5.9 FUEL CELL

- A fuel cell is an electrochemical device that generates electricity from an electrochemical reaction from fuel such as hydrogen and oxygen or another oxidizing agent.
- Other fuels used are hydrocarbons such as natural gas and alcohols. They are similar to battery but require constant input of fuel and oxygen for continuous electricity generation.
- Fuel cells are available in very small size (single fuel cell) with electricity- generating capacity of a few watts up to a big size (fuel cell stack) producing megawatts.
- All types of fuel cells have similar component parts in their design as they utilize two electrodes separated by a solid or liquid electrolyte that carries electrically charged particles between them.
- A catalyst is often used to speed up the reactions at electrodes. In addition, they are classified based on electrolyte material used.
- As they are static equipment and do not involve any intermediary steps of energy conversion, they are highly efficient and environmentally acceptable direct energy conversion method.
- The by-products of fuel cell apart from electricity generation are water, heat, and small amount of nitrogen oxide and other emission depending upon fuel source used.

The schematic diagram of fuel cell is given in Figure. It consists of the following parts:
1. Anode
2. Cathode
3. Electrolyte

Anode

It is a positive electrode and facilitates electrochemical oxidation offuel.

Cathode

It is a negative electrode and promotes electrochemical reductionof oxidant.

Electrolyte

- It is a solution of liquid, gases with salts and carries electrically charged particles between them.
- Any substance having free ions to make the substance electrically conductive is called electrolyte.
- When a salt, such as normal salt, is placed into a solvent, such as water, electrolyte solutions are formed. The salt dissolves into its ion components by dissociation or dissolving by the following dissociation reaction,

$$NaCl(s) \rightarrow Na+(aq) + Cl(aq)$$

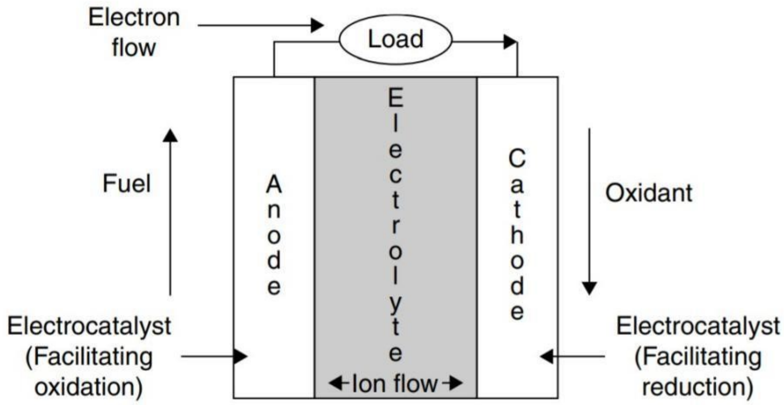

Fig 5.9.1. Schematic of fuel cell

[Source: "Renewable Energy Sources and Emerging Technologies" by D.P.Kothari, K.C Singal, Rakesh Ranjan, Page: 415]

- Many substances, such as carbon dioxide gas, dissolve into water, react with it, and produce ions.
- Apart from various methods involved in the formation of electrolytes, the electrolyte liquid conducts electricity when electrodes are connected to an external load.
- Electrolytes with high concentration of ion are called concentrated, whereas electrolytes with low ion concentration are called dilute. Electrolytes also act as a barrier between fuel and oxidant, and they never mix with each other and no combustion occurs.
- The fuel cell efficiency is, therefore, not limited by Carnot efficiency and has very high efficiency of about 40%–60% or (extended to 80% or so if waste heat is efficiently removed).
- Electron generated by oxidation reaction at the anode moves through external load circuit (flow of electricity generated) to the cathode and completes the reduction reaction.
- Polyelectrolyte and molten salt electrolytes have also been developed. Ions generated during oxidation or reduction is transported from one electrode to the other through ironically conductive but electronically insulating electrolyte.
- Electrolyte used determines the operating temperature and dictates the classification of fuel cell.

