FUEL CELLS IN AEROSPACE SYSTEMS

Narayan Thakur[1], Advait Inamdar[2], Deepak Pal[3]

[1]Narayan Thakur, Mechanical Engineer, A. P. Shah Institute of Technology, Thane, Maharashtra, India
[2]Advait Inamdar, Mechanical Engineer, A. P. Shah Institute of Technology, Thane, Maharashtra, India
[3]Deepak Pal, Mechanical Engineer, Rajendra Mane College of Engineering and Technology, Ratnagiri, Maharashtra, India

---***---

Abstract - *Fuel cells are regarded as a proven power source for manned spacecraft where they generate electric power from stored hydrogen and oxygen. These reactants are carried in cryogenic liquid form. The requirements for fuel cell systems on flying platforms include low weight, high reliability, and flexibility to temperature and density changes. Fuel-cell-powered air vehicles are mainly competitive in places where low power and high endurance are required. Small unmanned vehicles are already operating with suitable systems in quite a few numbers. Mainly polymer electrolyte membrane fuel cells (PEMFCs) have been considered, but for applications in transport aircraft, the solid oxide fuel cell (SOFC) is also considered because of its ability for reforming kerosene, which will last longer as a fuel. This paper gives a brief introduction on fuel cells, presents various types of fuel cells and their characteristics, and then discusses specific items related to aerospace applications.*

***Key Words*: Aerospace applications; Basic processes; Fuel cell types; Energy conversion efficiency; Electrolyte; Hydrogen peroxide.**

1.INTRODUCTION

A fuel cell is a very effective power source. It is commonly defined as an electrochemical device that converts the supplied fuel to electric energy and heat continuously as long as reactants are supplied to its electrodes. It has no moving parts, works quietly, and emits only water vapor. The sound created may come from an air compressor or a cooling fan, depending on the type of fuel cell and how it is operating or for what purpose it is used. In principle a fuel cell is working as a battery but it continues to operate as long as fuel is supplied. Basically the fuel cell is like a thin-layered sandwich consisting of two electrodes, an anode and a cathode, on each side of an electrolyte. Such a simple cell generates only a small amount of power and to generate a sufficient electric current a number of unit cells need to be assembled in the so-called stack. Ideally hydrogen is supplied on the anode side and oxygen or air on the cathode side. However, hydrogen is almost not freely available in the atmosphere because it attempts to find oxygen atoms for marriage and creates water. This attraction ability is taken care of in a fuel cell. Fig. 1 shows a principle sketch of the so-called proton exchange membrane fuel cell (a.k.a. polymer electrolyte membrane fuel cell, PEMFC) in which the electrolyte is a polymer. The hydrogen is supplied on the anode side and it tries to reach the oxygen on the cathode side. In doing so, it achieves assistance from a catalytic material such as platinum. On the catalytic material the hydrogen atoms are split up into protons and electrons, which find different ways to join with the oxygen. The protons cross the electrolyte, whereas the electrons need to take a way through the electric circuit to reach the cathode. In the process, electricity and heat are generated. As the protons are joining with the oxygen, water is created. The noble metal platinum is a key factor in PEMFCs and it is regarded as a stable catalyst. However, it is a limited resource and research work is underway to find a substitute for it.

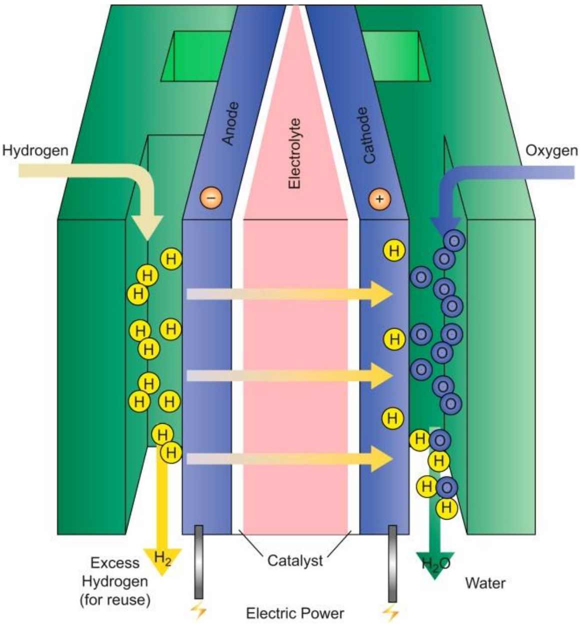

Figure 1 Principle sketch of a PEMFC.

