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Fuel Cell Technologies and Applications

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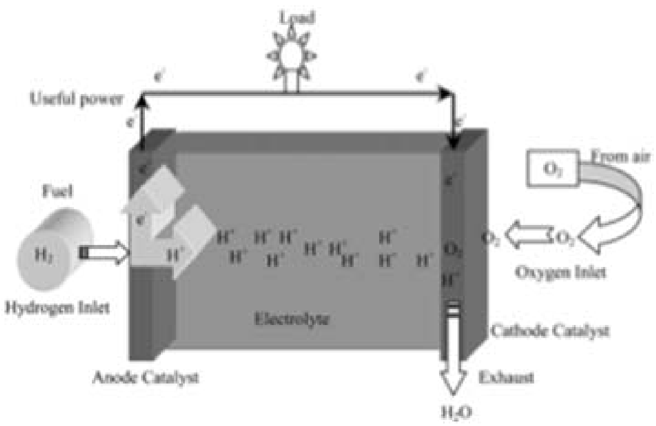
Abstract: ***This paper provides a review of the various technologies of fuel cells based on the publications throughout the past century. It also highlights the various applications of the fuel cell technology in day to day life resulting in the development of a viable option to the existing energy production techniques. As a clean fuel is used in the fuel cell technology to produce electricity, it results in almost zero emissions, thus being environment friendly and also offering high efficiencies and a constant source of power. Although the fuel cell technology seems to be an impressive alternative to the traditional technologies, certain challenges hinder the commercialization of this technology which has also been discussed in this review. Thus a lot of R&D needs to go into this technology until it becomes a large scale reality.***

Keywords: Fuel Cells, Fuel Cell Vehicles (FCV), Direct Alcohol Fuel Cells (DAFC), Membranes, Electrodes

1. Introduction

Fuel cell is an energy conversion device which produces electricity by electrochemically combining fuel (H_2) and oxidant (O_2 from air) through electrodes and across ion conducting electrolyte. The primary components of a Fuel cell are an ion conducting electrolyte, a cathode and an anode. The electrolyte separates the oxidants and the fuels and serves as a barrier for gas diffusion but permits ion transport. Alkaline Fuel Cells have an impressive specific power and energy density even at low temperature due to oxygen reduction kinetics being more facile in alkaline electrolytes than in acid based electrolytes. Flow of ionic charge through the electrolyte balances the flow of electronic charge through an external circuit and it is this balance that produces electric power. The energy security, clean emission and high efficiency mark the fuel cells as a viable option for the Internal Combustion Engines.

2. Parameters of a Fuel Cell and Their Working



Typical Fuel Cell Configuration

2.1 Electrodes

The electrode generally consists of a double layered structure having an active electro catalyst layer and a hydrophobic layer. The active electro catalyst layer consists of an organic mixture (Catalyst, carbon black and PTFE) whereas the hydrophobic layer is made by rolling a porous organic layer [2].The hydrophobic layer prevents the electrolyte from leaking into the reactant gas flow channels and ensures diffusion of cases to the reaction sight. The total electrode thickness is generally of the order of 0.2 to 0.5 mm. The electrodes bring about a reaction between the reactant and electrolyte without itself being consumed or corroded [4].Transport of gaseous/liquid species, ions and electrons is facilitated within electrodes and at the point where all the three meet (Triple point boundary) the electro catalyst reduces the oxygen at the cathode and oxidizes the fuel at the anode. Thus composite electrodes of which the electro catalyst is a component are generally preferred.

2.1.1 Anode

The anode disperses the hydrogen gas equally over the whole surface of the catalyst and conducts the electrons freed from hydrogen molecule to be used as useful power in an external circuit.

Anode Reaction: $2H_2 + 4OH^- \longrightarrow 4H_2O + 4\,e^-$

2.1.2 Cathode

The cathode distributes the oxygen fed to it over the surface of the catalyst and conducts the electrons back from the external circuit where they can recombine with hydrogen ions to form water.

Cathode Reaction: $O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$

2.2 Overall Reaction:

$2H_2 + O_2 \longrightarrow 2H_2O$ + electric energy + heat

The additional byproducts produced due to the overall cell reaction are water molecules and the heat liberated. The heat liberated can be removed by re-circulating the electrolyte and using it as a coolant liquid [2].This increases the efficiency of the Fuel Cell. The water molecules formed are removed by evaporation.

2.3 Electrolyte

The nature of the electrolyte determines the operating temperature of the fuel cell. The AFC generally uses a 30% KOH as an electrolyte and work at an operating temperature in the range of 50-200 0C.The fuel used in AFC is pure hydrogen or hydrazine. The PEMFC uses a polymer, a proton exchange membrane and generally have the operation temperature around 50-80 0C.PEMFC uses less pure hydrogen from hydrocarbons or methanol as a fuel. The electrolyte allows the flow of charged ions from one electrode to the other.

