CHAPTER 11

Geothermal Energy

11.1 INTRODUCTION

Geothermal energy is the thermal energy present in the interior of the earth. Geothermal energy can be extracted from earth's interior in the form of heat. Volcanoes, geysers and hot springs are visible signs of the large amounts of heat lying in earth's interior. The geothermal energy from earth's interior is almost inexhaustible. Although the amount of thermal energy within the earth is very large, but useful geothermal energy can be extracted at only certain suitable sites. It is impossible to extract heat when it is lying at a great depth from the surface. The centre of the earth is estimated to have a high temperature of about 10,000 K. The heat is generated within the earth due to the decaying process of radioactive isotopes. The molten rock within the earth is called magma, which is nearest to earth's surface with the temperature about 3000°C.

11.2 RESOURCES OF GEOTHERMAL ENERGY

- **Discuss the various types of geothermal resources.**

or

- **Discuss origin and types of geothermal energy. Briefly discuss hot spring and steam ejectors.**

or

- **Describe a geothermal field from which geothermal steam is obtained through hot springs?**

The molten mass of the earth is called magma. The earth's crust over the magma is about 32 km on average. However, at certain places owing the earth tremors the magma happens to come closer to earth's surface. This presence of hot magma near to earth's surface creates active volcanoes, hot springs and geysers. It also causes steam to vent through the fissures when underground water comes in contact with magma. There are five types of geothermal resources, which include hydrothermal, geopressured, hot dry rock, active volcanic vents and magma.

Hydrothermal resources contain superheated water, steam or both in fractured or porous rock, but further trapped by a layer of impermeable rock. Hydrothermal resource may give dry and pure steam with temperature above 240°C. However, majority of these resources have moderate temperatures ranging from 100 to 180°C, while few resources have high temperatures ranging from 150 to 200°C. To use hydrothermal energy, wells have to be drilled to reach a fissure or hydrothermal reservoir as shown in Figure 11.1.

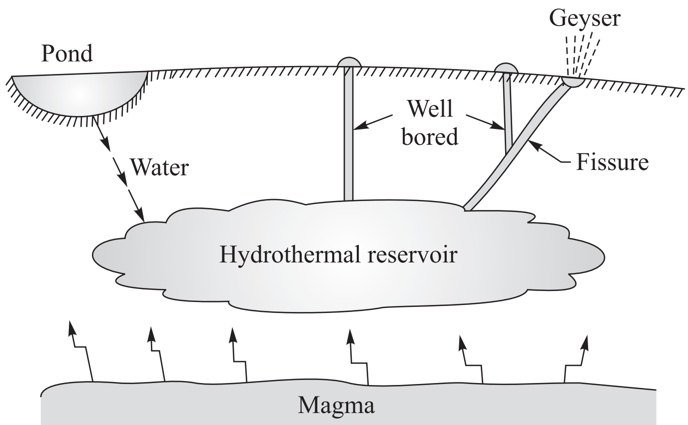


Figure 11.1 A hydrothermal resource.

Geopressured resource is hot water or brine trapped underground at the depth of about 2400–9100 m with temperature at about 160°C. The pressure of the water is about 1000 bar. Although it has great heat potential for power generation but it is uneconomical due to low temperature and high cost of drilling into earth's surface to such a great depth. In case brine has recoverable methane, brine water can be used with combustion of methane to generate electricity.

Hot dry rocks or petrothermal resources consist of high-temperature rocks ranging from 90 to 650°C. The rocks can be fractured and water may be circulated through the rocks to extract thermal energy.

Geothermal energy in the form of active volcanic vents occur in many parts of the world. There is molten rock or magma present in these volcanic vents at temperature ranging from 700 to 1600°C. Magma chambers have got huge thermal energy compared to other geothermal resources. However, extracting thermal energy from volcanic vents is difficult.

Molten rock or magma may be present at shallow depths at certain places. The heat can be easily extracted at these places.

Hot springs and steam ejector

There are certain regions where the heat of molten rock in the earth is pushed up through fault cracks near earth's surface within 2–3 km, thereby creating hot spots. In case vents exist, hot water and steam are violently and periodically ejected from these vents. The water ejecting from a hot spring is heated by geothermal heat. When water percolates deeply enough into earth's crust, it is heated as it comes in contact with hot rocks. The water in hot springs in non-volcanic areas is heated in this manner. When water gets mixed with mud and clay, it is called a mud hole and it produces boiling mud pond.

The high temperature near magma may cause water to boil and transform into superheated steam. When the steam ejects out through vents in earth's crust in a jet, it is called a geyser or steam ejector. When the water is ejected in the form of hot water, it is called hot springs. There are hot springs in many countries around the world. Many countries are famous for their hot springs. The countries such as Iceland, New Zealand, Chile and Japan are famous for their hot springs.

11.3 GEOTHERMAL POWER PLANTS

11.3.1 Hydrothermal Resources

- **Describe various energy extraction technologies used with hydrothermal resources.**

or

- **Describe a vapour dominated hydrothermal type geothermal power plant.**

or

- **Explain the working of geothermal power plants. Discuss the various technical developments.**

or

- **What do you mean by dry, wet and hot water geothermal systems?**

Hydrothermal resources are formed when underground water has access to high-temperature, porous rocks, capped by a layer of solid impervious rock. The entrapped water is heated by surrounding rocks. The hydrothermal resources can be classified depending on the heating of entrapped water as dry steam fields or vapour dominated resources, wet steam fields or liquid dominated resource and hot water resource. Vapour dominated fields can deliver steam with almost no water. Liquid dominated fields can deliver the mixture of steam and hot water, while hot water resource can only deliver hot water.

Vapour dominated plant

Water boils underground in a hydrothermal resource when it has pressure of about 7 atm and temperature of about 165°C. The dry steam fields are located at the Geysers region of California (USA), the Larderello (Italy) and the Matsukawa region of Japan. The plant consists of (i) production well to extract steam from the hydrothermal resource, (ii) a centrifuge separator to remove solid matter from the steam, (iii) a turbine to convert thermal energy into mechanical energy, (iv) a generator coupled to turbine to generate electric power,

(v) a condenser to condense wet steam exited from turbine into water by direct contact with cooling water and (vi) a cooling tower to cool warm water exited from the condenser and returning the cooled water to the condenser.

The excess water is disposed of in the reinjection well as shown in Figure 11.2. The cycle used in this system is called Rankine cycle.

