c) power units designed for outdoor use must be able to operate in extreme ambient conditions and (d) an operational life cycle which spans from 40,000 to 80,000 hours (five to ten years).

3.2.3. Applications for Portable Power Systems

Portable power systems based upon PEMFC technology consists of 2 main types of applications [56] (i) power cells for battery replacements with power below 100 W and (ii) portable generators with at least 1 kW power based on power cells. The main factors that must be considered in those systems are (a) the operative time of the battery and (b) the size and weight of the system. Power units with significantly higher power densities or larger energy storage capacities are suited for applications like portable computers, communication and transmission devices, power tools and remote meteorological or other observation systems. PEMFC detains many advantages like fast startup, simplicity of operation, zero emissions and potential for low capital and maintenance costs that have attracted many interests regarding DG (distributed generation) applications.

3.3. AFC Characteristics and Applications

Summarizing up what have been said AFCs can boast many advantages (i) high simplicity of the cell structure (ii) fast start up (iii) competitive costs for the cell construction (due to the simplicity of the materials involved) (iv) capacity to reach an electrical efficiency of 65% (which is really high for cold FCs) and (v) a life cycle time between 10,000 and 15,000 hours due to the good compatibility of the materials in the cell (however life cycles of 40,000 hours are required in order to a full commercialization of a FC technology).

As a result, if compared with PEMFCs, the AFCs are cheaper and more efficient. The reason which prevents the AFCs to become the dominant FC technology on the market is the carbon dioxide poisoning of the electrolyte. In fact, due to the high reactivity of hydroxide ions with carbon and its composites even the slightest quantity of carbon dioxide can greatly compromise the cell efficiency. This implies that the cell must be fueled with pure hydrogen and oxygen which is not a problem inside an environment like space but it becomes a great burden inside the earth atmosphere. As a matter of fact, very expensive purification systems are required in order to guarantee the gases purity thus greatly increasing the effective cost of a power generator based on AFCs. The result is that the AFCs are still the main technology used inside the space environment as well as inside many applications regarding submarines, but they are not considered a suitable technology for static or mobile applications on earth [58].

3.4. PAFC Characteristics and Applications

PAFCs are the most reliable fuel technology on the market characterized by the qualities which are listed below: (a) an operating life cycle which exceeds 65,000 hours with an operative temperature between 150°C and 220°C (b) an electric efficiency upto 40% which can be boosted upto 60% through the use of combined heath systems (c) partial immunity from carbon monoxide poisoning (it is immune only if there is not a high concentration of this element inside the gas) and (d) capability to use hydrogen fuels without high level of purity like reformed carbon fuels thus reducing the costs for power generation.

However, PAFCs can't really be considered a high temperature FC but more likely a technology between the low temperature FCs and the high temperature FCs. The operative temperature of the PAFCs is in fact too low to be successfully used inside big stationary power generating applications (>5 MW) due to the following reasons: (i) fuels with high levels of carbon monoxide like natural gasses and coal gasified gas can't be used without poisoning the platinum catalyst inside the cell and (ii) heated steam generated by PAFCs is too low in temperature to be used inside big combined heath systems. Such characteristics have made the PAFC an ideal candidate for early small and medium stationary applications. However, in order to begin a massive commercialization of the technology there are still some objectives that must be reached: (a) an operative life cycle of at least 80,000 hours and (b) a cost for power generation below 1,200 €/kW [59].

3.5. MCFC Characteristics and Applications

MCFCs are currently being developed and demonstrated in several countries around the world like USA, Japan, Korea and Germany. The applications that are being demonstrated ranges, regarding the generated power, between 125 kW and 1 MW [60]. The main advantages that the technology detains are summarized as follows: (a) MCFCs efficiency goes up to 45% and, since high temperature and steam is generated, if they are used with combined cycles heath systems the efficiency of the MCFCs applications exceeds 50%–60% (b) MCFCs can use a wide array of hydrogen rich fuel like natural gas or coal gasified gasses and, if the fuel reforming takes place inside the cell, the construction of an external reformer is not needed. These characteristics greatly reduce power generation costs and (c) the possibility to use standard and low-cost materials such as stainless steel and nickel-based alloys greatly participate in the reduction of the cell construction costs.