5.9.1 TYPES OF FUEL CELL

S. No	Fuel Cells	Temperature	Efficiency	Electrolyte	Catalyst	Charge Carriers
1	Alkaline fuel cell	60°C–90°C	50%–60%	35%–50% KOH	Nickel	Hydroxyl ions(OH−)
2	Polymer electrolyte fuel cell	50°C–80°C	50%–60%	Polymer membrane	Platinum	H−
3	Phosphoric acid fuel cell	160°C–220°C	40%–50%	Phosphoric acid	Platinum	H−
4	Molten carbonate fuel cell	620°C–660°C	60%–65%	Molten carbonate	Nickel	CO2
5	Solid oxide fuel cell	800°C–1000°C	55%–65%	Solid oxide CO, ZrO2/ Y2O3	Platinum (Pt) Catalyst No precious costly metal catalyst required	O−
6	Direct methanol fuel cell	0°C–60°C	30%–40%	Polymer membrane	Platinum–Ruthenium Pt–Ru	H+

Table 5.9.2 Types of Fuel Cells

[Source: "Renewable Energy Sources and Emerging Technologies" by D.P.Kothari, K.C Singal, Rakesh Ranjan, Page: 418]

5.5.1. SCHEMATIC AND WORKING OF DIFFERENT TYPES OF FUEL CELL

1. Alkali Fuel Cells

Alkali fuel cell is shown in Figure 5.9.3. It operates on compressed hydrogen and oxygen. They use aqueous electrolytes of potassium hydroxide. They were some of the earliest practical cells developed in 1960 and were used in the Apollo space programme for producing drinking water and generating electrical power.Although they are inexpensive compared with PEM cells, operating efficiencies of 60% are possible. Unfortunately, they have a low power output, and the catalyst is prone to poisoning from carbon dioxide in the atmosphere. They require pure hydrogen as a fuels and expensive platinum electrode catalyst.Power output of these cell stacks ranges from about 300 W to 5 kW.

A few salient features of alkaline cells are as follows:

1. There is an excess of OH+ ions and these play a key role in the reaction in cell.
2. At the anode, hydrogen gas reacts with OH+ ions, producing water and releasing electrons.
3. The electrons go round the external electrical circuit and reach the cathode.
4. At the cathode, they react with the oxygen and water, thereby producing more OH+ ions.

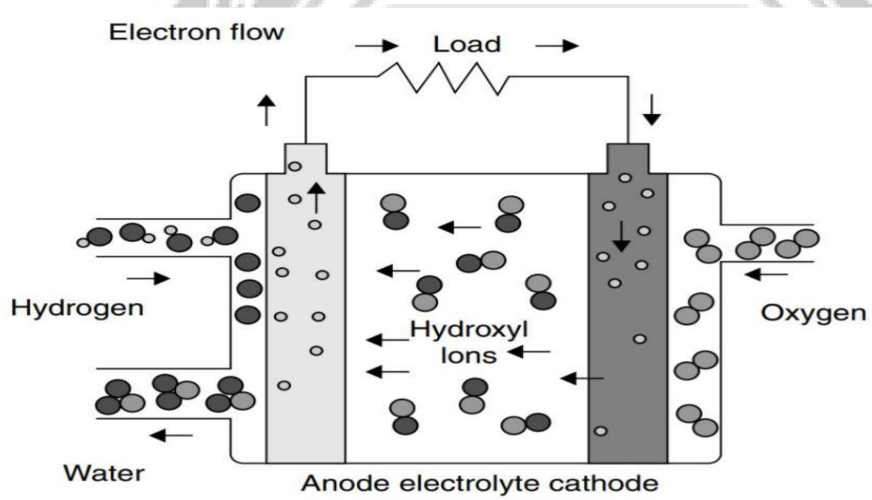

Figure 5.9.3. Alkali fuel cell

[Source: "Renewable Energy Sources and Emerging Technologies" by D.P.Kothari, K.C Singal, Rakesh Ranjan, Page: 419]

5. The OH+ ions move through electrolyte and electrons move round the electric circuit.
6. Water is produced at the anode twice as fast as it is used at the anode.

Fuel cell reaction is given as follows:

Anode reaction: $2H_2 + 4OH^+ \rightarrow 4H_2O + 4e^-$

Cathode reaction: $O_2 + 2H_2O + 4e \rightarrow 4OH^+$

Cell reaction: $2H_2 + O_2 \rightarrow 2H_2O$

2. Molten Carbonate Fuel Cells:

Molten carbonate fuel cell (MCFC) is represented in Figure 5.9.4.

It uses high-temperature compounds of salt (such as sodium or magnesium) carbonates (chemically, CO3) as the electrolyte. Efficiency ranges from 60% to 80%, and operating temperature is about 650°C.