3. History and Early Usage of Fuel Cells

Sir Humphrey Davy [1] in 1802 created the first simple fuel cell based on a compound (C/H_2O, $NH3/O_2/C$) delivering a feeble electric shock. Power generation attempts in the late half of the 19th century were very inefficient. LudwigMind who founded the International Nickel Company and various other Chemical Industries in England devised a process in which coal and coke were used together to produce a gas containing large proportion of hydrogen. He wanted to scale up the process so that he could deliver useful power from converted fuels but unfortunately the impurities in the industrial gas poisoned the Platinum Black catalyst leading to a higher cost of loadings of the catalyst making the process cost prohibitive. Another such power generation attempt was made by Thomas Edison [1] in 1882 when he built a coal burning power generation station in lower Manhattan. However the attempt was highly inefficient as he could convert only 2.5% of the available energy into electricity. These poor thermal efficiencies in power generation attempts provided major motivation for pioneers of fuel cell development.

Sir Francis Bacon [1] began his historical work on fuel cells in 1933.Bacon developed a high density AFC with 1.11 A/cm^2 at 0.6V at very high pressures. These cells employed Nickel electrodes with dual porosity structure which along with differential gas pressures across the cell provided thin electrolyte film in larger pores. However the performance of the electrodes was degraded rapidly due to corrosion of electrodes. Extensive experimentation led to the development of Nickel Oxide electrodes doped with lithium which were more corrosion resistant. This technology was further developed into a fuel cell system and was employed by the US Apollo Space program.

4. Significant Research in Fuel Cell Technology

Significant research in the fuel cell technology involves Novel methods for Carbon Dioxide Separation and the development of Direct Alcohol Fuel Cells (DAFC) which are electrochemical devices that directly convert the chemical energy stored in the liquid alcohol (methanol, ethnaol) which is used as a fuel into electricity. Based on the fuel used DAFC can be divided into two major categories.

4.1 Direct Methanol Fuel Cells (DMFC)

As the name suggests this type of fuel cells used the simplest alcohol i.e. methanol as the primary fuel in the fuel cell. This type of fuel cells have better electrode kinetics than any other type of fuel cells. However the toxicity of methanol, crossover of methanol through the electrolytic membrane and slow methanol oxidation kinetic are amongst the various problems that hinder the commercialization of this technology.

Increasing number of researchers are nowadays turning their interest towards Direct Methanol Alkaline Fuel Cells (DMAFC).It is a well-known fact that the methanol oxidation in alkaline media is kinetically faster in alkaline medium than in acidic medium and the risk of electrode corrosion is also reduced in alkaline media.

The charge carrier in DMAFC is the anion ion and it moves from cathode to anode during the cell operation. Thus synthesis of anion exchange membrane is the first step for DMAFC Applications.

4.2 Direct Ethanol Fuel Cells (DEFC)

Ethanol which is more environmental friendly and can be produced easily in large quantities from agricultural products or biomass is used as the primary fuel in Direct Ethanol Fuel Cells (DEFC)[5].Based on the type of electrolytic membrane used in the fuel cell,DEFC can be divided into two types.

4.2.1 Acid Membrane Direct Ethanol Fuel Cells

Considerable amount of efforts have been devoted to acid membrane DEFC resulting into significant progress into development of high performance of these kind of fuel cells. Research has shown that these type of fuel cells can obtain maximum power density, that of 60 wM/cm^2,the highest performance cited in literature so far[5].However in spite of high performance, the commercialization of these fuel cells remain an issue due to several reasons. The slow kinetic of ethanol oxidation reaction (EOR) results into serious activation polarization loss thereby affecting the overall cell performance. Also the cost of the acid electrolytic membranes are costly and a considerable amount of precious Pt loading is required to achieve a decent performance. The electrocatalyt PtSn which is generally used in these type of fuel cell suffer corrosion due to the acidic medium thus reducing the durability of the fuel cell. Considering all the above factors, Acidmembrane DEFCs fall out of favor as compared to the second type of DEFC viz. alkaline membrane DEFC.

4.2.2 Alkaline Membrane Direct Ethanol Fuel Cells

The most striking feature of these type of fuel cells is that the kinetics of the oxygen reduction reaction (ORR) is more facile in the alkaline media than in the acidic medium. The cathode potential of alkaline electrolytic membrane fuel cell is much higher due to the use of non Pt electro catalyst on the cathode which eliminates the oxidation of the fuel that maybe transported from the anode[5]. Till now efforts have mainly been concentrated on the synthesis of alkaline membranes and electro catalysts for the EOR and ORR in alkaline media whereas the system design and development of DEFC have not been addressed.