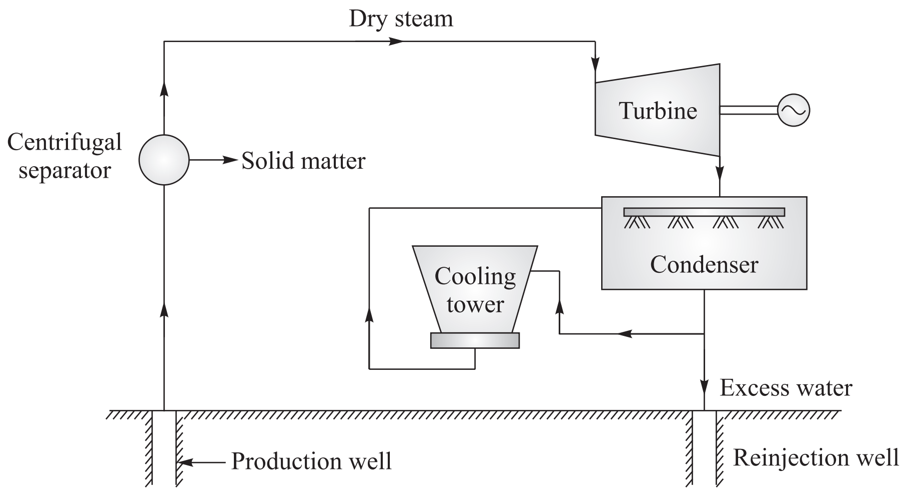


Figure 11.2 Dry steam hydrothermal plant.

Wet steam or liquid dominated

The wet steam or liquid dominated fields or resources can be further divided into high temperature (above 175°C) enabling the use of flash steam evaporator to produce dry steam and low temperature (range of 95–175°C) where geothermal heat is used to vaporise a violatic refrigerant.

(i) **Liquid dominated high-temperature plant or system.** The type of plant or system is used where hydrothermal reservoir has temperature and pressure of 230°C and 40 atm respectively. The plant consists of flash evaporator to obtain dry steam from high temperature wet steam by lowering pressure in it, turbine with directly coupled generator to extract energy from dry steam, condenser to condense used steam into water and cooling tower to cool the warm water. The excess water is disposed of in the ground as shown in Figure 11.3. In dual flash system, the hot water is flashed in two flash evaporators in two stages. Steam obtained in the first stage is used in low pressure turbine and steam is again flashed to obtain high pressure to be used in high pressure turbine as shown in Figure 11.4. The 50 MW Hatchobane plant, Kyushu in Japan is a double flash system.

(ii) **Liquid dominated low-temperature plant or system.** The water available from the hydrothermal reservoir is at low temperature range of 90–175°C, which is insufficient to produce steam using a flash evaporator. A low boiling point refrigerant is used as a working medium. The plant runs on binary cycle. The refrigerant is evaporated in a heat exchanger using the heat of water obtained from hydrothermal reservoir. The

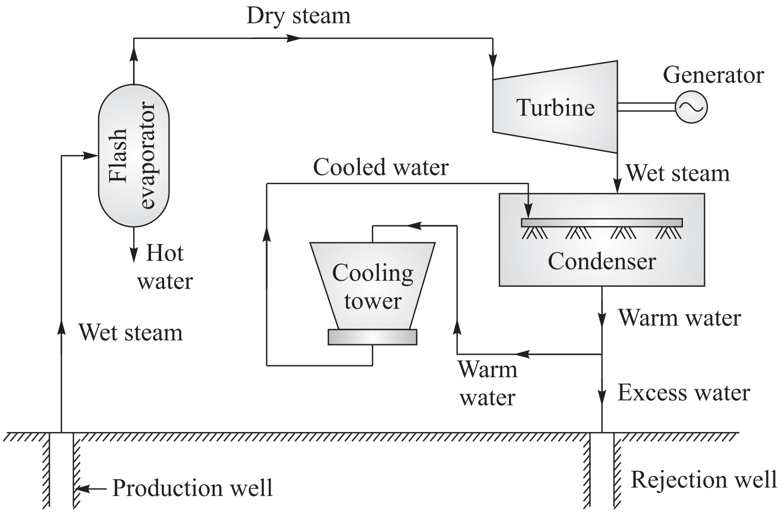


Figure 11.3 Single flash steam system in liquid dominated high-temperature plant.

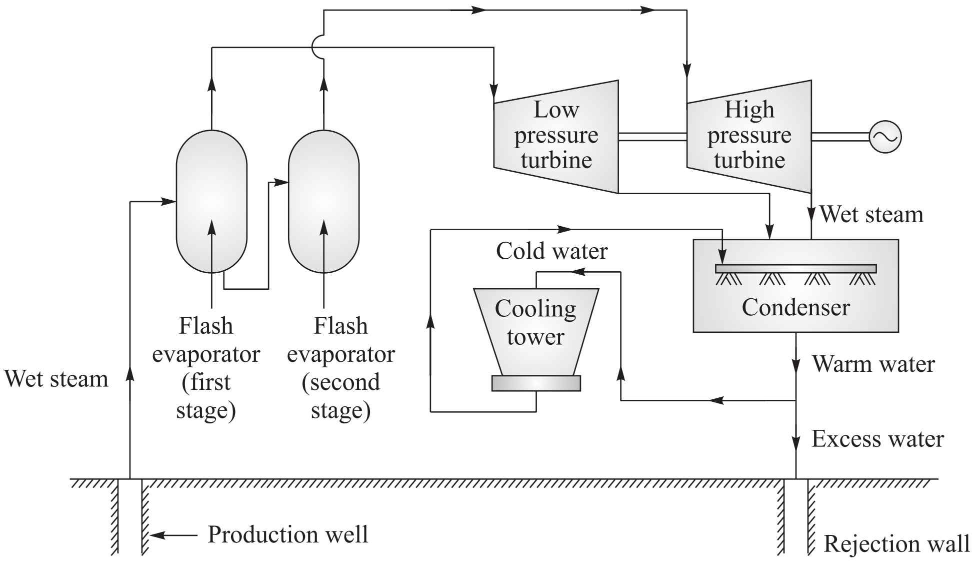


Figure 11.4 Double flash steam system in liquid dominated low-temperature plant.

refrigerant vapour runs the turbine with a generator coupled to it. The used refrigerant vapour is condensed in a condenser. The cooled water for cooling in condenser is obtained from a cooling tower. The binary cycle system is shown in Figure 11.5. Kamchatka binary cycle plant in Russia is a 680 kW capacity plant using hot hydrothermal water at 80°C. The working fluid is Freon-12.