1. When heated to about above temperature, these salts melt and become conductive to carbonate ions (CO_3^-).
2. These ions flow from the cathode to the anode.
3. At anode, they combine with hydrogen to give electrons, carbon dioxide, and water.
4. Electrons flow through external circuit and reaches to cathode.
5. Therefore, electricity is generated and heat is produced.

The chemical reaction taking place in the fuel cell is given as follows:

Anode reaction : $CO_3^- + H_2 \rightarrow H_2O + CO_2 + 2e^-$

Cathode reaction : $CO_2 + \frac{1}{2}O_2 + 2e \rightarrow CO_3^-$

Cell reaction : H_2 (g) + ½ O_2 (g) + CO_2 (Cathode) → H_2O (l) + CO_2 (Anode)

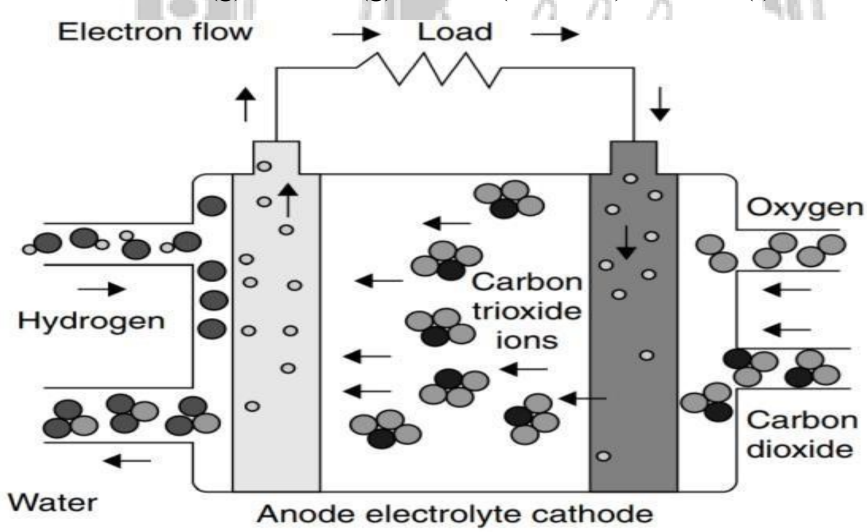

Fig 5.9.4 Molten Carbonate fuel cell

[Source: "Renewable Energy Sources and Emerging Technologies" by D.P.Kothari, K.C Singal, Rakesh Ranjan, Page: 420]

- Molten alkaline carbonate such as sodium bicarbonate is used as the electrolyte.
- The nickel electrode catalysts are inexpensive compared to the platinum used in other cells.
- Their unique chemistry needs carbon dioxide from the air as a part of the process.
- They can produce high powers up to 100 MW and can also be operated at high temperatures range of 650°C to 1,000°C. Because of their high working temperature, they

can operate directly with hydrocarbon gases which are reformed that less expensive within the cell and do not need a separate hydrogen supply.

- They are not so expensive in production and hence can be used for commercial uses. They have an efficiency of about 45%–55%

3. Phosphoric Acid Fuel Cells

Phosphoric acid fuel cells (PAFC) shown in Figure 14.8 use phosphoric acid(H_3PO_4) as the electrolyte.

The ionic conductivity of phosphoric acid is poor at low temperature. Other salient features are as follows:

1. The charge carrier is hydrogen ions.
2. At anode, hydrogen molecule is split into hydrogen ions (protons) and electrons.
3. The electrons flow through external circuit and produce electric power.
4. On the other hand, protons travel through electrolyte and combine with oxygen (usually from air) at the cathode.
5. At cathode, water is released.
6. Reactions in this fuel cell gives electricity and generate heat. In this cell, following chemical reaction takes place.

At anode $2H_2 \rightarrow 4H + 4e^-$

At cathode $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Cell reaction $2H_2 + O_2 \rightarrow 2H_2O$

Their name is derived from the high concentration phosphoric acid, which is used as the electrolyte material, and they became the first fuel cells to be sold commercially in the 1970s.

The efficiency is in the range of 40%–80%, and they operate at temperatures up to 220°C. Unlike other fuel cells that operate at this temperature, they are not susceptible to small amounts of carbon dioxide impurities in the hydrogen fuel.

