

UNIT-3

Geothermal Energy: Resources of geothermal energy, thermodynamics of geo-thermal energy conversion-electrical conversion, non-electrical conversion, environmental considerations.

Magneto-hydrodynamics (MHD): Principle of working of MHD Power plant, performance considerations.

Fuel Cells: Principle of working of various types of fuel cells and their working, performance and limitations.

3.1(a) Geothermal Energy:

- Geothermal energy is a form of renewable energy, having the source of natural heat inside the earth.
- It is inexhaustible like solar or wind energy.
- The geothermal energy in the form of heat energy can be utilized economically and efficiently for power generation and other applications with the existing available technologies.
- The sites from where the thermal energy can be extracted are called **geothermal fields**.
- The commercial utilization of this energy started first in Italy in Larderello in 1904, Lardell (1913), Iceland (1930) and other part of the world by 2000.
- In India about 50 shallow wells are drilled for steam production in J&K belt.
- The thermal springs are found in different parts of India *i.e. Himachal Pradesh, Maharashtra, Cambay of Gujarat, Uttar Pradesh and some parts of Bihar and near Jawai in Assam.*

3.1(b) Origin of Geothermal Energy:

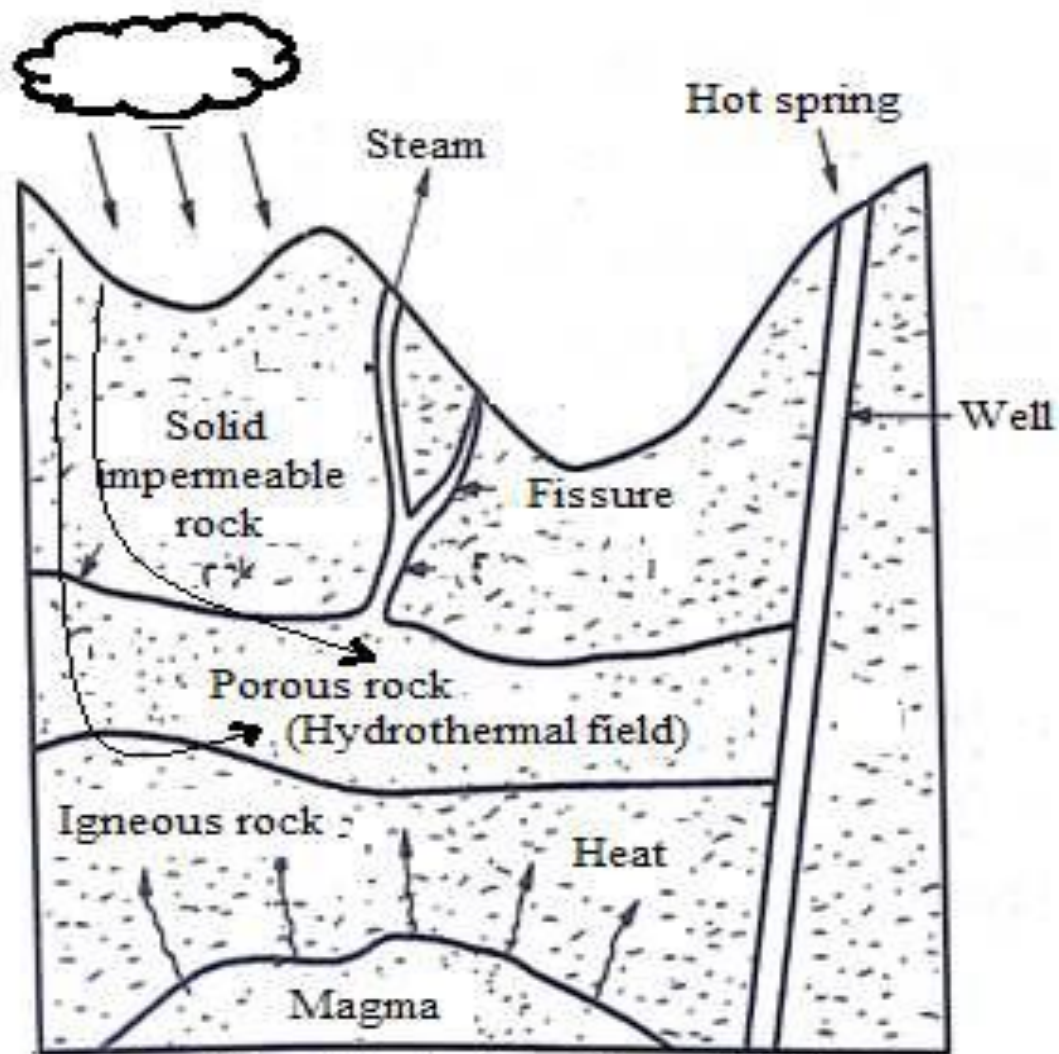


Fig. A typical geothermal field

- The earth's interior having mass of hot liquids, gases and steam is cooling slowly and the temperature of the earth's core is estimated to be about 4000°C.
- The average geothermal heat dissipated from the land is about 0.06 W/m² as compare to solar heat energy of 1 kW/m².
- Below the solid crust is the molten mass called magma which is still in the process of cooling.
- The earth's vibrations caused the magma to come near the earth surface thus causes active volcanoes, hot springs and geysers water exists.
- The hot magma near the surface solidifies into igneous rock. The heat of magma is conducted upwards into this rock and ground water that finds its way down to this rock through fissures in it will be by the heat of the rock or by mixing with hot gases and steam emanating from the magma.
- The heated water will then rise upward by convection into porous and permeable reservoir above the igneous rock. It is covered by the layer of solid impermeable rock. It traps the hot water in the reservoir called hydrothermal field.
- A well made by drilling hole in the upper crust in the region of geothermal field can be used to trap steam for use in a conventional power plant. The steam originating from magma is called meteoritic steam, largest source of geothermal steam.

3.1(c) Classifications of Geothermal Energy Resources/Systems:

- Geothermal resources vary in temperature from 30-350 °C and consist of dry, a mixture of steam and water or hot water only. The water is the transfer medium in order to extract geothermal heat from the earth. Table given below lists the basic technologies normally utilized according to resources temperature.

Reservoir Temperature	Reservoir Fluid	Common Use	Technology Commonly Used
High Temperature >180-200 °C	Water or steam	Power Generation	Flash Steam; Combined (Flash & Binary) Cycle Direct Fluid Use; heat Exchangers; Heat Pumps
Medium Temperature 100-180 °C	Water	Power Generation	Binary Cycle Direct Fluid Use; heat Exchangers; Heat Pumps
Low Temperature	Water	Direct Use	Direct Fluid Use; heat Exchangers; Heat Pumps

- The geothermal energy systems may be classified as:
1. Hydrothermal; 2. Hot dry rock (HDR); 3. Geo-pressured system;

Classifications of Geothermal Energy Resources/Systems:

1. Hydrothermal

a. Dry steam fields (Vapour dominated)

b. Wet steam fields (Liquid dominated)

(i) High Temperature Wet Steam System

(ii) Low Temperature-Binary Fluid System

2. Hot dry rock (HDR) or Petro-Geothermal Systems

3. Geo-pressured system

3.1(d) Hydrothermal (Convective) Resources:

- These resources are located at shallow to moderate depths of 100 m to 5 km and in such, water is heated by contact with the hot rock and high pressurized steam is generated up to about 350°C.
- These resources further divided into following categories, depending upon whether steam or hot water is the dominating product.
 - 1. Dry steam fields (Vapour dominated)**
 - 2. Wet steam fields (Liquid dominated)**

3.1(d.1) Dry Steam / Vapour Dominated Systems:

- Such system delivers steam with little or no water of high pressure and temperature up to 200°C.
- This steam is used to generate electrical energy by electromechanical energy conversion.
- The steam extracted from such fields may contain some amount of water and solid particles; those are removed in a centrifugal separator.
- This pure dry steam is then directly supplied to a steam turbine, which is coupled to a generator.
- The condenser is used to condense the exhaust steam for recirculation purpose of cold water.
- This cold water is either sent to chemical recovery or it is reinjected into hot field with the help of condensate pump.
- The main drawbacks of these plants are the presence of corrosive gases and abrasive materials which cause the environmental problems.