2. TYPES OF FUEL CELLS

There are several types of fuel cells and each one has advantages and disadvantages. Table 1 describes a brief summary of some types of fuel cells and their characteristic features, operating temperatures, and areas of application. More detailed descriptions are presented in the following sections.

2.1. PROTON EXCHANGE MEMBRANE FUEL CELLS OR POLYMER ELECTROLYTE FUEL CELLS (PEFCS)

This fuel cell operates at a relatively low temperature, about 80 C. The energy conversion efficiency, i.e., conversion of the hydrogen energy to electricity is in the order of 50–60%. The electrolyte is a solid polymer in which protons are mobile. This is the fuel cell type being promoted and introduced as the power source for ground vehicles. It has a good start-up behavior at low temperatures and is small and compact. It is also considered as the power source in portable units, as well as in large stationary power plants. An advantage is that the electrolyte is a solid phase in form of a thin membrane of a polymer. The surrounding catalyst is platinum. This cell is sensitive to the purity of the hydrogen fuel. PEMFCs were used on the first manned spacecraft. The platinum catalyst is very costly, but nickel-tin catalysts have been discovered. As an effect, fuel cells can be a possible substitute for batteries in spacecraft.

Table 1 Principle Operation of Some Fuel Cell Types

Fuel Cell Type	**Mobile Ion**	**Operating Temperature, °C**	**Applications**
PEMFC and PEFC	H^+	30–100	Vehicles, mobile equipment, low-power CHP systems
DMFC	H^+	20–90	Portable electronic systems with low power, long operating times
PAFC	H^+	~200	Large numbers of 200-kW CHP systems
AFC	OH^-	50–200	Space vehicles
MCFC	CO_3^{2-}	~650	Medium- to large-scale CHP systems
SOFC	O^{2-}	500–1000	All sizes of CHP systems

CHP, combined heat and power; PEFC, polymer electrolyte fuel cell.

2.2. ALKALINE FUEL CELLS

This has been used in space vehicles for generation of electricity and drinkable water for astronauts. The conversion efficiency is about 70%, and the operating temperature is in the range of 150–200°C. The electrolyte mainly consists of potassium hydroxide (KOH). Some interests have also been shown for their use in ground vehicles. An advantage of this fuel cell type is that it does not depend on platinum as the catalyst. Carbon dioxide may affect the conversion and it is generally required that the supplied air and fuel must be free from CO2, otherwise pure oxygen and hydrogen must be used. This fuel cell type was used on the Apollo and Shuttle Orbiter craft.

2.3. PHOSPHORIC ACID FUEL CELLS (PAFCS)

This fuel cell type has been commercially in operation for a while. It has found applications in, e.g., hospitals, hotels, offices, airports, and schools. The conversion efficiency is relatively low, about 40–50%. The operating temperature is in the range of 150–200°C. Both the electricity and steam can be taken care of. The electrolyte is an acid of phosphorus. This fuel cell type resists pollution created by the hydrogen fuel particularly at high temperatures. At low temperature, carbon monoxide may damage the platinum layer on the catalyst. Units of this fuel cell type are often big and heavy but the technology is regarded as mature.

2.4. SOLID OXIDE FUEL CELLS

This fuel cell type is regarded as a candidate for large units even at remote locations. It has also found application as auxiliary power units (APUs) even in vehicles. The electrolyte is in a solid state and commonly made in a hard ceramic material based on zirconium oxide. The operating temperature is higher, around 1000°C; hence, high reaction rates can be achieved without expensive catalysts and gases, e.g., natural gas, can be used directly or internally reformed without the need of a separate unit. The conversion efficiency is about 60%. It may also be integrated with a steam turbine to generate additional electricity. It does not necessarily require pure hydrogen as the fuel.

2.5. MOLTEN CARBONATE FUEL CELLS (MCFCS)

The electrolyte consists of a melt of carbonates of lithium, sodium, and potassium. The conversion efficiency is about 60%, and the operating temperature is about 650°C. It needs carbon dioxide in the air to work. The high operating temperature means that a good reaction rate is achieved by using a relatively cheap catalyst, namely, nickel. The nickel catalyst also forms the basis of the electrode. Its simplicity is partly offset by the nature of the electrolyte, which is a hot and corrosive mixture of lithium, potassium, and sodium carbonates. Similar to other high-temperature fuel cells, it can be combined with a steam turbine to generate additional electricity. It can be operated with other hydrogen carriers rather than pure hydrogen. The high-temperature operation, as for solid oxide fuel cells (SOFCs), may have a severe effect on the cell components.