However, the high temperatures involved and the electrolytes chemistry are the cause of the following disadvantages: (i) a low operative life cycle due to the corrosion caused by the electrolyte used, the loss of the electrolyte due to the high temperature (ii) slow starting times determined by the need to reach an operative temperature of 650°C and (iii) impossibility to re-start the cell stack after a shut-down. Therefore, although there are demonstration programs all around the world, there is still a large effort in terms of research and development which is being carried on by many organizations, industrial companies and universities. Those efforts are focused upon the improvement of the cell operative life cycle and the increase of the power density of the cell.

3.6. SOFCs Characteristics and Applications

SOFCs represents one of the most efficient and interesting technology among FCs. Currently there are many high temperature SOFCs systems with a power around 10 kW which are being demonstrated. Moreover, there is a big interest into the development of low temperature SOFCs for the use in automotive systems [61]. Compared to the other FC technologies, SOFCs presents the following advantages: (a) highest electric and thermal efficiency (up to 80% with combined heath systems) among all the FCs (b) no need to use noble metals as catalysts inside the cell or other expensive materials (c) possibility to use many different low-cost hydrocarbon fuels (biogas, coal gas and natural gas) (d) a long operative life cycle due to the low degradation of the materials (e) structural simplicity of the cell permits the simplification of the production lines (f) very low emissions both in terms of NOx and SOx if the cell is supplied with hydrocarbon fuels (zero emissions if the cell is supplied with pure hydrogen) and (g) low noise production system [62].

The disadvantages are the long starting times (which is a common disadvantage among high temperature FCs) needed in order to reach the proper operative temperature required by the cell electrolyte and the thermo-mechanical problems due to coupling of materials with different thermal expansion coefficients. The poor ability to thermal cycling of the SOFC cells imposed to use this type of FC only for stationary applications to achieve significant lifetime. Due to their high efficiency, low costs and environment friendly characteristics, SOFCs will be a candidate, after the PAFC technology, to reach a full commercialization on the FC market. In particular high expectations are placed on stationary and distributed power applications both inside North America and Europe. Since SOFCs characteristics are highly suitable even for portable applications there are a lot of research efforts focused on the reduction of the cell operative temperature. The aim of those researches is to obtain a reduction around 450-600°C. Steady progress is also being made in terms of the development of auxiliary power sources for private homes and automobiles.

3.7. Future Directions of Fuel Cell Science and Technology

Future development and implementation of FC technology would depend on upward trend in global oil price, depletion of oil wells, fall in oil well discovery and the improvement of hydrogen energy infrastructure. The concern for environmental pollution and damage from the emission of automobile, thermal power plant, petroleum-crude refinery would catalyze the process of development unless financial benefits in terms of lowering of pollution damage cost are perceived by users and the manufacturers. Infrastructure development of the hydrogen energy encompasses production, distribution, dispensing and safety regulations of fuels (e.g., hydrogen, alcohol, esters and natural gases, naphtha and synthesis gases), which is directly fed to the FCs or to the fuel processor. Out of these hydrogen and alcohols can be generated from renewable sources (wind, solar power in water electrolysis, biomass gasification and fermentation) and others including hydrogen and alcohol can also be generated from fossil fuel. In the former case, greenhouse gas emission is much lower and almost negligible.

One can dream of zero emission of air pollutant and greenhouse gases from automobiles and stationary power plants except for the case of biomass gasification. In the latter case, the air pollutant will be generated in a centralized location and cities will be free of pollution, which is otherwise generated from automobile using internal combustion engine. It should be noted that the hydrogen FC vehicle (H_2FCV) and H_2FCV-hybrid electric vehicle offers least environmental damage among all the advanced options. When fueled with hydrogen derived from natural gas, pollution damage costs, 1/8 as large as for today's gasoline internal combustion engine vehicles without carbon dioxide sequestration and 1/15 as large with carbon dioxide sequestration. Although economics does not work out at present for PEMFC based automobile or SOFC based stationary power plant with present inadequate hydrogen infrastructure but it is hoped that with the increase in crude price, no new crude or gas reserve findings, increase in FC stack efficiency and decrease in cost of the FC and improvement of hydrogen energy infrastructure facility, the FCV and distributed power generation from FC will become more profitable leaving aside the cost benefits due to less environmental pollution [63].