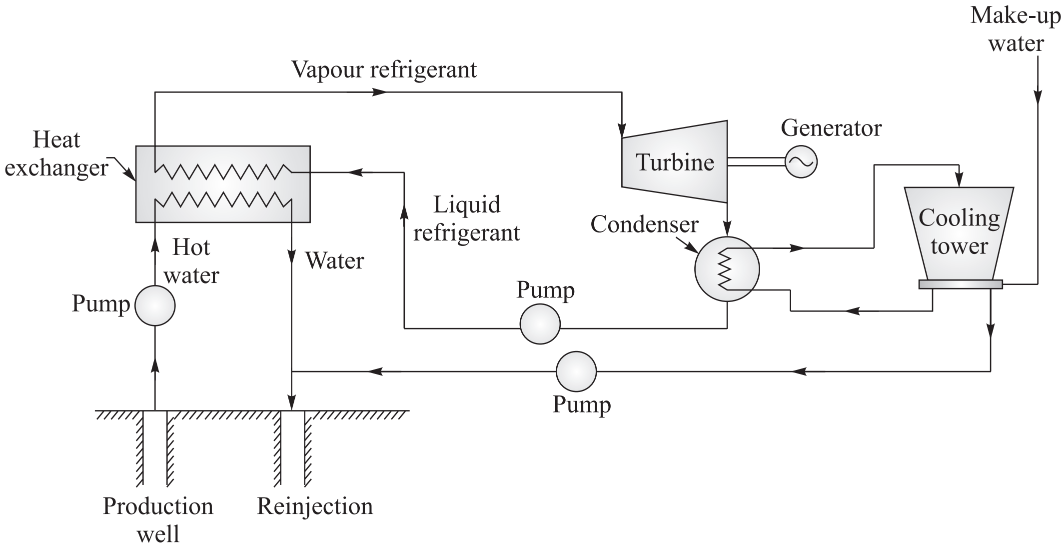


Figure 11.5 Binary fluid hydrothermal system (low temperature).

11.3.2 Hot Dry Rock Resource

- **Describe a hot dry rock geothermal resource power plant.**

Hot dry rocks (HDR) resources or dry geothermal fields are much more common than hydrothermal reservoirs. The working of high dry rock binary fluid system is shown in Figure 11.6. These HDR resources are more accessible compared to hydrothermal resources. The underground hot dry rocks due to geothermal heating have temperatures exceeding 200°C and there is no water in their vicinity. Water as heat transfer fluid has to be injected into a man-made reservoir in the hot dry rocks field. After drilling and fracturing of the field, a man-made reservoir is created.

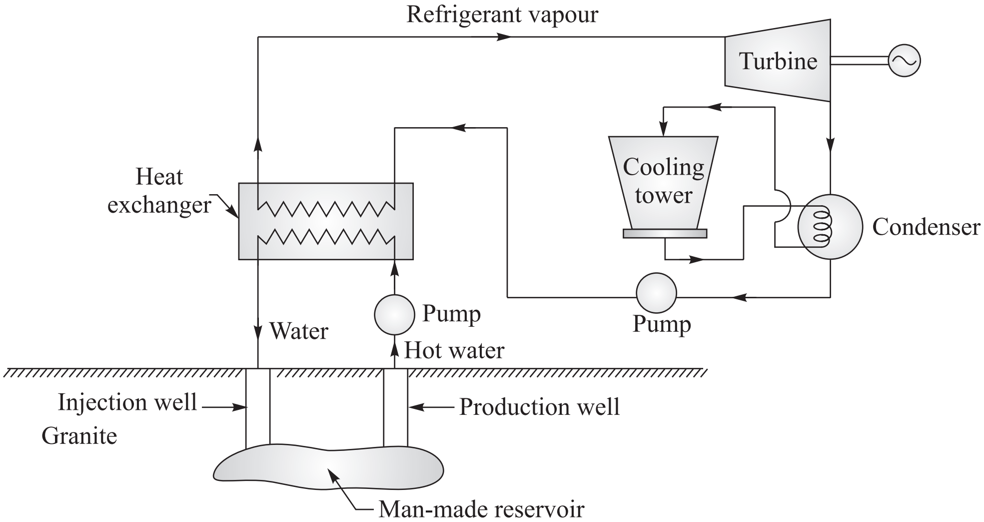


Figure 11.6 High dry rock binary fluid system.

Injection for wells pumping inside and production or extraction wells for hot water pumping out are drilled. A series of injection wells and extraction wells can be drilled to tap a sufficient amount of geothermal energy. The hot water extracted from the man-made reservoir is made to vapourise low boiling point refrigerant which is used to run a turbine coupled with a generator. The refrigerant vapour exiting the turbine is condensed in a condenser which is pumped into the heat exchanger again. The viability of extracting energy from a dry field depends upon the degree to which the resource field can be fractured to develop man-made geothermal reservoir.

11.3.3 Comparison of Geothermal Power Plant with Convention Thermal Power Plant

- **What are the main differences between conventional thermal power plant and geothermal power plant?**

The main differences between the geothermal power plant and the conventional thermal power plant are as follow:

(i) The temperature and pressure in the geothermal power plant are less (about 170°C and 8 atm) compared to those in the conventional thermal plant (temperature about 540°C and pressure about 160 atm). The efficiency of geothermal plant is about 15% while it is about 40% in case of the conventional thermal plant.
(ii) The size of a geothermal power plant depends on the amount of geothermal energy available. The size of a geothermal plant is generally small on account of smaller thermal potential of the site.
(iii) Geothermal power plant needs a larger flow of geothermal fluid due to lesser temperature and pressure compared to conventional power plant.
(iv) Geothermal power plant has to be located where geothermal fields exist. It is technically infeasible to transport geothermal energy over long distance. The transmission cost of power for geothermal power plant is more.
(v) Hydrothermal plant does not need water for cooling purpose unlike conventional power plant.
(vi) Hydrothermal plant causes lesser pollution compared to conventional power plant.
(vii) Hydrothermal plant does not need any supply of fuel.

11.3.4 Non-Electrical Applications of Geothermal Energy

- **What are the non-electrical applications of geothermal energy?**

The non-electrical applications of geothermal energy are as follow:

(i) The low and moderate temperature hydrothermal fluids can be used for cooking and bathing. The eye and skin diseases are curable due to the presence of sulphur in hydrothermal fluids. Hot springs and health spas are very popular due their health benefits.
(ii) The hydrothermal fluids can be used as a heat source for space and water heating.

(iii) The hydrothermal fluids can be used for industrial purpose, such as drying applications in food, chemical and textile industries.
(iv) The hydrothermal fluids can be used in agriculture for crop drying and washing.
(v) The hydrothermal fluids can be used for warming fish ponds in acqua culture.
(vi) Hydrothermal fluids can be used as hot water supply for public institutions and business district heating for group of buildings, especially in cold countries such as New Zealand and Iceland.

11.3.5 Advantages and Disadvantages of Geothermal Energy

- **What are the advantages and disadvantages of geothermal energy over other energy forms?**

or

- **What are the merits and demerits of geothermal energy?**

The main advantages of geothermal energy are as follows:

(i) It is a reliable source of energy.
(ii) It is in continuous supply.
(iii) Its availability is independent of weather.
(iv) It has an inherent storage capability and it does not require any storage device.
(v) Small space is required to install the plant.
(vi) It does not require any supply of fuel to generate heat.
(vii) It is the least polluting.
(viii) It is versatile in use.
(ix) It is cheaper than other energy sources.