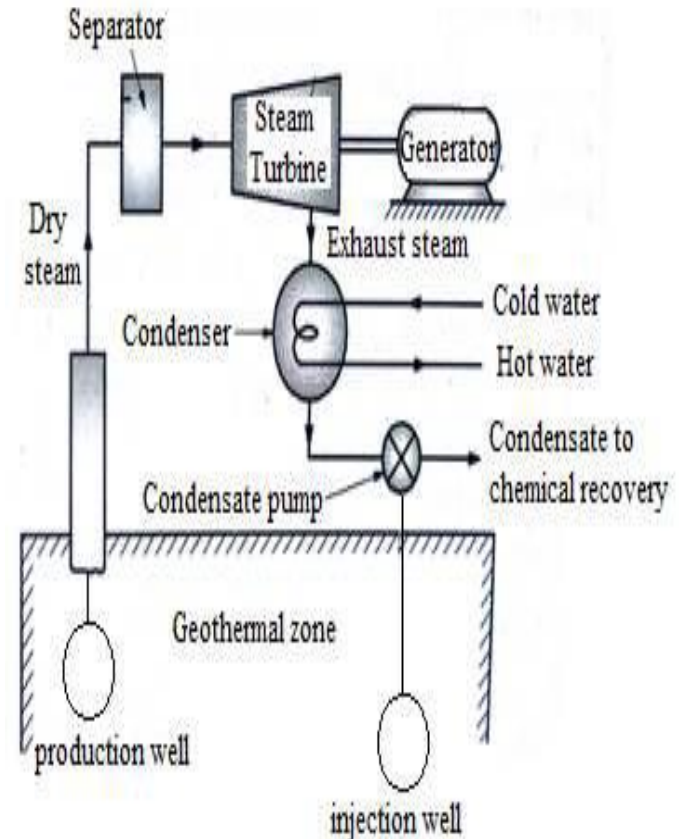


Fig. Dry steam power plant

3.1(d.2) Wet Steam / Liquid Dominated Systems:

The temperature range of such fields is in the range of 100°C - 315°C and these fields deposit hot water without much amount of steam. These can be further classified and explained in following categories:

(i) High Temperature Wet Steam System:

- The high temperature wet steam system having resource temperature above 180°C, suitable for power generation.
- In such systems the hot water with steam at high pressure and high temperature is extracted by deep wells drilled into the ground.
- This hot underground water from a depth of about 1 km (point. A) at high pressure (about 35 – 40 bar) reaches the well head (point. B) at lower pressure, this process produces two phase mixture having the steam of low quantity.
- This mixture is fed to flash chamber / brine separator which separates dry steam from brine (which is collected from bottom).
- This dry steam is supplied to steam turbine which is coupled to a generator, produces electrical energy.
- The hot brine is re-injected into the ground along with steam condensate from the condenser.

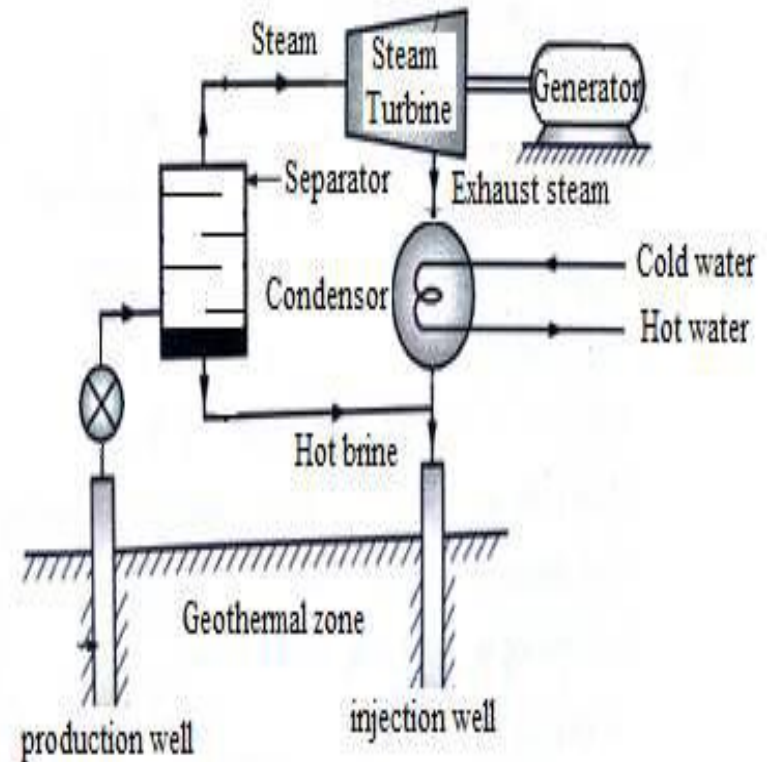


Fig. High temperature wet steam system

(ii) Low Temperature-Binary Fluid System:

- These hydrothermal resources are available in the temperature range of 90°C – 170°C which is not suitable for production of two phase mixture of steam.
- In such situation to utilize this geothermal heat, a fluid of low boiling point (*e.g. isobutene*) is used under pressure in a primary heat exchanger.
- The fluid vapour so generated is passed through a turbine
- where it expands and this mechanical power of turbine is converted into electrical energy by a generator.
- The exhaust of the turbine is passed through a heat exchanger and condenser where it is cooled and then condensed.
- The thermal fluid after transferring heat is re-injected through a well into the ground.

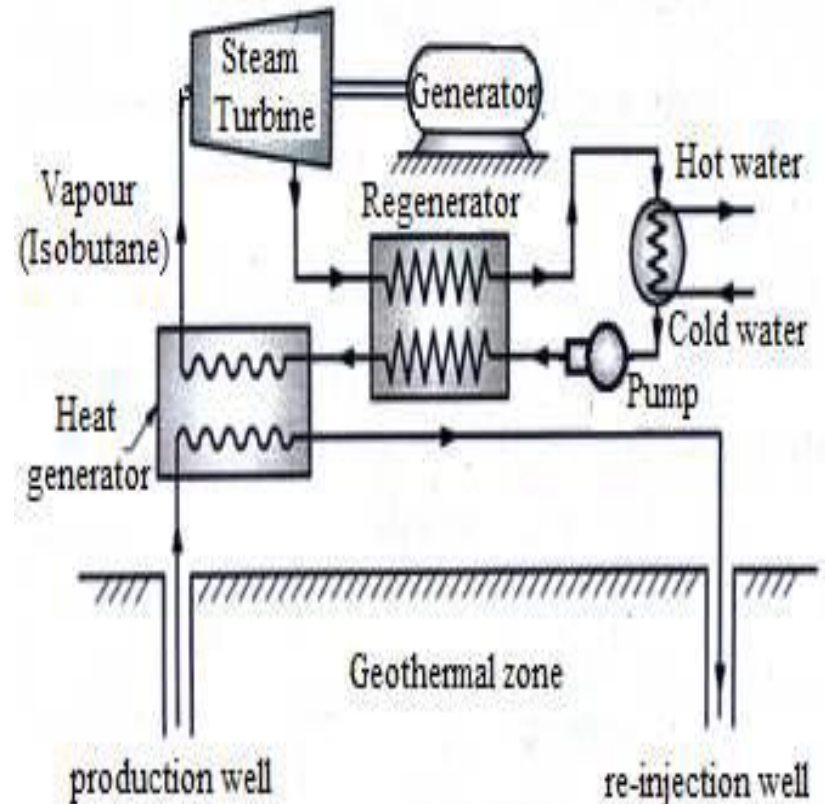


Fig. Low temperature binary fluid system

3.1(e) Hot Dry Rock (HDR) or Petro-Geothermal Systems:

- Hot dry rock receives heat energy from molten rock (magma).
- These reservoirs are artificially created by fracturing deep compact rocks up to depth of 8 -15 km by hydraulically / chemically or by nuclear explosion for injecting high pressure water.
- The water is pumped into the fractured well (injection well) and withdrawn from another well (production well) to extract heat to generate steam for power production.
- To prevent mixing of water in the reservoir the depth of production well is kept slightly less than reinjection Well.