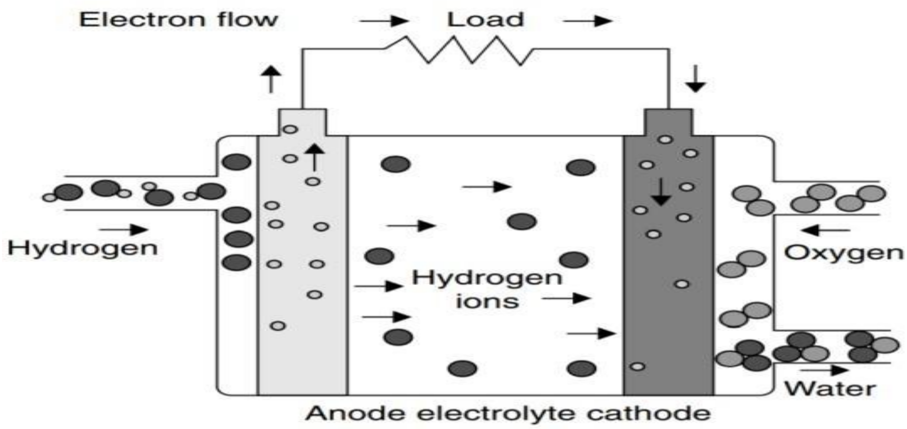

Fig 5.9.5 Molten Carbonate fuel cell

[Source: "Renewable Energy Sources and Emerging Technologies" by D.P.Kothari, K.C Singal, Rakesh Ranjan, Page: 421]

- This makes them better suited for large-scale usage.
- The primary application of these fuel cells is power supply for individual buildings,such as small businesses, hospitals, nursing homes, hotels, schools, and utility.
- Their advantages include high efficiency, low susceptibility to carbon dioxide poisoning, and stability over extended periods of time.
- The main disadvantage is that start-up is difficult because phosphoric acid is solid at room temperature but liquid at operating temperature.

4. Proton Exchange Membrane Fuel Cells

- They have been in development since the 1960s and are available in the stack of output range of 50–250 kW and operating efficiency of 40%–50%.
- As they operate at about 100°C, they widely preferred fuel cell for the automobile industry and hand-held equipment's.
- Low operating temperature allows for much faster start-up time. Advantages include fast start-up, compact design, and easy sealing.
- The main disadvantage is that cogeneration is not beneficial at such a low operating temperature. In addition, platinum catalyst used on both sides of the membrane, however, increases the cost of fuel cells. Schematic arrangement of hydrogen–oxygen proton-exchange membrane fuel cell (PEMFC) is given in Figure 5.9.6.

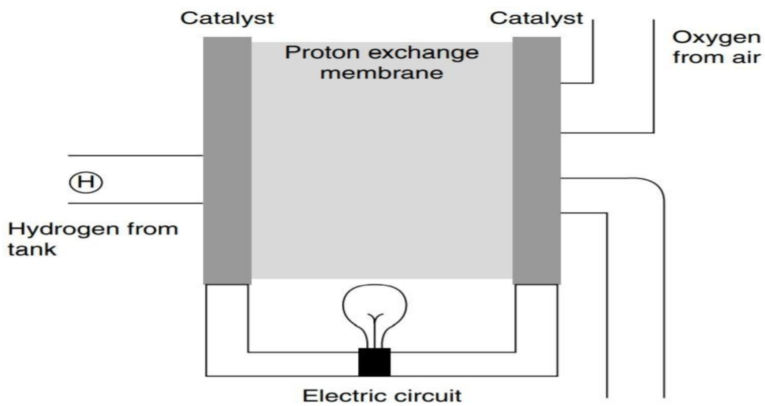

Fig 5.9.6 Proton Exchange Membrane Fuel Cells

[Source: "Renewable Energy Sources and Emerging Technologies" by D.P.Kothari, K.C Singal, Rakesh Ranjan, Page: 421]

Its working principle can be understood as follows:

1. Hydrogen is pumped to anode electrode where it diffuses to the anode catalyst and dissociates into protons and electrons.
2. Oxygen is pumped into cathode from air for reaction with hydrogen.
3. Multi-facilitated proton membranes are created when protons react with oxidants. The protons are conducted through the membrane to the cathode.
4. Electrically insulating property of membrane forced the electrons to flow through external load circuit and go to cathode.
5. Oxygen molecules with electrons and protons to form water at cathode electrode.