2.6. DIRECT METHANOL FUEL CELLS (DMFCS)

This is a variant of the PEMFC but the methanol reacts directly in the anode rather than in a separate reformer upstream the fuel cell. The conversion efficiency is about 30–40%, and the operating temperature is in the range of 50–100°C. The loss in the reformer is eliminated. It may find applications in portable computers and mobile phones.

2.7. REVERSIBLE FUEL CELLS

A cell that can be operated both as a fuel cell and as an electrolyzer is called a reversible fuel cell. In case of surplus of electricity available from the wind or the sun, the cell can be operated to generate hydrogen by electrolysis of water. As it operates in the fuel cell mode, it uses hydrogen as the fuel and generates electricity.

2.8. PROTON CERAMIC FUEL CELLS

This is a fuel cell that is under development. The idea is that the ceramic electrolyte should be able to conduct protons. The operating temperature is about 700°C, and hydrogen is oxidized directly at the anode. A reformer is not needed. This fuel cell type is believed to be able to combine the advantages of the high-temperature fuel cells and the PEMFCs because of the use of a ceramic electrolyte.

3. BASIC TRANSPORT PROCESSES AND OPERATION OF A FUEL CELL

The fuel cells discussed so far function in the same manner. At the anode a fuel, commonly hydrogen, produces free electrons, and at the cathode, oxygen is reduced to oxide species. Depending on the electrolyte, either protons or oxide ions are transported through the ion-conducting, but electronically insulating, electrolyte to combine with oxide or protons to produce water and electric power. The reactions at the anode and cathode sides must proceed continuously and then the electrons produced at the anode have to pass an electric circuit to the cathode. Ions need to migrate through the electrolyte. The electrolyte is only permitted to transport ions not electrons. However, the reaction characteristics at the anode and cathode are different for different fuel cells but the overall reaction is the same.

3.1. ELECTROCHEMICAL KINETICS

Studies of electrochemical kinetics are important for design and operation of fuel cells. The electron transfer rate at the electrodes or the current produced by the fuel cell depends on the rate of electrochemical reaction. The processes governing the electrode reaction rates are the mass transfer between the bulk solution and the electrode surface, the electron transfer at the electrode, and the chemical reactions involving electron transfer.

3.2. HEAT AND MASS TRANSFER

A number of transport processes occur in a fuel cell. The reactant gases flow through the gas flow channels and reactant gas species are transported from the gas flow channels and through the porous electrodes. Ions are transported through the membranes or the electrolyte and electrons are transported through electrodes and interconnect. Fig. 2 gives a principle illustration. Poor transport of heat and mass contributes to the loss of fuel cell performance. Charge transport contributes to ohmic losses and the mass transfer of the reactant gases impacts the mass transfer losses.

3.3. CHARGE AND WATER TRANSPORT

Electrons and ions are produced and consumed in two electrochemical reactions at the anode–electrolyte and cathode–electrolyte interfaces. The electrons are transported through the el and interconnect to the external electric circuit. Ions are transported through the electrolyte from the electrode where they are produced to the electrode where they are consumed. Ohmic voltage losses are caused by the resistances to the motion of ions through the electrolyte as well as that of electrons through the electrodes, interconnect materials, and contact interfaces. Ion transport is also important for the transport of water in PEMFCs.

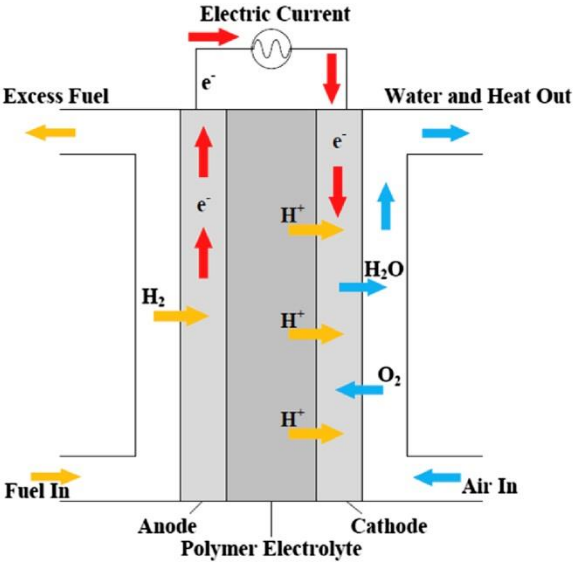

Figure 2 Fluid flow and heat and mass transfer in a fuel cell of three layers.

4. AEROSPACE APPLICATIONS

Use of hydrogen in flying vehicles has a long history. It started with balloons and then continued with airships. However, after the Hindenburg accident, use of hydrogen as power source became less popular.