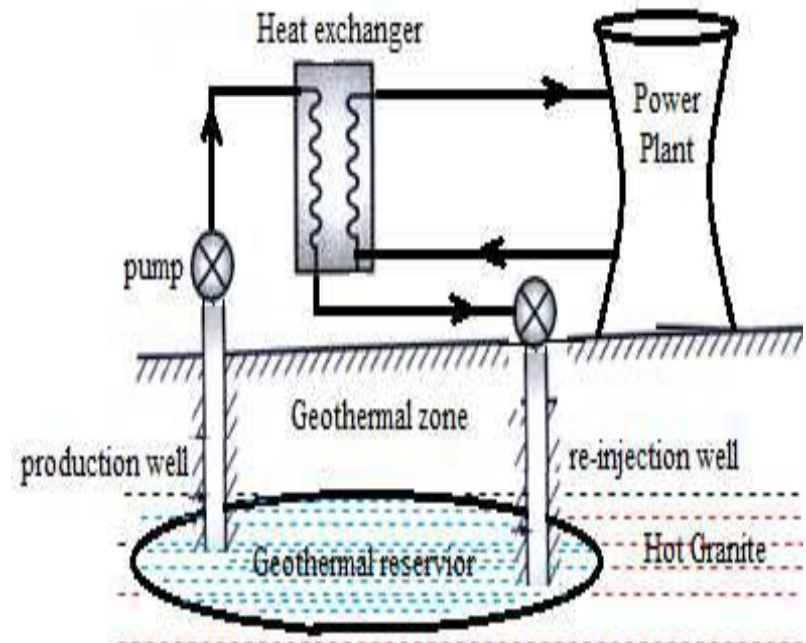


Fig. Hot Dry Rock (HDR) or Petro-Geothermal Systems

3.1(f) Geo-pressured Systems:

- These reservoirs were developed by sand deposits carried down by rivers and entrapped brine and natural gas at depth of 4-6 km and are located at different levels and at different places.
- These systems comprise of heavily compressed sediments that contain heat, methane and pressurized hot water.
- When well is drilled in this zone the reserve energy comes out in the form of high pressurized water having temperature about 160°C, heat and natural gas (methane) which are useful for power generation.
- These sources have been found in offshore wells in Texas and US Gulf Coast areas.

(i) Advantages of Geo-thermal Energy

1. It may be used in both energy supply, with power generation and direct heat use.
2. It is an inexhaustible source of energy.
3. It is almost free of pollution.
4. Independent of weather condition.
5. More reliable source of power generation than other renewable energy sources.

(ii) Disadvantages of Geo-thermal Energy

1. Causes corrosion, erosion, and chemical deposition due to the presence of sufficient amount of CO₂, CH₄, N₂, NH₃ and H₂S.
2. Noise pollution because of well drilling, centrifugal separators.
3. Proper re-filling of water is necessary.
4. It causes settlement of land.
5. Life of plant is low compared to conventional power plants.

(iii) Environmental impact:

- Some part of condensable gases (CO_2 , H_2S , NH_3 , CH_4 , N_2 and H_2) and radio actives are escaped to environment at various points and cause air pollution.
- There is possibilities of seismic disturbance because of extraction and re-injection of saline.
- Water pollution of rivers and lakes is a potential hazard as geo water contains high amount of dissolved solid with silica.
- The heat energy of turbine exhaust steam is rejected to atmosphere in cooling towers. It causes dense fog, increase in moisture.
- In such systems soil erosion takes place due to drilling of wells in geothermal fields.
- The exploitation of geothermal energy may cause earthquakes also.

3.1(g) Potential of Geo-thermal Resources in India:

In India about 150 known geothermal sites which can produce working fluids up to 170°C. Main locations of such fields are:

(i) Geothermal Fields of Puga-Chhumathang valley in J&K: A pilot project for space heating involved construction of a shed at an altitude of 4000 m and 4400 m in Ladakh district, Jammu & Kashmir and using steam at 125°C.

(ii) Manikaran (Himachal Pradesh): This project “cold storage plant” has been recently commissioned by the collaboration of Geological Survey of India, IIT Delhi, and H.P. Government.

(iii) Geothermal Fields of Beas and Parbati Valleys, Himachal Pradesh: Beas and Parbati valleys are well known for their hot springs in Kulu district, Himachal Pradesh. The spring’s temperature varies from 22°C to 59°C in Beas and 21°C to 96°C in Parbati valley at an altitude between 1300 m to 3000 m.

(iv) Sohana near Delhi,

(v) Tuwa in Gujrat

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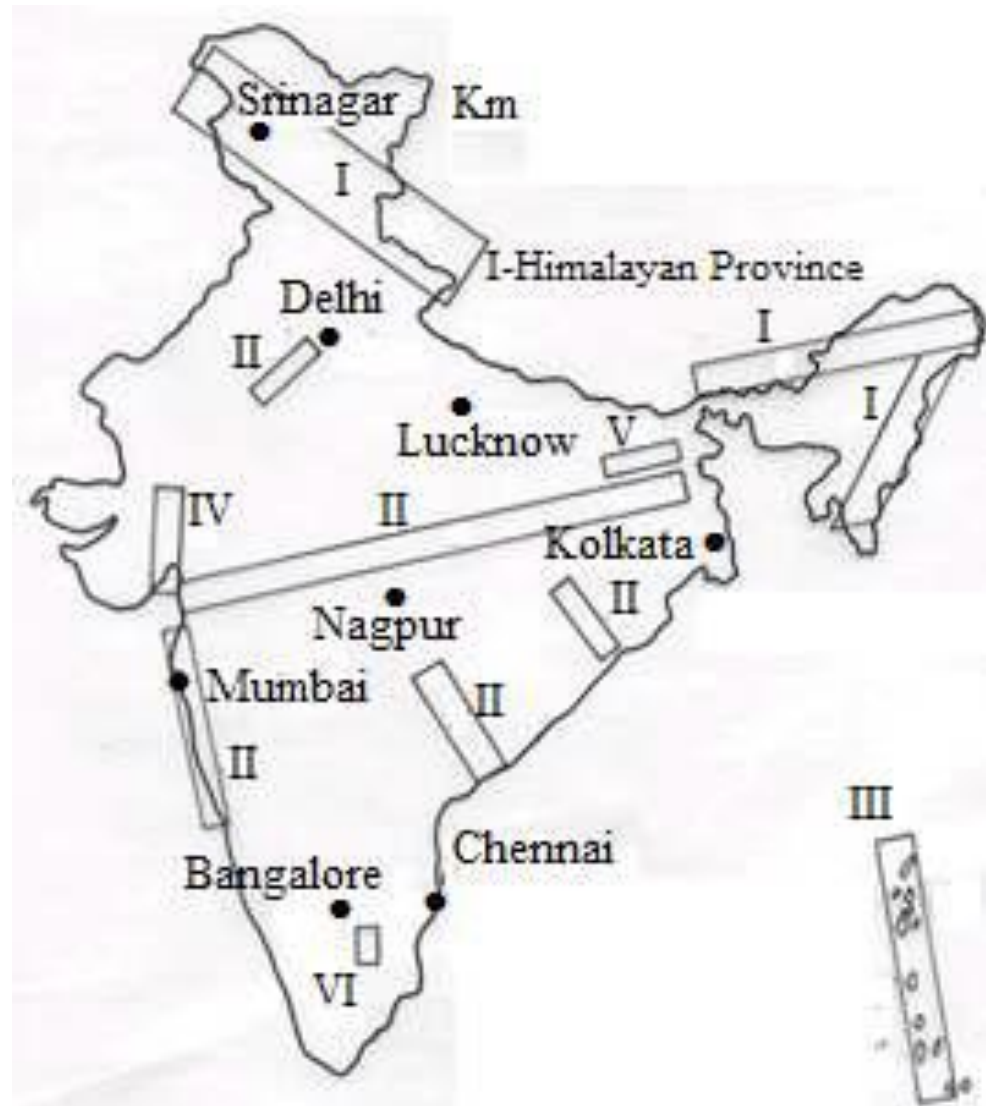
I-Himalayan Province,