The major disadvantages of geothermal energy are as follows:

(i) Geothermal energy is available as low-grade heat, that is, temperature of geothermal fluid is low.
(ii) Geothermal fluids also bring dissolved gases and solute, which lead to air and land pollution.
(iii) Removal of heated water from the hydrothermal reservoir may lead to land subsidence or seismic imbalance.
(iv) Drilling and blasting of wells may cause instability of land structure and may develop risk of any earthquake or seismic imbalance.
(v) Geothermal energy cannot be transported over long distances (less than 30 km).
(vi) The life of plant equipment is limited due to corrosive and abrasive nature of geothermal fluids.

11.3.6 Materials for Geothermal Plant Equipment

- **Describe the characteristics of the materials used for different components of a power plant using geothermal energy.**

The steam and water from hydrothermal reservoirs contain (i) non-condensable gases such as H_2S, NH_3, CH_4, CO_2, H_2 and N_2, (ii) dissolved solids such as silica, (iii) entrained solid particles and (iv) sand.

Hydrothermal fluids are both corrosive and abrasive in nature. Hence, following materials which can withstand corrosive and abrasive nature of hydrothermal fluids are used:

(i) **Carbon steel.** It is used for pipes and separator to carry dry and wet steam.
(ii) **Stainless steel.** It is used for nozzles and diaphragms. However, 12–13% chrome stainless steel is used in the construction of rotor of the turbine.
(iii) **Redwood and Douglas-fir wood.** It is used for construction of cooling tower or as filling material. Plastic such as polyvinyl chloride can also be used.
(iv) **Platinum or gold rhodium.** The plating of platinum or gold rhodium is provided on electrical contacts.
(v) **Tin.** Tin plating is provided to all insulated copper.
(vi) **Austenitic stainless steel.** It is used for making metal components of condensor.
(vii) **Aluminium and stainless steel.** Aluminium and stainless steel have good corrosive resistance properties and used for construction of structures exposed to corrosive environment.

11.3.7 Environmental Problems from Geothermal Energy

- **What are the environment problems caused by Geothermal energy?**

The geothermal fluids have dissolved solids, entrained solid particles, non-condensable gases and sand. These solids and non-condensable gases create following environmental problems:

(i) The emission of H_2S, CO_2 and other toxic gases into the atmosphere during operation of the plant is a source of pollution to the environment. H_2S gas has annoying smell and it also forms sulphuric action when it comes in contact with water. A 200 MW geothermal plant may emit about 520 kg of H_2S gas per day in the atmosphere.
(ii) The effluents from geothermal fluids during conversion are highly mineralised. These effluents can pollute the water streams or underground water source if disposed of without treatment. Certain effluents contain boron, fluorine, mercury and arsenic compounds which are extremely harmful to animal and plant life. Special waste treatment plants are required to handle such pollutants.
(iii) Hydrothermal plant discharges a much larger proportion of heat to atmosphere due to its lower efficiency. Excess heat dissipation in atmosphere has an adverse impact on the environment of the nearly area.
(iv) Large extraction of geothermal fluids may pose a risk of seismic disturbances.
(v) Geopressured water carries large quantities of sand creating environmental problem and its disposal also poses a problem.
(vi) H_2S and NH_3 gases are corrosive and toxic. These gases adversely affect the buildings, plant and animal life of surrounding areas.

11.3.8 Criteria for Selection of Geothermal Site

- **What are the major criteria for selecting a site for power generation from geothermal energy?**

The criteria for selecting a site for geothermal power generation are as follow:

(i) Vapour dominated geothermal site is preferred as it is possible to obtain dry steam at about 200°C and pressure of 8 atm.
(ii) Site should facilitate easy drilling to reach geothermal energy resource with least cost.
(iii) Site should have sufficient geothermal energy to run a plant of adequate power capacity.
(iv) Site should be near the load centre to reduce the cost of transmission.
(v) The dissolved gases and solids in the geothermal fluids should be as little as possible.

11.3.9 Potential of Geothermal Energy in India

- **What is the potential of geothermal resources in India?**

or

- **Write a note on "utilisation of geothermal resources in India."**

As a result of studies and surveys carried out for the assessment of geothermal energy resources in India, about 340 potential hot springs have been identified throughout the country. These hot springs are perennial and can continuously provide hydrothermal fluids. The hydrothermal fluids have temperatures varying from 37 to 90°C. Majority of these resources have low temperatures and these can be utilised for direct thermal application. Few hydrothermal resources are suitable for electric power generation as hydrothermal fluids have sufficient high temperatures. The potential of these resources has been estimated to be about 10,000 MW. The pilot plants have been commissioned at Manikaran (HP), Puga and Chumanthang (J&K). The potential sites as identified are:

- The Himalayas (Puga valleys, Manikaran)
- Sohana
- West coast (Unai)
- Cambay (Tuwa)
- Son–Narmada–Tapi (SONATA)
- Godavari
- Mahanadi

Following hydrothermal plants are being planned:

(i) Binary cycle geothermal plants at Puga valley as hydrothermal fluids have moderate temperatures.
(ii) A 300 kW demonstration power plant by NHPC at Tattapani is being planned.
(iii) Exploratory studies at Satluj Spiti, Beas and Parvati valley (HP), Badrinath-Tapovan (Uttaranchal) and Surajkund (Jharkand) are being carried out.

As most of the hot springs are located in rural areas, these springs can be used to meet the requirement of thermal energy of small-scale industry.

11.3.10 Exploration and Development of Geothermal Resources

- **Describe the various stages of exploration and development of geothermal resources.**

Most of hydrothermal resources manifest themselves as hot springs and geysers. However, their energy potential can be determined by actual drilling. There are certain procedures to determine or forecast their potential. The forecasting of potential can be made on the basis of rate of hot water flow from the hydrothermal reservoir, chemical composition of surface and groundwater, the change of earth's electrical resistivity at the site of hydrothermal reservoir and the change of seismic measurements at the site of hydrothermal reservoir. The various stages of exploration and development are as follows:

(i) Study and forecasting the energy potential of the hydrothermal reservoir.

(ii) Exploratory drilling and production testing. The drilling for hydrothermal exploration is more difficult and costly compared to drilling in petroleum exploration.

(iii) Field development which includes drilling of deep drilled survey wells.

(iv) Pilot or moderately sized plant is installed and operated to gather more information about geothermal field.

(v) The heat content of the geothermal reservoir declines with usage and it provides useful information about both the size of plant and the life of plant which can run on the geothermal reservoir. A geothermal reservoir should provide energy for at least 50 years or more.

(iv) Thermoelectric generator can be operated with the help of heat obtained by the solar collector.

(v) Thermoelectric generator can be operated using heat obtainable from decaying radioisotopes.

9.4 MAGNETOHYDRODYNAMIC POWER CONVERSION

- **Briefly explain magnetohydrodynamic power conversion.**

Magnetohydrodynamic (MHD) is a method in which the kinetic energy of charged particles in a conducting material in the presence of a magnetic field is directly converted into electrical energy. In actual practice, the heat is used to provide energy for the motion of charge carriers in a conducting material which can be obtained by burning of fossil fuels. This heat is converted directly into electrical energy.