Table 1 Different Types of FCs

Type of FCs	Operating Temperature (°C)	Power (kW)	Efficiency (%)	Applications
PEM	60-110	0.01-250	40-55	Portable, mobile and low power generation
AFC	70-130	0.1-50	50-70	Mobile, space and military
PAFC	175-210	50-1000	40-45	Medium to large scale power generation
MCFC	550-650	200-100,0000	50-60	Large scale power generation
SOFC	500-1000	0.5-2000	40-72	Vehicle auxiliary power unit

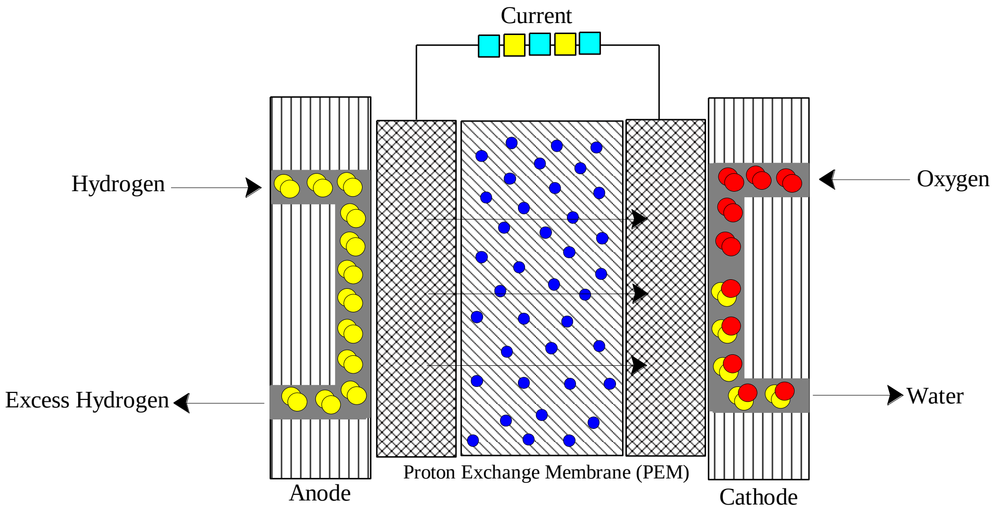

Fig.1 Schematic representation of PEMFC

Table 2 Comparison of Different Types of FCs

Components	Materials	Manufacturing Process
MEA membrane	Polymer matrix with attached sulfonic acid groups	Complex manufacturing process
Electrode substrate	Carbon paper PTFE	Attached to membrane through hot pressing
Catalyst	Pt (0.4–4 mg=cm^2)	Deposited between the electrode membrane and the electrode substrate
Other stack components Flow field plated (including cooling plates)	Graphite, stainless steel and carbon polymers etc.	Machined out of bulk material, stamped and injection molded
Non repeating components	Off the shelf components	Simple machining