II- Aravali, Naga Lucha, West Coast,

III- Gondwana, Son-Narbada,
Volcani Arc (Andaman Province),

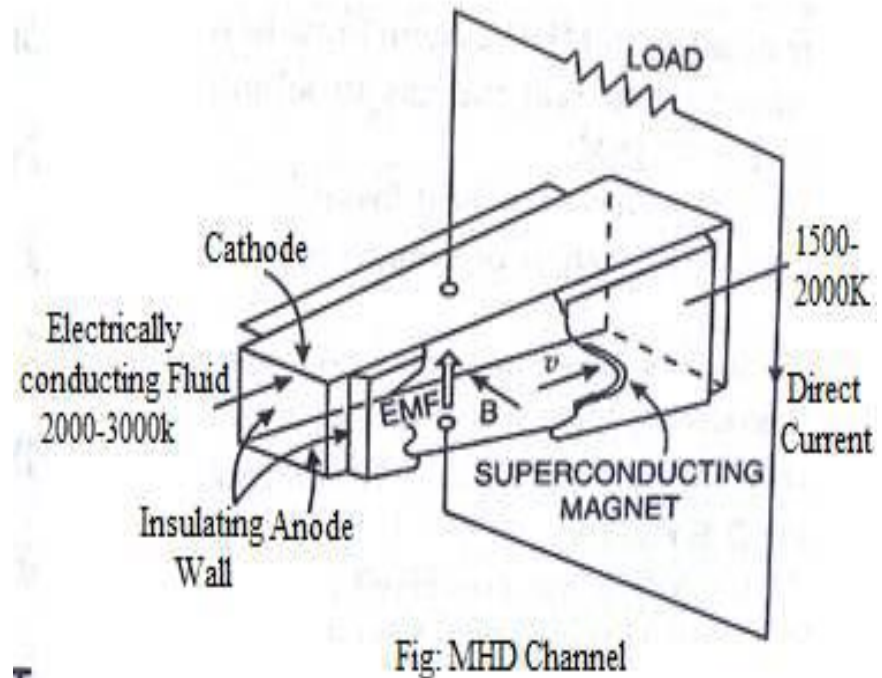
IV- Deep Sedimentry Basin,

V- Radio Active Province,



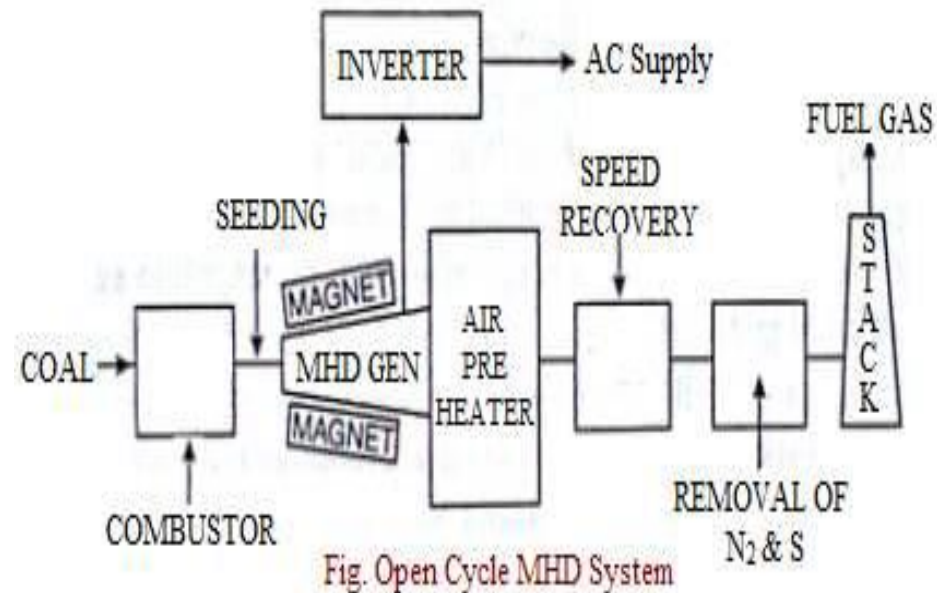
Magneto Hydrodynamic Generator

- **MHD** is a device which converts heat energy of an ionized fluid at high temperature directly through the applied magnetic field, without a conventional electric generator.
- In such systems power generation is based on the Faraday's law of electromagnetic induction.
- In such condition when plasma passes through a strong magnetic field then force begin to act on its ions, this force act on plate P1 for +ions and towards P2 for -ions. Due to migration of these charges a potential difference creates between the plates.
- If a load is connected between these plates then electricity begin to flow. This process takes place in MHD channel.



(i) Open Cycle MHD Systems:

- In an open cycle system the working fluid is used on the once through basis. The working fluid after generating electrical energy is discharged to the atmosphere through a stack.
- Generally coal is used as fuel as it produces more conductive plasma; this is because of more carbon atom as compared to hydrogen atom.
- The working temperature of such MHD generators lies approximately in the range above 2300°C.
- The different parts of open cycle generator are:



- (a) **Compressor:** Compressor is used to raise the pressure of the air supplied in combustion chamber for efficient burning of fuel. The pre-cooled air is compressed in compressor before being supplied in the pre-heater.
- (b) **Pre-heater:** The compressed air pre-heated in the pre-heater at 1100°C from the exhaust gases of the generator to increase the combustion efficiency of working fluid.
- (c) **Combustor:** The fluid is burnt in this section of generator in the presence of hot air coming from pre-heater & gas is seeded with cesium to ionize the gas.
- (d) **Nozzle:** The high temperature gases after combustor pass through convergent-divergent nozzle to increase its velocity of order of 1000 m/s .
- (e) **Generator Duct:** It is made of heat resisting & insulating material. The high magnetic flux is applied in this section of the duct at perpendicular to flow direction of gases. As the moving gas cuts the line of magnetic flux the induced electric field produces DC current through generator in this section. The duct is water cooled to remove the heat.
- (f) **Inverter:** The generated DC is converted into AC by using the inverter before supply to grid.
- (g) **Gas Chamber:** The exhaust hot gasses passes through the air cleaner to control the pollution & remove harmful gases.
- (h) **Seed Recovery System:** Seed material is expensive & need recovery system along with open MHD power cycle for further use. The removed seeds are supplied back in the combustor.

(ii) Closed Cycle MHD System:

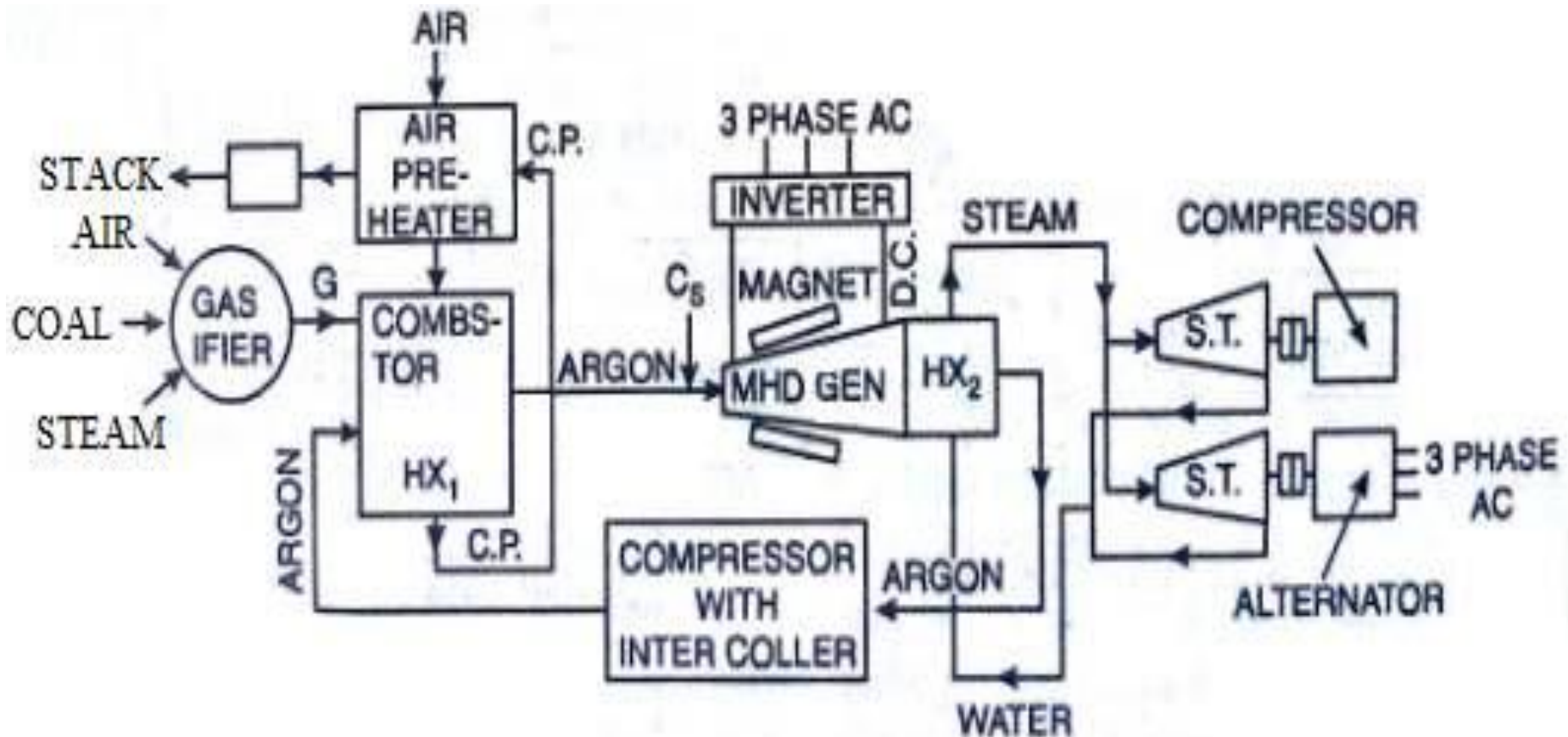


Fig. Closed Cycle MHD System

HX₁ - Heat Exchanger 1, HX₂ - Heat Exchanger 2, G- Gas, C.P- Combustion products, Cs-Cesium injection, ST- Steam turbine, P- removal of nitrogen and sulphur