9.4.1 Principle of Operation of an MHD Generator

- **Describe the principle of operation of an MHD generator. Derive an expression for maximum power generation per unit volume of the generator.**

To understand the principle of an MHD generator, consider a conducting gas (conductivity of σ measured in mho/m) which is made to move at a speed $\vec{u}$ across a magnetic field ($\vec{B}$). Two electrodes (area A) are held perpendicular to both the speed $\vec{u}$ and the magnetic field $\vec{B}$ with distance d between them as shown in the Figure 9.7. The interaction of conducting gas and magnetic field induces an electric field E at right angles to both speed $\vec{u}$ and magnetic field $\vec{B}$. The magnitude of this electric field is the cross product of $\vec{u}$ and $\vec{B}$, that is, $E = \vec{u} \times \vec{B}$. There are two forces acting on the induced charge q, which are

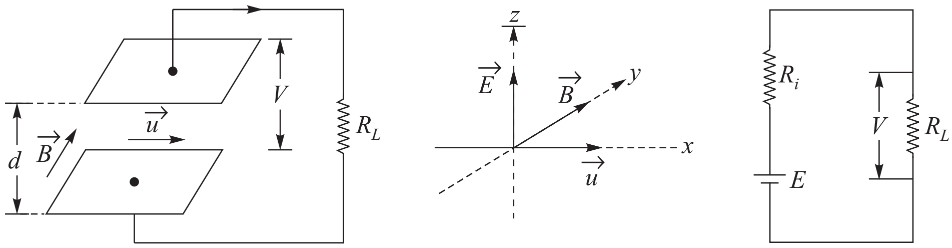


Figure 9.7 Principle of MHD generator. (a) Application of magnetic field $\vec{B}$ on moving gas $\vec{u}$. (b) Induced electric field. (c) Equivalent electric circuit.

(i) Lorentz force acting upward which is formed due to induced current and magnetic field and equal to quB and (ii) force qE due to electric field (E) created by positive charge particles moving to upper plate and negative charge particles moving to lower plate, resulting in the development of a potential difference V across the plates ($E = -V/d$). Hence, the total force acting on the charged particles is given by

$$F = qE + quB$$

$$= -q\frac{V}{d} + quB \tag{9.1}$$

In the open circuit condition when no current flows, charge carriers are not moving between the plates; that is, the force F acting on charged particles is zero. In this condition, the voltage V between the plates is V_0. Putting these values in Eq. (9.1), we get

$$F = -q\left(\frac{V_0}{d}\right) + quB = 0$$

or $$V_0 = Bud$$

The value of V_0 can be increased by increasing magnetic field, gas speed and distance between the plates. The current starts flowing across the plates when external load is applied to the plates. The maximum power output which takes place when load resistance (R_L) is equal to internal resistance (R_i) of the MHD generator. Power output is given by

$$P_{max} = V \times i = i^2 \times R_i = i^2 R_L$$

But $$V_0 = i \times R_i + i \times R_L$$

or $$i = \frac{V_0}{R_i + R_L}$$

∴ $$P_{max} = i^2 R_i$$

$$= \left(\frac{V_0}{R_i \times R_L}\right)^2 \times R_L$$

$$= \frac{V_0^2}{4R_i}$$

But $$V_0 = Bud$$

∴ $$P_{max} = \frac{B^2u^2d^2}{4R_i} \tag{9.2}$$

The R_i of MHD generator is the resistance of conducting gas which depends upon conductivity σ, area A and distance d.

$$R_i = \frac{1}{\sigma} \times \frac{d}{A}$$

Putting this value in Eq. (9.2), we get

$$P_{\max} = \frac{1}{4}\sigma u^2 B^2 (Ad)$$

But volume of gas = Ad

Hence, the maximum power output per unit volume is given by $P_{\max}$ per unit volume $= \frac{1}{4}\sigma u^2 B^2$.

9.4.2 MHD Generator

- **Explain the operation of an MHD generating system.**

or

- **What are the major advantages and limitations of the MHD generating system?**

An MHD generator is shown in Figure 9.8. It consists of a divergent channel, a conducting gas flowing in it, magnetic field applied at right angles to the channel length and two electrodes provided at right angles to the magnetic field. The conducting gas is ionised by making it flow through a nozzle at the high temperature and speed. The ionised gas expands as it moves through the length of the channel, resulting in its exit at lower temperature and pressure. The interaction of flow of ionised gas and magnetic field produces electric power output across the electrodes. Hence, MHD generating system acts as a heat engine which receives heat at a high temperature and it converts a part of this heat into useful electrical energy, while rejecting remaining heat at a lower temperature. The efficiency of MHD generating system is about 20–25%. The gas exiting from MHD generating system can be used to produce steam when it is associated with a conventional steam plant. The efficiency of 50–60% can be achieved by using a combination of MHD generating system and a conventional thermal power station.

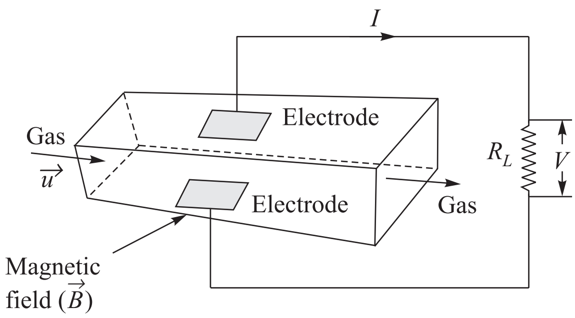


Figure 9.8 An MHD generator.

Advantages

The advantages of MHD generating system are as follow:

(i) Higher efficiency of 50–60% can be achieved by using a hybrid plant consisting of an MHD generating system and a thermal power plant.
(ii) It has no moving parts.
(iii) It can be started up quickly.

(iv) Its output can be easily controlled by adjusting strength of magnetic field and speed of ionized gas.
(v) It is a source of pollution-free power.

Limitations

The limitations of an MHD generating system are as follow:

(i) It requires a very high temperature for ionization of gas.
(ii) It needs special materials to be used in its equipment which can withstand high temperatures and thermal stresses.
(iii) Its equipment has limited life due to high temperatures and thermal stresses.
(iv) Its output power is direct current. Suitable inverters are required to convert DC into AC output.
(v) It requires power to maintain the magnetic field.
(vi) It requires cooling of electrodes.