The chemical reaction of cell is as follows:

At anode $2H_2 \rightarrow 4H^+ + 4e^-$

At cathode $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Cell reaction $2H_2 + O_2 \rightarrow 2H_2O$

5. Solid Oxide Fuel Cells

Schematic arrangement of solid oxide fuel cells (SOFC) is shown in Figure 5.9.7

- It uses calcium or zirconium oxide (hard ceramic compound of metal) as electrolyte and oxygen as charge carrier. The oxygen from air joins with electrons in the cathode to create oxygen anions.
- The oxygen ions are transported through the solid electrolyte to the anode. At anode, the oxygen ions combine with hydrogen to create water and release electrons. The electrons

go through the circuit to power the load and then go back to the cathode to restart the cycle.

- Advantages include high efficiency when combined with a turbine and a high tolerance to impurities in the fuel.
- Disadvantages include expensive materials and failure of seal materials at the high operating temperatures. They deliver power output up to about 100 kW at the operating efficiency of about 60%. They are used in big, high-power industrial applications and in large scale, central electricity-generating stations.

Its working principle is explained as follows:

1. Oxygen molecules from air are broken into oxygen ions with the addition of electrons at the cathode electrode.
2. The oxygen ions are conducted through electrolytes and reach the anode.
3. At anode, oxygen ion combines with hydrogen and electrons are released.
4. Free electrons travel through external load circuit and produce electric power and heat.

Chemical reaction taking place in fuel cell is given as follows:

At anode $2H_2 + 2O^- \rightarrow 2H_2O + 4e^-$

At cathode $O_2 + 4e^- \rightarrow 2O^-$

Cell reaction $2H_2 + O_2 \rightarrow H_2O$

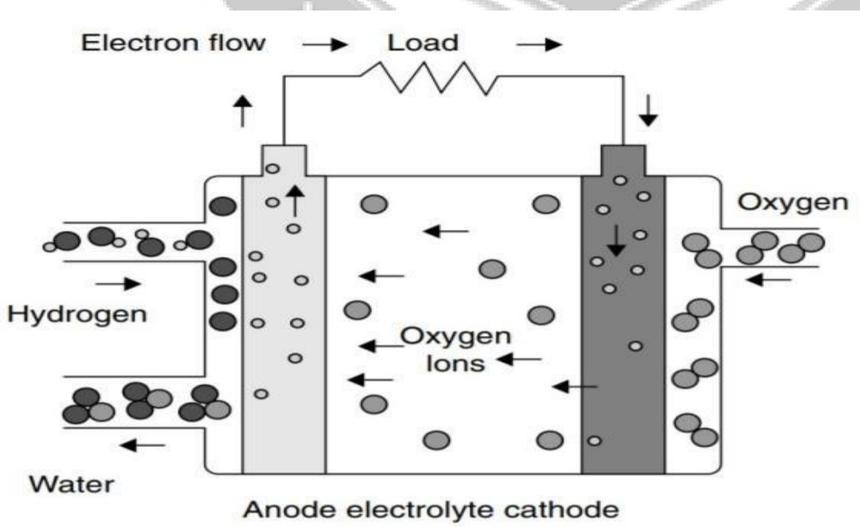

Fig 5.25 Solid Oxide Fuel Cell

[Source: "Renewable Energy Sources and Emerging Technologies" by D.P.Kothari, K.C Singal, Rakesh Ranjan, Page: 422]

5.9.2. APPLICATIONS OF FUEL CELL

- Providing power for base stations or cell sites
- Electric vehicles
- Automobiles
- Airplanes, boats, submarine systems
- Distributed generation
- Emergency power systems are a type of fuel cell system, which may include lighting, generators and other apparatus, to provide backup resources in a crisis or when regular systems fail. They find uses in a wide variety of settings from residential homes to hospitals, scientific laboratories, data centers
- Telecommunication equipment and modern naval ships.
- An uninterrupted power supply (UPS) provides emergency power and, depending on the topology, provide line regulation as well to connected equipment by supplying power from a separate source when utility power is not available. Unlike a standby generator, it can provide instant protection from a momentary power interruption.
- Base load power plants
- Solar Hydrogen Fuel Cell Water Heating
- Hybrid vehicles, pairing the fuel cell with either an ICE or a battery.
- Notebook computers for applications where AC charging may not be readily available.
- Portable charging docks for small electronics (e.g. a belt clip that charges a cell phone or PDA).
- Smartphone, laptops and tablets.
- Small heating appliances
- Food preservation, achieved by exhausting the oxygen and automatically maintaining oxygen exhaustion in a shipping container, containing, for example, fresh fish.
- Breathalyzers, where the amount of voltage generated by a fuel cell is used to determine the concentration of fuel (alcohol) in the sample.
- Carbon monoxide detector, electrochemical sensor.