Research shows that the performance of these cells improve as the operating temperature increases. This is due to the increase in the electrochemical kinetics of both the EOR at the anode and the ORR at the cathode which results in a consequent rise in the cell voltage. Also with an increase in the temperature the conductivity of the ions increases and the cell resistance increases thus improving the performance of the cell. Research has shown that for a fixed alkali (KOH) concentration there exists an optimum ethanol concentration at which the cell has a high performance. On the other hand with an increase in the KOH concentration the cell voltage in the current density region increases. In high current density region there exists and optimum KOH concentration for which the fuel cell yields the best performance.

4.3 Novel Methods for Carbon Dioxide Separation

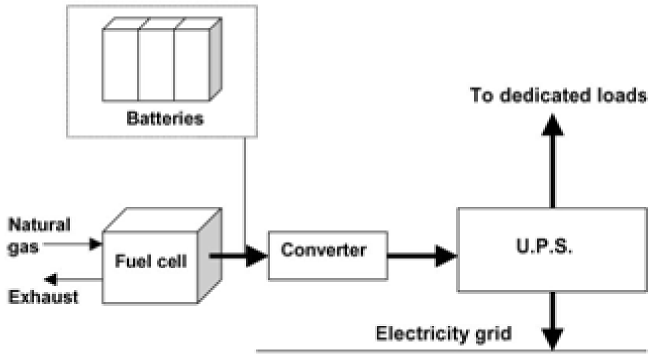
Carbon Dioxide formation in the fuel cells results in the poisoning of the catalyst. The various novel methods have been developed for the Carbon Dioxide capture from the fuel cells resulting in the better efficiency of the fuel cell. Use of electrochemical pumps for separation of Carbon Dioxide from fuel gas provides a simple and cost effective method for Hydrogen separation and CO_2[7].This technology is based on the readily available solid oxide electrodes with the application of an external EMF. Membranes for CO_2 separation by size exclusion or chemical affinity membranes infused by functional groups selective for CO_2 is also a technique for CO_2 separation. An emerging technology for CO_2 capture is the method of chemical looping. In this method the oxygen necessary for fuel combustion is provided by regenerative metal oxide catalysts [7].Use of lattice oxygen from these catalysts as oxygen instead of oxygen from air results in the formation of flue gas which is concentrated by CO_2.

5. Current Status and Applications

5.1 Power Plants and Small Scale Applications

Development of a polymeric membrane with protonic conductivity properties and which is applicable as a solid electrolyte for fuel cells has revolutionized the expected applications and has proved as an alternative for internal combustion engines [3]. Driving force for technology improvements includes potential application of polymer fuel cells with direct supply of methanol (DMFC).

Fuel cell based UPS includes direct current electricity production from a fuel cell connected directly to a conventional UPS. The surplus electricity produced can be supplied to grids and emergency batteries can be reduced in capacities [3]. Medium sized power plants seem to be the optimized size for fuel cells as the technology is sufficiently reliable for development of fuel cells up to 200kw.The high performance co-generation plants can be designed as well as plants integrated with micro turbines. Natural gas from existing grids can be used as fuel for these plants.

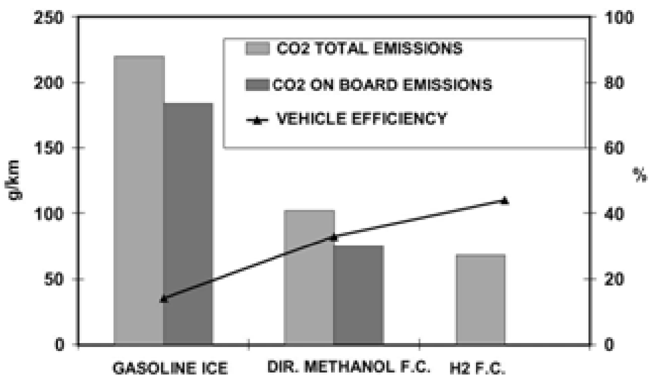


Solid Oxide fuel cell technology offers systems with good power density (300 mW/cm^3), high operating temperature (1000^{o}C – 800^{o}C), good fuel flexibility and very high electrical performance mainly if integrated with micro turbines. Development of such plants critically requires the production of Heat Exchangers (Cell and Turbine Integrated) whose materials resist at temperatures greater than 700^{o}C, the reduction in the cost of volume produced, low cost manufacturing and optimum integration between major components. The first prototypes of MW plants installed in the world were 4.5MW New York power plant and 4.5MW Tokyo power plant. Both of these plants operate on PAFC technology.