9.4.3 Seeding of Carrier Gas in MHD Generator

- **Why is ionizing of carrier gas necessary? How can ionizing of carrier gas be achieved?**

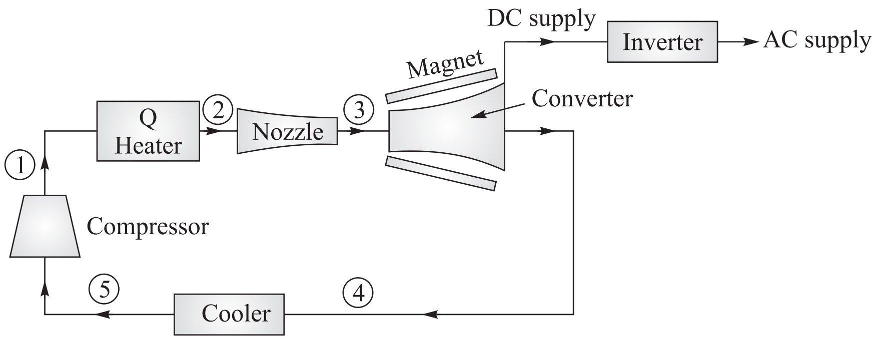
In the MHD generator, the solid conductor is replaced by a gaseous conductor; that is, ionized gas is employed as the conducting fluid. Ionization is produced by

(i) Thermal means by heating the gas to an elevated temperature
(ii) Seeding the carrier gas with substances such as cesium or potassium vapours which get ionized at relatively low temperatures
(iii) Incorporating a liquid metal into the flowing carrier gas.

9.4.4 Overall Power Cycle with MHD Converter

- **Explain an overall power cycle with an MHD converter.**

An overall power cycle with an MHD converter is shown in Figure 9.9.



1. High pressure gas; 2. High pressure and temperature gas; 3. Ionized gas at high temperature and speed; 4. Gas at low temperature speed and ionization; 5. Low volume of gas for compression

Figure 9.9 Overall power cycle with MHD convertor closed system.

In this power cycle, an MHD convertor is used in place of a gas turbine. A compressor is used to elevate pressure. Heat is added at high pressure. The flow is accelerated before it enters the MHD converter.

- **What are the factors which reduce the efficiency of the MHD converter?**

The factors which can reduce the efficiency of the MHD converter are as follows:

(i) Dissipation of energy at internal resistance of the ionized gas
(ii) A space charge barrier developed at the surface of the electrodes
(iii) Heat dissipated from the electrodes and converter's walls
(iv) Energy lost due to fluid friction
(v) Hall effect losses resulting from current induction in the direction of the flow. These losses increase when the seeded combustion gases are used as working fluid. The hall effect develops a voltage gradient in a direction perpendicular to the applied magnetic field and current flow.

- **How is the energy for motion of the conducting gas derived? Is MHD converter or heat engine more suited to fossil fuels?**

The energy of motion of conducting gas is derived from heat obtained by burning fossil fuels. Hence, MHD generator is a device for converting heat energy directly into electrical energy without a conventional heat engine turbine and electric generator. MHD conversion can take better advantage of the high–temperature heat generated by the combustion of fossil fuels than heat engine. As a result, high thermal efficiency is possible from MHD conversion. The MHD generator is used in topping cycle with a steam turbine in the bottoming cycle and this combined cycle can give the efficiency of 50–60%.

9.4.5 MHD Systems

- **How MHD systems are classified? Describe them in brief.**

MHD conversion systems can operate in open or closed cycles. In open cycle system, the working fluid is used only once and the working fluid after generating electrical energy is discharged to the atmosphere. In the closed cycle system, the working fluid is continuously recirculated instead of wasting out to the atmosphere. The working fluid after generating electrical energy is reheated and returned to the converter for reuse.

In the open cycle system, air is generally used as working fluid. In the closed cycle system, helium or argon gas is used as the working fluid.

In the open cycle system, the hot combustion gases after seeding can be used directly as the working fluid. However, in the closed system, heat is transferred from the combustion gases to the working fluid by means of a heat exchanger.

9.4.6 Open Cycle Systems

- **Describe an MHD open cycle system.**

The arrangement in the open cycle system is shown in Figure 9.10. In this system, oil or gasified coal is used as fuel. The fuel is burnt in a combustor and hot gases (2500 K) from combustor are then seeded (cesium or potassium), which helps in the ionization of gases and their better conductivity. The gases are passed through the nozzle where they are accelerated. The MHD generator is a divergent duct with external cooling and applied perpendicular magnetic field to the motion of gases. A number of electrode pairs are inserted in the duct to conduct the direct electric current generated in the convertor to an external load. The direct current power is converted into AC power by means of an inverter.

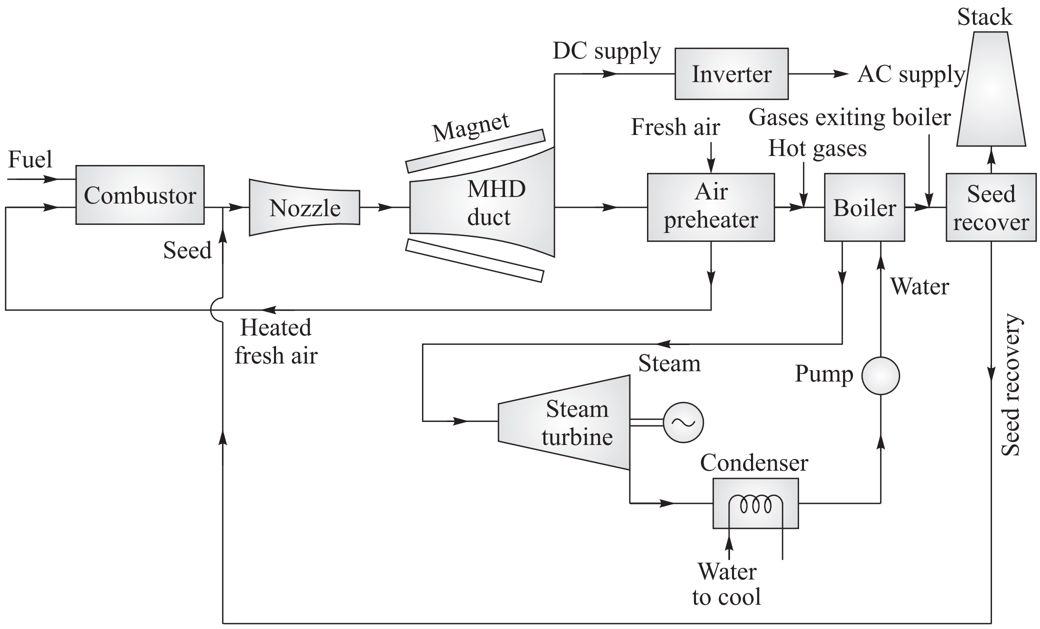


Figure 9.10 An open cycle MHD generator.