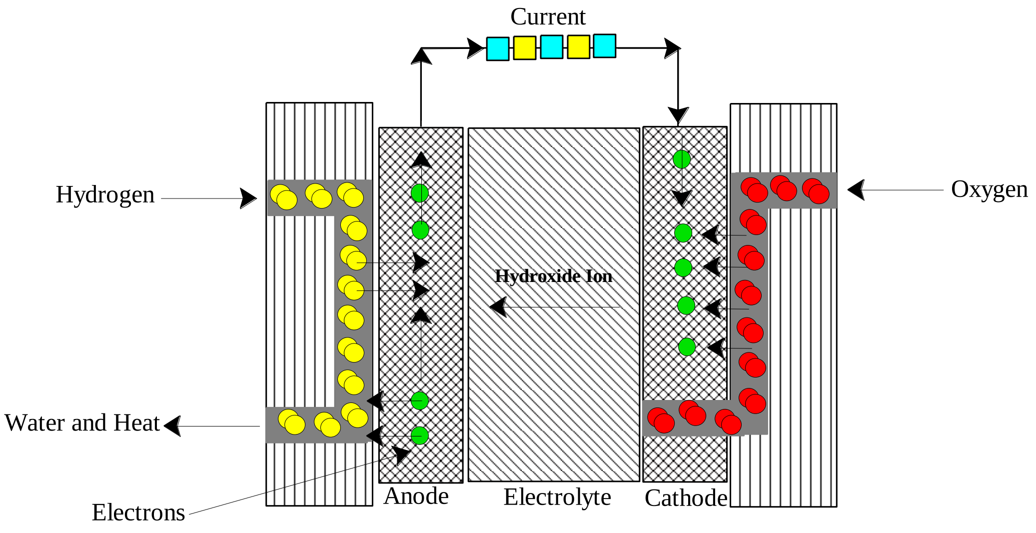

Fig.2 Alkaline Fuel Cell

Table 3 Components of AFC

Component	Material	Manufacturing Process

Anode	PTFE Powder, Graphite Powder, Catalyst (Pt or Pd 0.12–0:5 mg=cm^2) Ni–Al and Ag	Mechanical processes involving grinding, dispersion, filtering, rolling and drying
Cathode	PTFE Powder, Graphite Powder and Catalyst: (Pt or Pd 0.12–0:5 mg=cm^2) Ni–Al, Ag	Mechanical processes involving grinding, dispersion, filtering, rolling and drying
White Layer (For both Anode and Cathode)	PTFE Powder	Pre-forming and rolling
Module Current collectors	Nickle mesh	Pressed to black and white layers
Plastic frames	ABS Plastic	Injection molding and manual assembly with electrodes
Spacers	Unknown	-
Stack assembly	-	Plastic frames and friction-welded to module casing for sealing