- In this system the very high thermal efficiency is achieved with low cycle cost in closed plant & provides more useful power at low temperature at 1600°C. The ducts of these units are small because of high pressure.
- Helium or argon is used as working fluid, heated in heat exchanger & get ionized, alkali metals is mixed with inert gas to provide the necessary conductivity in closed cycle plant, where recovery is possible.
- The working fluid in closed cycle is seeded with Cesium and circulated in a closed loop. Gas is burned in the combustor is supplied in the heat exchanger, where the heat is transferred to the working fluid.
- The ionized gas passes through the magnetic field to produce DC power.
- The combustion products are discharged to the atmosphere after removal of heat in heat exchanger.
- It shows the schematic of liquid metal MHD generator. The superheated metallic vapour is expanded through the supersonic nozzle and enters in the generator in liquid form with velocity of 150 m/s.
- The electrical conductivity of metallic vapour is poor. That brings the overall conversion efficiency lower than that of gas as a working substance.

(iii) Hybrid MHD Generator:

- The hybrid MHD generator is developed to improve the thermal efficiency of plant. The efficiency up to 60% is achieved in the hybrid system.
- The working gas enters in the MHD at 3000°C and will leave at 2000°C through the steam turbine coupled with generator.
- A steam power plant is connected along with MHD generator to use the remaining energy of exhaust gases of MHD generator and converted it into electrical energy.
- The MHD plant may be open or a closed type. This steam power plant works on Rankine cycle.

Working principle of MHD power generation

When a charged particle moving in a magnetic field, having charge q and velocity v , then the force acting on it:

$$\vec{F} = q(\vec{v} \times \vec{B}).$$

If \vec{E} is the electric field acts, then the total force:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \dots \dots \dots (1)$$

The velocity to be used in above equation (1) is the vector sum of gas velocity v and the particle drift velocity u . Thus force is given by:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B} + \vec{u} \times \vec{B}) \dots \dots \dots (2)$$

can be written as:

$$\vec{F} = q(\vec{E}' + \vec{u} \times \vec{B})$$

where

$$\vec{E}' = (\vec{E} + \vec{v} \times \vec{B}) \dots \dots \dots (3)$$

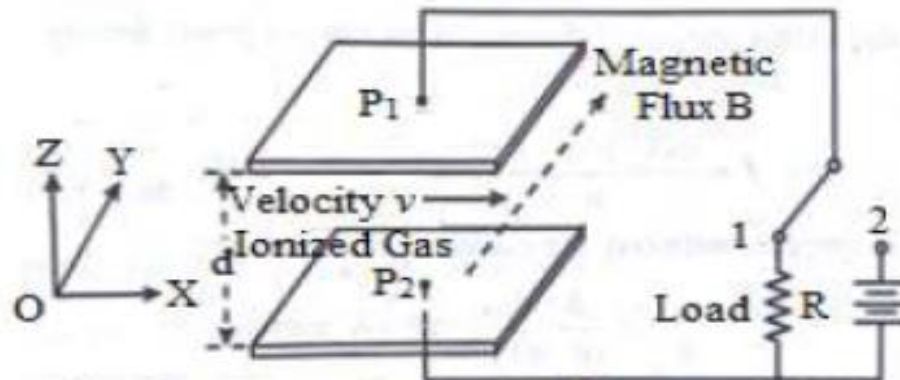


Fig: Directions of magnetic flux, gas velocity and force in MHD system

From figure, the motion of gas is in x-direction. magnetic field B is in y-direction and the force on the particle is in z- direction.

If the distance between the plates be d , then the electric intensity b/w the plates is $\vec{E}_z = -\vec{V}/d \dots \dots \dots (4)$

The total electric field is: $\vec{E}' = -\vec{E}_z + B\vec{v} = \frac{1}{d}(Bvd - V) \dots \dots (5)$

The electromagnetic fields \mathbf{E}_z and \mathbf{B} acting on the moving gas produce the same force on the ions as the electromagnetic field E_z' and \mathbf{B} produce on gas with zero average velocity. The term Bvd gives the internal e.m.f. (or open circuit voltage) of the MHD generator.

If R_0 and R_L be the internal resistance of generator and load resistance respectively then the current I through the circuit be:

$$I = \frac{V_0}{R_0 + R_L} \dots \dots \dots (6)$$

So the power output: $P = V_0 I = I^2 R_0 = \left(\frac{V_0}{R_0 + R_L} \right)^2 R_0$

The power delivered to the load is maximum when load resistance $= R_L = R_0$

$$P_{max} = \frac{V_0^2}{4R_0} = \frac{(Bvd)^2}{4R_0} = \frac{B^2 v^2 d \sigma A}{4} \dots (7)$$

σ = conductivity of gas (Ω^{-1}/m); A = electrode surface area (m^2)

So maximum power output per unit volume $= \frac{B^2 v^2 \sigma}{4}$

The maximum current

$$I_{max} = \frac{V_0}{R_0 + R_L} = \frac{Bvd}{2R_0} = \frac{ABv\sigma}{2}$$

Advantages & Disadvantages of MHD System:

Advantages of MHD

1. These systems having higher efficiency (60-65%) because of higher operating temperature.
2. Requires less area and maintenance as compare to conventional power plants of same capacity.
3. Less pollution to the environment because of less fuel consumption as compared to other conventional power plants.
4. They are compact in size, have low specific weight and high power density, having instant operation and suitable as peak load.
5. Provides direct conversion of heat directly into electrical energy.

Disadvantages of MHD

1. Power generation in MHD is directly proportional to square of magnetic flux, it needs very large power to create it which increases to cost of the system.
2. High temperature gases causes corrosion and chemical erosion.
3. It is difficult to built equipments to withstand very high temperature, used in MHD.
4. High initial cost due to large sized magnets and equipments.
5. High thermal and frictional losses.

Fuel Cells

- A **fuel cell** is a device that converts the chemical energy from a fuel into electricity through a chemical reaction with oxygen or another oxidizing agent.
- Fuel cells are different from batteries in that they require a constant source of fuel and oxygen/air to sustain the chemical reaction; however, fuel cells can produce electricity continuously for as long as these inputs are supplied.
- There are many types of fuel cells, but they all consist of an anode, a cathode and an electrolyte that allows charges to move between the two sides of the fuel cell.
- Electrons are drawn from the anode to the cathode through an external circuit, producing direct current electricity.
- The main difference among fuel cells are the types of electrolyte used hence they are classified on the basis of electrolyte they use.

Working Principle of Fuel Cells

The basic design features of a fuel cells are:

- The electrolyte substance. The electrolyte substance usually defines the type of fuel cell.
- The fuel that is used. The most common fuel is hydrogen.
- The anode catalyst breaks down the fuel into electrons and ions. The anode catalyst is usually made up of very fine platinum powder.
- The cathode catalyst turns the ions into the waste chemicals like water or carbon dioxide. The cathode catalyst is often made up of nickel but it can also be a nanomaterial based catalyst.

Its working may be explained as:

- The cell consists of two electrodes between which electrolyte (40% KOH) is filled and serves as a carrying media for charged ions.
- The fuel (usually hydrogen) is supplied at anode side and oxidant (oxygen or air) at the cathode side.
- The electrolyte between the inner face of the both electrodes is kept stirred to prevent stay of ions for long time at the surface.
- The formed ions migrate through electrolyte to the opposite side of electrodes because of pressure difference between the reactant gases and the electrolyte.
- Sometimes catalysts (generally Platinum) are used to increase the reactivity at electrodes for breaking the fuel molecules.
- During chemical reaction H^+ and OH^- ions are produced as an intermediate product.
- The H^+ ions migrate to the cathode and reacts with oxygen to form water and vice-versa for oxygen ions.
- The electrons released at a anode travels through the external circuit to form the oxidizing products and the reactions are taken place.