As the working fluid travels along the duct, its energy is used and converted into electricity. The temperature of gases continuously falls and the ionization of gases also reduces. When the degree of ionization becomes insufficient, the gases have to be discharged off from the convertor. At this stage, the temperature of gases is about 1900 K and 25–35% of heat energy of the gases has been converted into electrical energy in the convertor. The gases are now used in (i) preheator to heat fresh air for combustion and (ii) waste heat boiler to generate steam. The steam generated is used in a steam turbine with a directly coupled generator which converts 25–30% of total heat into the electrical power. The gases exiting the boiler are passed through a seed material removal device before discharging to the atmosphere using a stack. The bottoming cycle consists of boiler, steam turbine, condenser and pump.

9.4.7 Closed Cycle System

- **Describe an MHD closed cycle system.**

In a closed cycle system, argon or helium gas is used as the carrier gas. The Brayton cycle is used for the heat conversion. The gas is compressed and heat is supplied using a heat exchanger marked as (1). The fuel is burnt in a combustor. Gasified coal is used as the fuel and hot combustion gases supply heat to the carrier gas through the heat exchanger marked as (2). The combustion gases exiting the combustor after transferring heat to the carrier gas are passed through an air preheater to heat the supply air before entering the combustor. The combustion gases after exiting from preheater are discharged to atmosphere using a stack. As the combustion gases and carrier gas are operating separately, there is no problem of extracting the seeding material in this system compared to the open system.

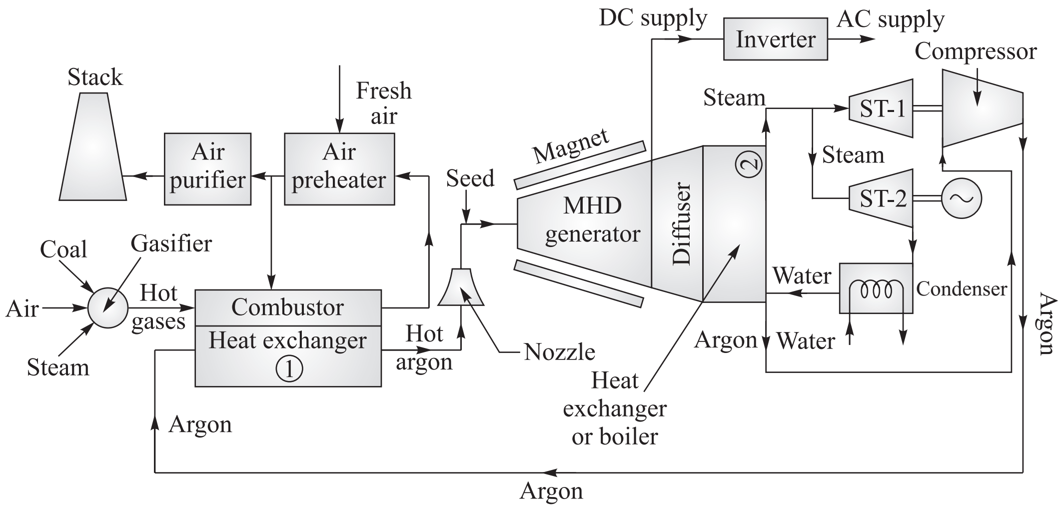


Figure 9.11 A closed MHD system.

The hot argon gas is seeded with cesium and hot carrier gas is passed through the MHD convertor at high speed with the help of a nozzle. The DC power generated by MHD convertor is converted into AC power with the help of an inverter.

The hot carrier gas exiting from the MHD convertor is slowed down using a diffuser. The hot carrier gas is passed to a waste heat boiler or heat exchanger (2) to generate steam. This steam is used for running the compressor to compress the carrier gas with the help of the turbine (1) and for driving the turbine (2) coupled with generator to generate electricity. The carrier gas is returned back to the primary heat exchanger (1) after passing through the compressor.

A closed cycle system can provide more useful power conversion at the lower temperature of about 1900 K compared to 2500 K for open cycle system. The lower operating temperature in closed system allows a wider choice of materials to be used with the system.

- **What is a liquid metal-inert gas carrier system?**

In this system, instead of seeding, a liquid metal such as sodium, potassium or lithium is incorporated into the inert carrier gas for providing conductivity in the gas. These metals are excellent electrical conductors in liquid state but their vapours are poor conductor. The working of the system is similar to the closed MHD system as shown in Figure 9.11.

9.4.8 Materials for MHD Generators

- **What are the requirements of materials used in an MHD generator?**

The requirements of materials are as follows:

(a) **Electrodes**

(i) Should have high conductivity
(ii) Structurally stable at high temperature
(iii) Carbides, silicides and borides are used

(b) **Duct liner**

(i) Should be electrical insulator
(ii) Must be thermal insulator
(iii) Al_2O_3MgO and $MgAl_2O_3$ are used

(c) **Magnet**

(i) Stronger than permanent magnet or ferromagnet
(ii) Materials to have high melting point
(iii) Water–cooled electromagnets
(iv) Cryogenically cooled electromagnet
(v) Superconducting magnets.

9.5 THERMIONIC POWER CONVERSION

- **What do you understand by thermionic emission effect? Also, describe the working and construction details of a basic thermionic generator.**

A thermionic generator consists of two metals (called electrodes) which have different values of work function (work function is the energy needed to overcome the force of attraction acting on an electron in order to make it free). These metallic electrodes are sealed into an evacuated glass vessel. The electrode with the larger value of work function is maintained at a higher temperature compared to the electrode having the lower value of work of function. The hot electrode can now emit electrons due to supplied heat energy, and therefore this electrode is called emitter. The colder electrode can collect electrons, and therefore it is called collector. The emitter becomes positive on emitting electrons while the collector becomes negative due to collection of electrons. Owing to collection of charges, a voltage is developed between the electrodes and a direct current starts flowing in any external circuit connecting the electrodes. The developed voltage depends on the difference of work functions of the metal electrodes. The heat energy at the emitter must be sufficient to free electrons from the emitter surface, that is, more than the work function of the emitter electrode. When these electrons strike the collector, their kinetic energy must be higher than the work function of the collector so that electrons can be absorbed in the collector. The heat of absorption must be released from the low-temperature collector. The absorbed electrons cause higher energy level at collector than that at emitter, and so a potential difference is developed between

CHAPTER 7

Electrochemical Effects and Fuel Cells

7.1 INTRODUCTION

Fuel cells operate on the principle of electrochemistry. Fuel cells have been extensively used for aerospace applications. The fuel cell uses fuel and oxidant. It directly converts fuel and oxidant into electrical energy without any combustion. A fuel cell is similar to a Primary battery in which fuel and oxidant are stored externally. The electrical power is obtained from it by passing fuel and oxidant whenever needed. As the conversion of chemical energy of fuel is obtained directly without an intermediate thermal stage or combustion, the efficiency of conversion by a fuel cell is high and it is not limited by Carnot cycle efficiency of heat engine. The efficiency of fuel cell is generally about 60% with the voltage output of about 0.7 V. Hence, several fuel cells are to be connected in series to obtain the desired voltage. On the basis of both the type of electrolyte and type of the fuel and oxidant, there are various types of fuel cells used for different applications.