The fuel cells made a comeback for use in the aerospace applications. The first practical application in space was the Gemini project in the 1960s and the fuel cell used was a polymer electrolyte fuel cell (PEFC). The alkaline fuel cells (AFCs) were used in, e.g., the Apollo vehicles for the lunar trips. With the fuel cells, it was possible to generate electricity even when the vehicle and its solar cells were not exposed to the Sun's radiation. The resulting product could be used as drinkable water. Nowadays, PEFCs or PEMFCs are considered again for aerospace applications.

Fuel cells are more efficient than secondary batteries. Theoretically a fuel cell is able to deliver 500 kWh/kg of hydrogen plus oxygen. The currently best lithium batteries can deliver about 120 kWh/kg. Fuel cells can convert fuel to electric power with an efficiency of over 80%. Typically a diesel combustion engine cannot provide efficiency better than 40% at its optimum speed and load. For space applications with long discharge times, the mass of the fuel cell and other process units is less compared to that of stored fuel, oxidant, and tankage. For applications that run for a short time at moderate power levels, the mass of the fuel cell and other process units is significant, and reduces their competitiveness compared to batteries.

The fuel cell for space applications has specific system requirements and different operating conditions and designs because of the isolated low-gravity environment in space when compared to ground operation.

For ground applications at atmospheric pressure, air can be supplied as the cathode gas and hydrogen as the anode gas. The fuel cell reaction produces water and electricity. The water must be evaporated by compressed air because if water remains in the path in the separator, it may block the flow of the reactant air. However, proton conduction in the membrane requires water, and the air is humidified before being supplied to the fuel cell. Obviously, the fuel cell at ground applications requires humidification of the supplied gas and dehydration of the separator to balance the complicated humidity conditions inside the fuel cell.

For space applications, it is very important to prepare a simple system. High power or energy density and air-independence are required. As the spacecraft is very isolated in the Earth's orbit, all reactant materials must be carried inside the spacecraft. In order to minimize the weight, pure anode and cathode materials must be used and should be completely consumed. The produced water must be collected. This has created a renewed interest on the use of PEMFCs in these applications. Another type of fuel cell using novel fuel and oxidizer has also been investigated for space power systems. This is because of the revived interest on using hydrogen peroxide in aerospace power applications. Hydrogen peroxide (H2O2) is used directly at the cathode. The fuel on the anode side is hydrogen gas and an aqueous NaBH4 solution. It has been found that the direct utilization of H2O2 and NaBH4 at the electrodes resulted in about 30% higher voltage output than that of a regular H2–O2 fuel cell. Both NaBH4 and H2O2 are in aqueous form and the combination has some operational advantages. A Nafion membrane is used as the electrolyte. The catalysts are commonly platinum based. The carbon substrate used is here called reactant diffusion layer instead of gas diffusion layer because the peroxide reactant is in the liquid phase. The design is compact and it is ideal for space applications where a high-energy-density fuel is required and air is not available.

Hydrogen peroxide is commonly used in rocket propulsion and air-independent power systems. It has also found utilization in underwater power systems. It is a powerful oxidizer and is safe. After it is decomposed, it gives only oxygen and water and thus creates no environmental problems. The benefits of a direct hydrogen peroxide fuel cell over fuel cells using gaseous oxygen are higher current density because of larger oxidizer mass density, single-phase transport on the cathode side of the fuel cell increases the reaction rate, and elimination of the oxygen reduction over potential problem.

5. CONCLUSION

Fuel cells are lighter, more efficient, and more adaptable to temperature and density changes. Aerospace systems have high heat flux requirement, so they need lightweight, high-performance, light-weight equipment that can withstand low to no atmospheric pressure. Fuel cells meet these power requirements for aerospace systems, and this paper addresses different types of fuel cells.

REFERENCES

[1]Revankar S, Majumdar P. Fuel cells—principles, design and analysis. New York: CRC Press; 2014.

[2] Singhal S.C, Kendall K. High temperature solid oxide fuel cells-fundamentals, design and applications. Oxford, UK: Elsevier; 2004.

[3] Hodgers G, ed. Fuel cell technology handbook. New York: CRC Press; 2003.

[4] Barbir F. PEM fuel cells, theory and practice. New York: Academic Press; 2012.

[5]Sunden B, Faghri M, eds. Transport phenomena in fuel cells. Southampton, UK: WIT Press; 2005.

[6]Larmine J, Dicks A. Fuel cell systems explained. London, UK: J. Wiley & Sons; 2000.