Classification of Fuel Cells

(a) Based on the Type of Electrolyte

- (i) Phosphoric Acid Fuel Cell (PAFC)
- (ii) Alkaline Fuel Cell (AFC)
- (iii) Polymer Electrolytic Membrane Fuel Cell (PEMFC) or Solid Polymer Fuel Cell (SPFC) or Proton Exchange Membrane Fuel Cell (PEMFC)
- (iv) Molten Carbonate Fuel Cell (MCFC)
- (v) Solid Oxide Fuel Cell (SOFC)

(b) Based on the Types of the Fuel and Oxidant

- (i) Hydrogen (pure)–Oxygen (pure) fuel cell
- (ii) Hydrogen rich gas–air fuel cell
- (iii) Hydrazine–Oxygen/hydrogen peroxide fuel cell
- (iv) Ammonia–air fuel cell
- (v) Synthesis gas–air fuel cell
- (vi) Hydrocarbon (gas)–air fuel cell
- (vii) Hydrocarbon (liquid)–air fuel cell

(c) Based on Operating Temperature

- (i) Low temperature fuel cell (below 150°C)
- (ii) Medium temperature fuel cell (150°C – 250°C)
- (iii) High temperature fuel cell (250°C – 800°C)
- (iv) Very high temperature fuel cell (800°C – 1100°C)

(d) Based on Application

- (i) Fuel cell for space applications
- (ii) Fuel cell for vehicle propulsion
- (iii) Fuel cell for submarines
- (iv) Fuel cell for defense applications
- (v) Fuel cell for commercial applications

(e) Based on the Chemical Nature of Electrolyte

- (i) Acidic electrolyte type
- (ii) Alkaline electrolyte type
- (iii) Neutral electrolyte type

Phosphoric acid fuel cell (PAFC):

- In these cells **phosphoric acid (H_3PO_4)** is used as a nonconductive electrolyte to pass positive hydrogen ions from the anode to the cathode. PAFC is a non-conductive liquid acid which forces electrons to travel from anode to cathode through an external electrical circuit.
- The hydrogen ion production rate on the anode is small so platinum is used as catalyst to increase this ionization rate.
- These cells commonly work in temperatures of **150 to 200** degrees Celsius.
- This high temperature will cause heat and energy loss if the heat is not removed and used properly.
- This heat can be used to produce steam for air conditioning systems or any other thermal energy consuming system.
- The chemical reaction in this fuel cell are as follows:

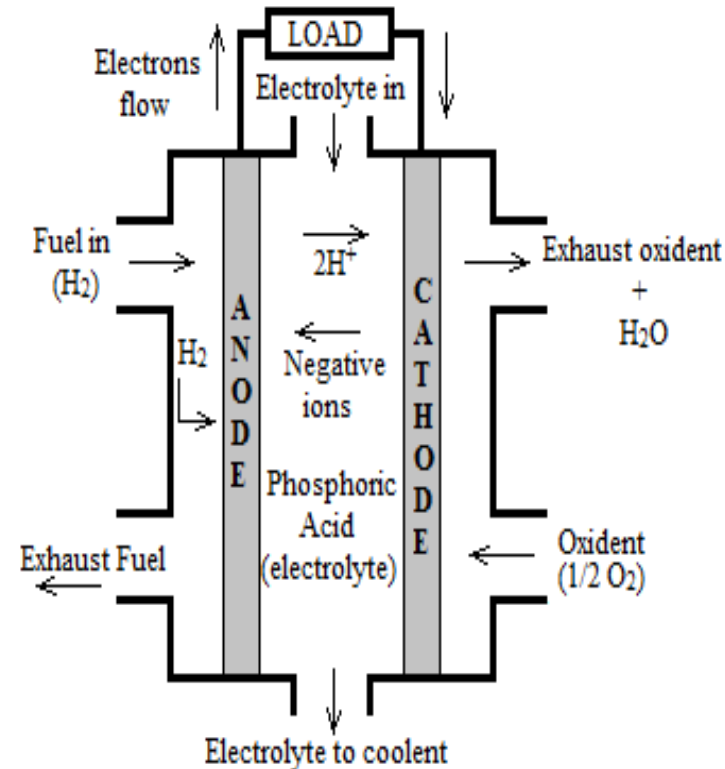
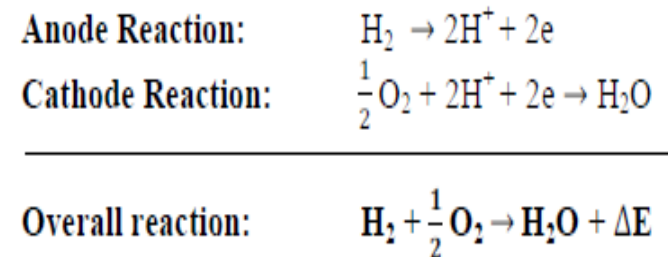


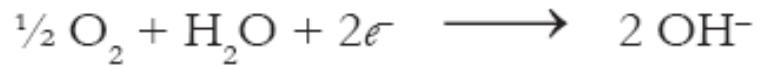
Fig. Phosphoric Acid Fuel Cell



Phosphoric acid fuel cell (PAFC):

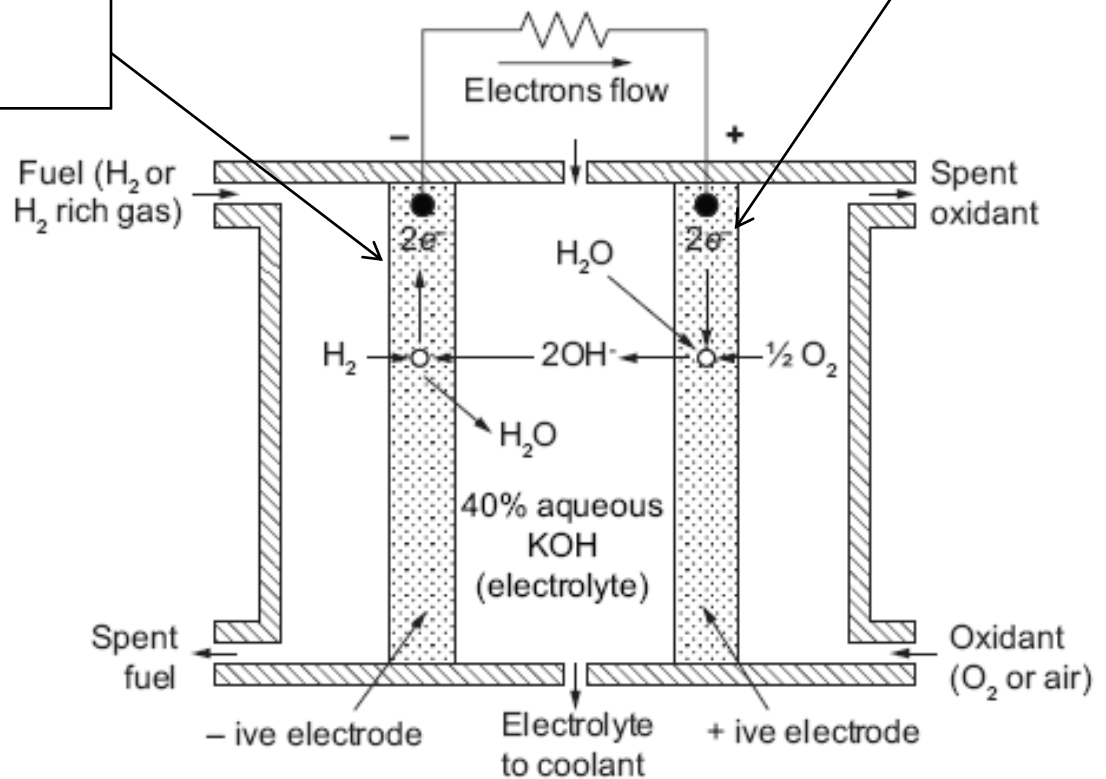
- It is the most commercially developed fuel cell
 - Operating temperature is 150 – 200
 - EMF under open circuit – 1.23 – 1.15V, under rated current 0.7 – 0.8V
 - Toshiba and Fuji Electric are the main manufacturers
- Advantages:
 - H₂O rejecting electrolyte
 - high temps favour H₂O₂ decomposition
 - $\text{O}_2 + \text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2\text{O}_2$
 - Stable H₂O₂ lowers cell voltage and corrodes electrode
- Problems:
 - CO poison the anode
 - low conducting electrolyte