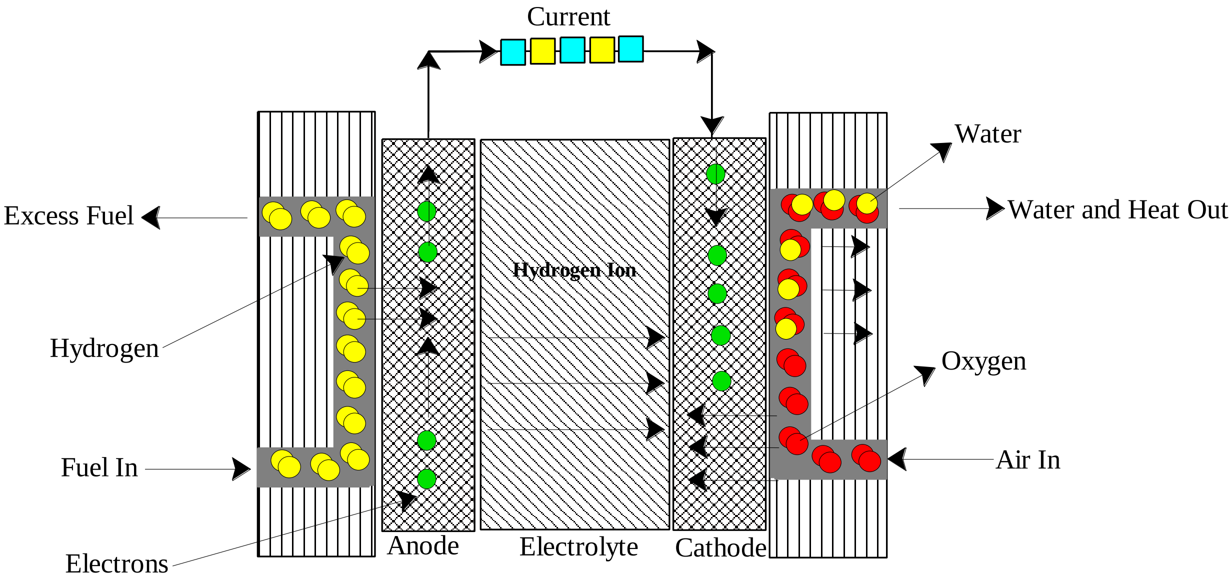

Fig.3 Phosphoric Acid Fuel Cell

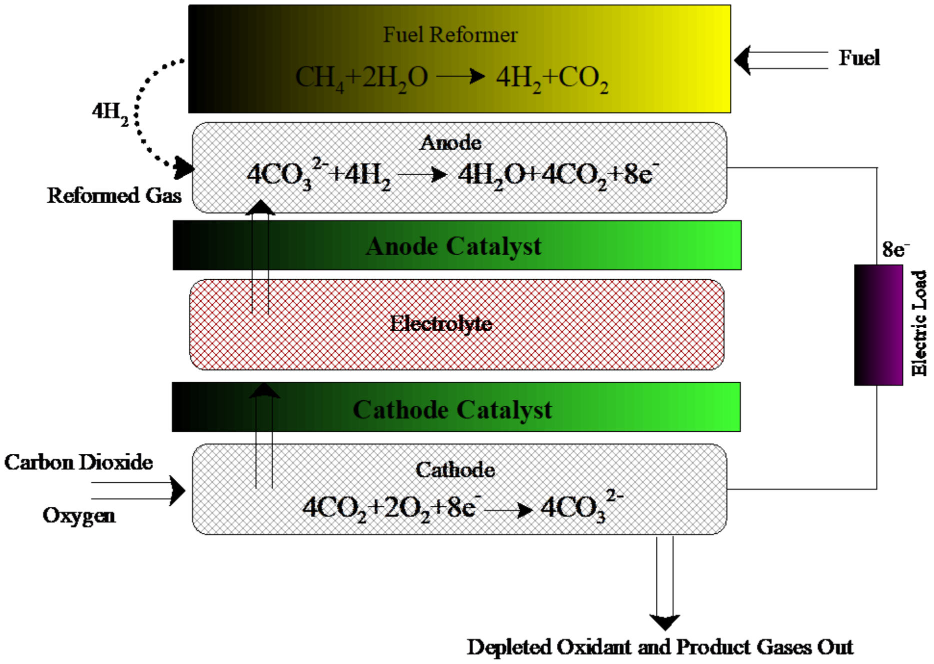

Fig.4 Schematic representation of molten carbonate fuel cell

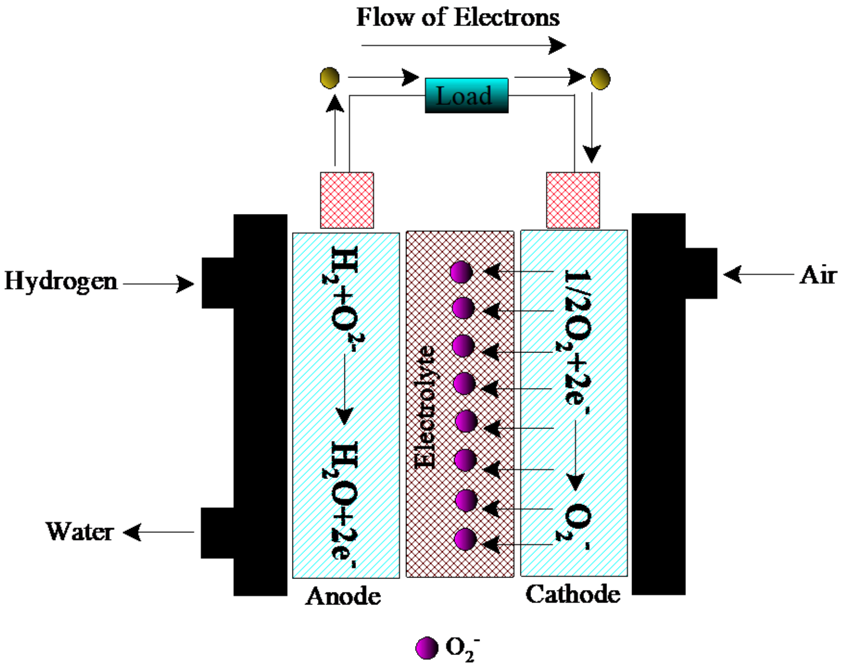

Fig.5 Solid Oxide Fuel Cell

Table 4 Potential performance of SOFC operating at 1000°C

Design	Potential Difference	Power Density	Efficiency
Tubular	0.65 Joules/Coulombs	0.261 W/cm^2	50%
Planar	0.8 Joules/Coulombs	0.318 W/cm^2	61%