5.2 Fuel Cell Vehicles (FCV)

A fuel cell can be used in a car both as an Auxiliary Power Unit (for on board devices like electronic devices, cooling system, controlling devices etc) or for power generator for an electric engine in a hybrid vehicle. When fuel cells work as an APU the car uses an IC Engine and part of fuel is converted into electricity through Fuel Cell more efficiently than through the traditional route. Most important contribution of this technology is as a power generator for electric vehicles.

Two types of Fuel Cell Vehicles are proposed.



CO_2 emissions and efficiency for traditional ICE and methanol or hydrogen Fuel Cells

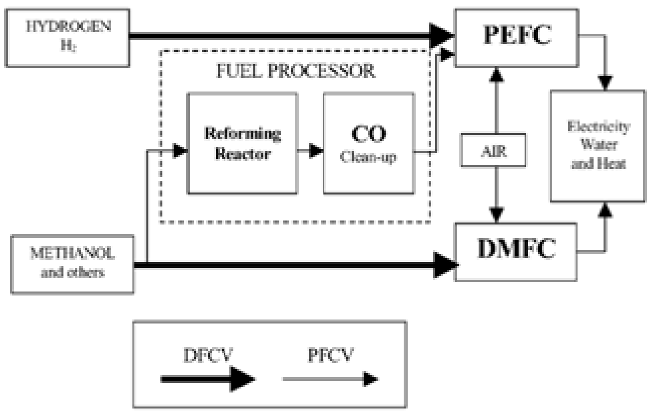
5.2.1 Direct Fuel Cell Vehicle (DFCV)

In this type of FCV fuel is electrochemically oxidized inside the Fuel Cell. The technology used in DFCV is PEFC if H_2 is fed to the Fuel Cell or DMFC if methanol is fed as the fuel. Even if for DFCV, the CO_2 emissions are considerably lower than an IC Engine and the efficiency significantly higher, few problems need to be addressed before this technology is commercialized [3].

Special attention must be devoted to the fuel production and the infrastructure. Costly changes are needed to make methanol available at filling stations but the same is even more expensive in the case of hydrogen. Hence hydrogen can initially be produced at filling sites by on site processors based on steam reforming or partial oxidation of natural gas and stored. Hydrogen can further be produced from methanol, ethanol or gasoline and used as a fuel in the future.

Methanol can be obtained from natural gas as well as biomass as it is liquid at atmospheric pressure and temperature. There is no distribution system for methanol currently but it can be handled in almost the same was as gasoline.

A technical problem also arises that of the onboard hydrogen storage and DMFC stacks. Generally to overcome this problem containers are used to store hydrogen at 200 atm pressure and storage capacity of 0.5 – 2 kWh/Kg[3].These containers consists of carbon/aramidic fibers that weigh 3-4 times less than metallic containers and have a high safety potential due to their strength. Cryogenic hydrogen has many advantages over pressurized hydrogen, providing an energy density of 6 kWh/Kg.



Functional scheme of direct (DFCV) and processed (PFCV) fuel cell vehicle systems

5.2.2 Processed Fuel Cell Vehicle (PFCV)

In this type of FCV system, the primary fuel is transported inside the vehicle to the fuel processor (FP) which produces H_2 rich gas which in turn is supplied to the FC stacks to produce electricity. This system uses a multi fuel configuration which allows the use of different fuels such as methanol, propene, gasoline etc. Composition of gas produced by onboard Fuel Processor remains an issue for efficient operation as the presence of CO_2 causes a rapid decrease in the Fuel Cell performance.

6. Major Challenges

As seen in the review the major challenge is the large scale commercialization of the fuel cells as a viable alternative to the current sources of energy. Fuel cells being a clean source of energy with almost zero emissions can play an important role to preserve the depleting exhaustible energy resources. However the high cost due to the complex structure and design constraints due to the materials can also be a major challenge. The CO_2 poisoning of the catalyst also prevents the commercialization of the fuel cells. Thus new technology needs to be invented to minimize the effect of poisoning of the catalyst and also to reduce the cost due to loading of expensive materials like Platinum. The large scale production and availability of fuels for Fuel Cell Vehicles at low costs and setting up infrastructure for the same is also an issue that needs to be addressed for the commercialization of the technology.

7. Conclusion

Thus it can be concluded from this review that Fuel Cell technology can be an interesting alternative to the traditional means of energy production especially when natural energy resources are getting depleted at a fast rate. The energy security, constant power production, clean emissions, quiet operations and high efficiencies mark the fuel cell technology as a vital technology for the future. However a lot depends upon the overcoming of the various major problems that hinder the fuel cell technology from being commercially viable. The author is of the opinion that a lot of research needs to go into improving the current level of advancement of this technology before it becomes practically applicable in the day to day life.

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