Alkaline Fuel Cell (AFC)



Anode: C/Pt or
C/Raney Ni/Pt

Cathode: C/Pt



Alkaline Fuel Cell (AFC)

- 60% efficiency in space application
- Both electrodes are fabricated with an active layer of platinum catalyst on carbon support / binder that is backed by a wet-proofed Teflon (PTFE, polytetrafluoroethylene) bonded carbon layer .
- Electrolyte - in space applications used a gel-stabilized electrolyte matrix.
- Liquid matrix is better because it can be circulated.
- Circulating electrolyte removes water formed at anode, acts as coolant and prevents carbonates from building up in electrolyte matrix
- Operates up to $1\text{A}/\text{cm}^2$ at 0.7V

Alkaline Fuel Cell (AFC)

□ Advantages:

- Low cost electrolyte solution (KOH 30-35%)
- Non-noble catalyst withstand basic conditions
- O₂ kinetics faster in alkaline solution

□ Problem Areas and Solutions:

■ Catalysts

- Pt – expensive
- Pt/Co alloys; similar ability to reduce O₂
- CO₃²⁻ builds up in electrolyte and clogs pores - CO₂ + 2OH⁻ → CO₃²⁻ + H₂O
- Fe sponges can be inserted to absorb CO₂

Molten Carbonate Fuel Cell (MCFC):

- In these fuel cells mixture of H_2 and CO is used as fuel and O_2 or air as oxidant.
- MCFCs use lithium potassium carbonate salt as an electrolyte, and this salt liquefies at high temperatures, allowing for the movement of charge within the cell – in this case, negative carbonate ions.
- Working range of such fuel cells is $650^\circ C - 700^\circ C$.
- The hydrogen in the gas reacts with carbonate ions from the electrolyte to produce water, carbon dioxide, electrons and small amounts of other chemicals.
- The electrons travel through an external circuit creating electricity and return to the cathode.
- Oxygen from the air and carbon dioxide recycled from the anode react with the electrons to form carbonate ions that replenish the electrolyte, completing the circuit.
- The chemical reactions can be expressed as follows.

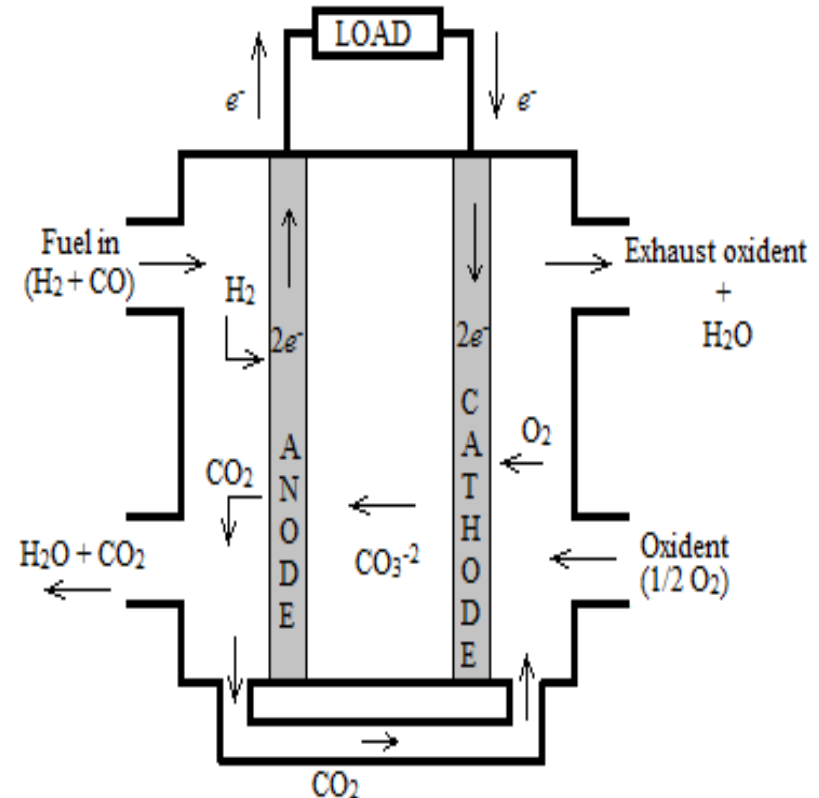
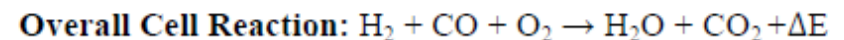
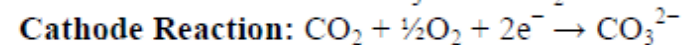
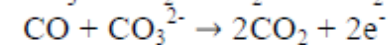
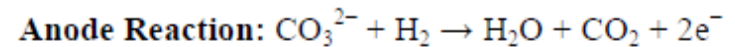


Fig. Molten Carbonated Fuel Cell



Proton Exchange Membrane Fuel Cells (PEMFCs)

- These are also known as a "solid polymer electrolyte fuel cell" (SPEFC).
- In this type of fuel cell, solid polymer membrane of an organic material such as polystyrene is used as electrolyte.
- On the anode side the H^+ ions are conducted through the membrane to the cathode, but the electrons are forced to travel in an external circuit (supplying power) because the membrane is electrically insulating.
- On the cathode catalyst, oxygen molecules react with the electrons (which have traveled through the external circuit) and protons to form water.
- The chemical reactions can be expressed as follows.

Anode Reaction: $H_2 \rightarrow 2H^+ + 2e^-$

Cathode Reaction: $O_2 + 2H^+ + 2e^- \rightarrow H_2O$

Overall Cell Reaction: $H_2 + O_2 \rightarrow H_2O + \Delta E$

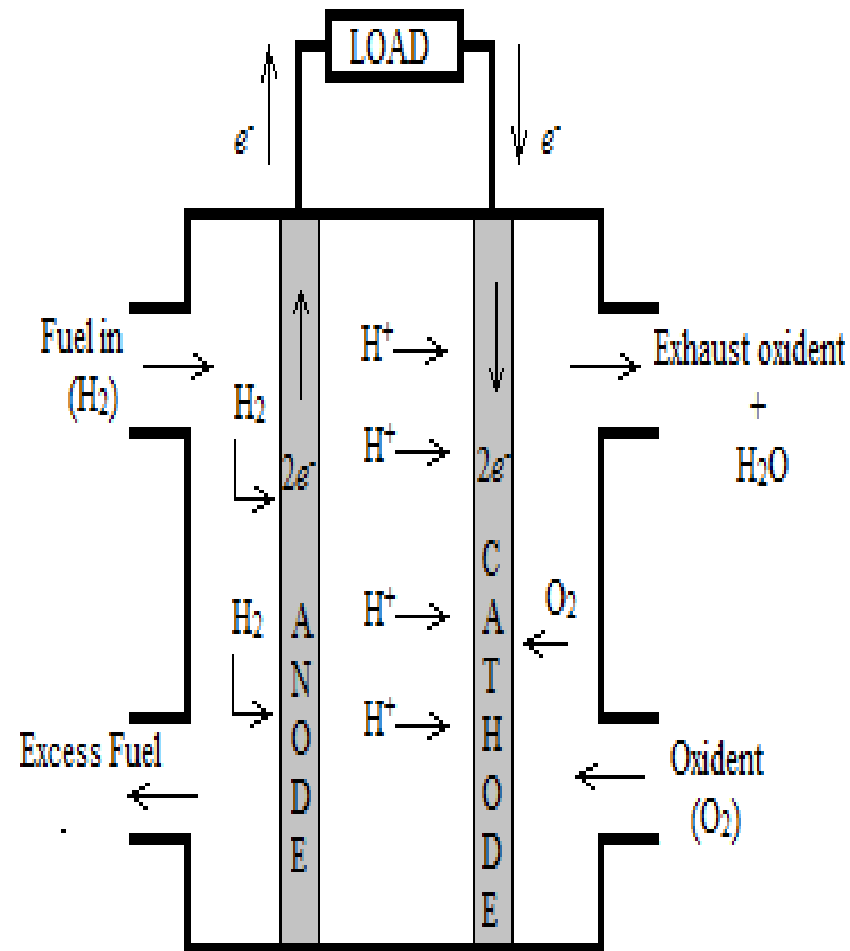


Fig. Proton exchange membrane fuel cells (PEMFCs)

Solid Oxide Fuel Cell (SOFC)

- Solid oxide fuel cells (SOFCs) use a solid material, most commonly a ceramic material (e.g. zirconium dioxide) as the electrolyte.
- They require high operating temperatures (800–1000 °C), due to which no catalyst is required.
- The anode in such cells is made up of porous nickel and cathode is of metal oxide.
- The output voltage is about 0.65V at about 8000C.
- Generally H₂ is uses as fuel in this cells but other fuel may be methanol, ammonia and hydrazine (N₂H₄).
- These cells having efficiency about 60%-70%.
- The chemical reactions can be expressed as follows.