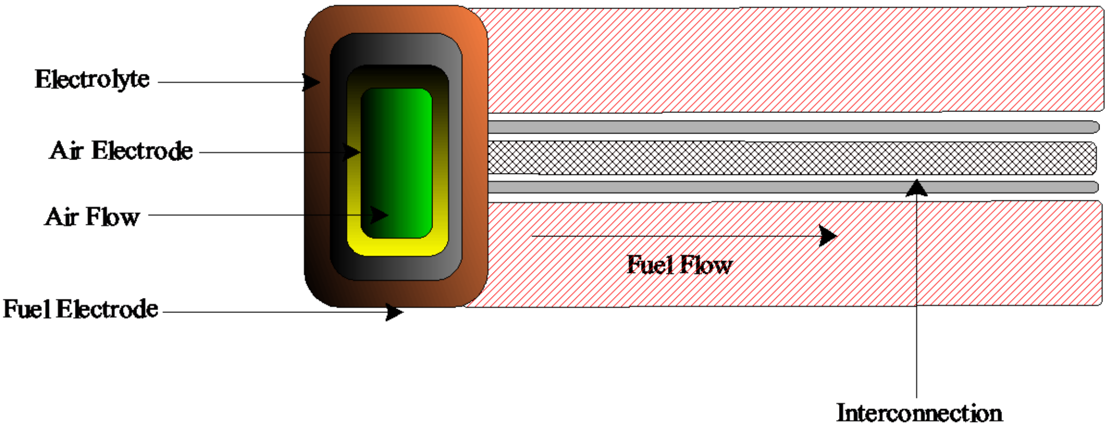

Fig.6 Tubular Solid Oxide Fuel Cell

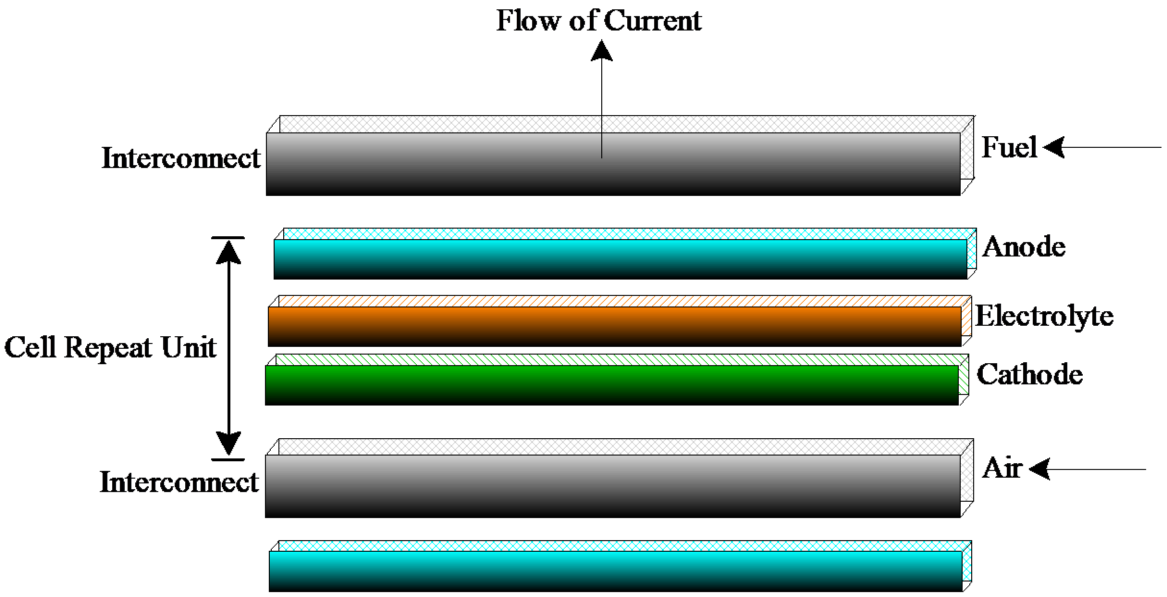

Fig.7. Planar Solid Oxide Fuel Cell Configuration

Table 5 Comparison between some properties of Planar and Tabular SOFC

Properties	Planar	Tabular
Ease of fabrication	Easy	Difficult
Cost of fabrication	High	Low
Ease of sealing	Difficult	Easy
Long-term stability	Fair	Excellent
Thermo-cycling stability	Fair	Good

Conclusion

Today the world is going to find the several ways in the progress of energy generation and conversion which have the key factor to increase the economy of a nation and play a vital role in interaction between nature and society. Since yet, fossil fuels have the main lead to provide the energy resulting environmental pollution and greenhouse emission, especially toxic gasses, such as carbon dioxide and carbon monoxide cause the health hazard in urban areas. The great opportunity for FCs is issued from the fact that this technology connects two basic future energy carriers: electricity and hydrogen. FCs are the most appropriate technology for the conversion of the hydrogen's chemical energy to electricity, due to the high conversion efficiency. Furthermore, it is a common belief that we are witnessing the beginning of an extremely exciting time for FC and hydrogen technologies, driven primarily by three forces: the recognition of hydrogen as an attractive and important energy storage platform by energy utilities; the interest of major global telecoms in FC backup power; and the commercialization of fuel cell electric vehicles (FCEV) by the world's major automakers. With an increasing number of truly global companies utilizing and investing in FC technology and with the supply chain improvements and technology recognition that will come with the mass manufacture of passenger vehicles, the FC industry is becoming increasingly well-aligned for global success. FC, which is electrochemical device, has taken considerable attention in the sight of industrialist to replace the conventional fossil fuels driven energy conversion technologies towards FCs operated energy conversion technologies.

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