Anode Reaction: $2\text{H}_2 + 2\text{O}_2^- \rightarrow 2\text{H}_2\text{O} + 4\text{e}^-$

Cathode Reaction: $\text{O}_2 + 4\text{e}^- \rightarrow 2\text{O}_2^-$

Overall Cell Reaction: $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O} + \Delta E$

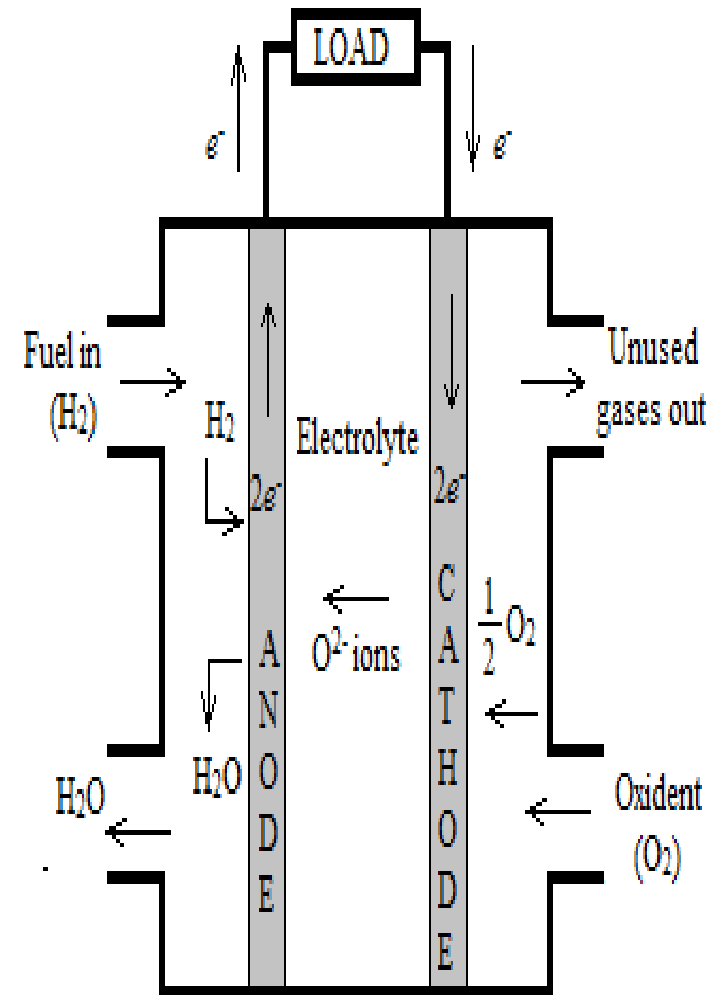


Fig. Solid oxide fuel cells

Regenerative Fuel Cells (RFC)

- A regenerative fuel cell or reverse fuel cell (RFC) is a fuel cell operate and run in a closed loop, where reactants are regenerated from the products.
- These cells produce electricity from fuel (H_2) and oxygen and generate energy and water as by a product.
- The excess water is divided into H_2 and O_2 by electrolysis using electricity from other sources like solar, wind etc.
- The chemical reactions can be expressed as follows.

Anode Reaction: $H_2O + 2e^- \rightarrow H_2 + O_2^-$

Cathode Reaction: $O_2^- \rightarrow 1/2O_2 + 2e^-$

Overall Cell Reaction: $H_2O \rightarrow 1/2O_2 + H_2$

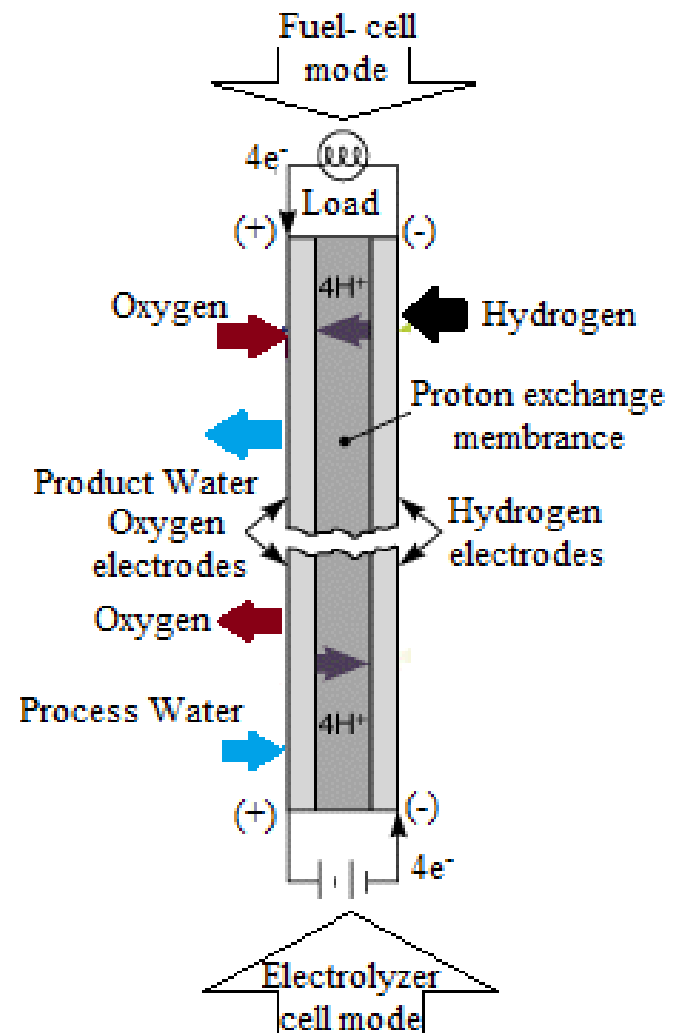


Fig. Regenerative Fuel Cell

Performance Analysis of Fuel Cell

In fuel cell the electro-chemical reaction takes place and electrical power and produced. Fuel cell's performance may be describes with the help of Gibbs energy equation. The energy balanced equation may be describes as: $G = H - T.S$ (1)

or for a constant temperature process: $\Delta G = \Delta H - T\Delta S$ (2)

but from the first law of thermodynamics: $Q + W = \Delta H$ (3)
(where W is work in, and is negative)

From second law of thermodynamics: $Q = T\Delta S$ (4)

So from equations (3) & (4) : $W = \Delta H - T\Delta S$ (5)

This applies for a chemical process at constant temperature and pressure, and is the maximum possible useful work or available energy, known as the “free energy”.

So it is clear from equations (2) & (5): $W_{max} = - \Delta G$ (6)

The ratio of work output to the energy supplied of the fuel cell is defined as the efficiency, η of energy conversion of fuel cell. Therefore:

$\eta = \frac{\text{output work}}{\text{energy supplied}} = \frac{W}{-\Delta H}$	and its maximum efficiency:	$\eta_{max} = \frac{W_{max}}{-\Delta H} = \frac{-\Delta G}{-\Delta H}$
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Advantages, Disadvantages & Applications of Fuel Cells

Advantages

- Less pollution and higher efficiency.
- Less maintenance required.
- Since there is direct conversion of energy so efficiency is high.
- Water is formed as product which may be used for many other applications.
- Having fast starting time.

Disadvantages

- High initial cost.
- Short life because of degrading of electrodes.
- Proper handling is required due to operate with hydrogen and oxygen.
- Efficiency goes down with time.

Applications of Fuel Cells

- Used in automotive vehicles.
- Power generation up to 1 MW.
- Used for space applications.
- Used for military applications.
- Used for submarine applications.

END OF UNIT 3