7.2 FUEL AND OXIDANT

- **What do you understand by oxidation and reduction?**

Oxidation and reduction are two electrochemical reactions. Oxidation is a reaction in which electrons are liberated from a fuel and reduction is a reaction in which electrons are consumed. The oxidation reactions are as follow:

$$X \longrightarrow X^{n+} + n \times e$$

$$H_2 \longrightarrow 2H^+ + 2 \times e$$

The reduction reactions are as follows:

$$Y + n \times e \longrightarrow Y^{ne}$$

$$O_2 + 4 \times e \longrightarrow 2O^{2-}$$

- **Explain the combustion reaction process.**

The combustion is a process of burning a fuel in oxygen. The combustion reaction involves the transfer of electrons from a fuel (thereby getting oxidised) to the oxidant (thereby getting reduced). In the heat engine, fuel and oxidant are intimately mixed so that electrons directly pass from fuel to the oxidant, thereby producing combustion and heat as given below:

$$H_2 \text{ (fuel)} \longrightarrow 2H^+ + 2e^-$$

$$O_2 \text{ (oxidant)} + 4e^- \longrightarrow 2O^{2-}$$

$$4H^+ + 2O^{2-} \longrightarrow 2H_2O + \text{Heat}$$

- **Explain the electrochemical conversion of fuel and oxidant in a fuel cell.**

The fuel cell represents one of the most successful ways of bypassing the heat cycle. It converts the chemical energy of fuel directly into electricity with the help of an oxidant.

The fuel cell consists of two electrodes connected externally by a metallic circuit through which the valence electrons can move from the fuel electrode (anode) to the oxidant electrode (cathode). In the cell, the ions of electrolyte move from cathode to anode electrode, thereby completing the circuit for current to flow. The chemical equation to describe the reaction is as follows:

$$\text{Fuel} + \text{Oxidant} = \text{Products}$$

The reaction at anode electrode is as follows:

Anode: $\text{Fuel} \longrightarrow \text{ions} + \text{electrons}$

Cathode: $\text{Oxidant} + \text{electrons} \longrightarrow \text{ions}$

The electromotive force (e.m.f.) which helps to drive electrons liberated at anode electrode through the external circuit load is proportional to the Gibbs free energy change taking place in electrochemical reactions.

- **What are the different combinations of the fuel and oxidant used in fuel cells?**

or

- **List the fuels used in fuel cells.**

The various combinations of the fuel and oxidant are shown in Table 7.1.

TABLE 7.1 Fuel and oxidant

S.No.	*Fuel*	*Oxidant*
1.	Hydrogen	Oxygen
2.	Hydrogen–rich gas	Air
3.	Ammonia	Air
4.	Hydrocarbon (liquid)	Air
5.	Synthesis gas	Air
6.	Hydrocarbon (gas)	Air

- **What are the differences in combustion and electrochemical reaction in a fuel cell?**

The differences in combustion and electrochemical reaction in fuel cell are as given in Table 7.2.

TABLE 7.2 Differences in combustion and electrochemical reaction in a fuel cell

Combustion	*Electrochemical reaction in a fuel cell*
Mixing of fuel and oxidant takes place	No mixing of fuel and oxidant is allowed
Oxidation and reduction reaction taking place simultaneously	Oxidation and reduction reaction taking place independently at anode and cathode electrodes
Heat is generated	Electricity is directly generated
No electrolyte is required	Electrolyte is required so that ions can flow from cathode to anode internally to complete the circuit for current to flow
Output is heat which is low grade energy. A turbine and a generator are required to obtain high-grade mechanical or electric energy	Output is electrical energy, which is a high-grade energy
Efficiency is limited to Carnot cycle efficiency, which is less	Efficiency is high
Combustion creates pollution	It is pollution-free conversion reaction
Cannot be controlled	Can be controlled by regulating fuel and oxidant supply

- **What are the differences between fuel cell and primary battery?**

The differences between fuel cell and primary battery are shown in Table 7.3.

TABLE 7.3 Differences between fuel cell and primary battery

Fuel cell	*Primary battery*
Oxidant and fuel are stored externally to the cell, that is, reactants are fed externally	No such oxidant and fuel are provided separately, that is, reactants are stored in cell
It has two electrodes and electrolyte	It has also two electrodes and electrolyte
Electrodes are catalytic and relatively stable	Electrodes take part in electrochemical reaction and these electrodes are consumed
It cannot store electrical energy. The electric supply is available when fuel and oxidant are supplied It cannot be charged and discharged	It can store electrical energy. It can be charged and discharged
Reactants (fuel and oxidant) have to diffuse through the electrodes. Electrodes are porous	No diffusion of reactants is required Electrodes are solid
No replacement of electrodes is required	Electrodes are to be replaced periodically

7.2.1 Primary and Secondary Fuel Cells

- **What are primary and secondary fuel cells?**

A primary fuel cell is a fuel cell in which the reactants (fuel and oxidant) are passed through the cell only once and the products of reactants are discarded. Hydrogen–oxygen fuel cell is a primary fuel cell.

A secondary fuel cell is a cell in which the reactants (fuel and oxidant) are passed through the cell many times. The products of the reactants are regenerated by thermal, electrical or photochemical methods. These fuel cells are also called regenerative or reversible fuel cells.

7.3 FUEL CELL

7.3.1 Principle of Fuel Cell

- **Explain the fuel cell technology in detail.**

or

- **Explain the working principle of fuel cell with the help of a neat sketch.**

or

- **Discuss the working of a hydrogen–oxygen fuel cell.**

or

- **What do you understand by fuel cell? Describe a hydrogen–oxygen fuel cell with a sketch showing reaction.**

or

- **Explain the basic principle of fuel cell with reference to hydrogen–oxygen fuel cell.**

Principle of fuel cell

A fuel cell converts chemical energy of a fuel directly into electrical energy. Fuel gas diffuses through the anode and it gets oxidized. On oxidation, the fuel gas releases electrons to the external circuit. The oxidant gas diffuses through cathode and it is reduced by the electrons coming from external circuit to cathode. The fuel cell keeps the fuel and oxidant separate without mixing, but it allows the transfer of electrons from the fuel to the oxidant by an external electric circuit containing a load. The electromotive force which helps to drive electrons (liberated from fuel at anode electrode) through the external circuit load is proportional to the Gibbs free energy charge taking place during the electrochemical reactrons of fuel and oxidant.

The fuel cell consists of two electrochemically conducting electrodes separated by an electrolyte. The arrangement of fuel cell components is shown in Figure 7.1. The electrodes are made of porous nickel material to collect charges and concentrated phosphoric acid is filled between the electrodes, which acts as the electrolyte. The pores enable better contact between gas, electrolyte and electrode for faster electrochemical reaction. The fuel (hydrogen) is fed into the anode side of the cell. The fuel (hydrogen) is oxidised and liberated electrons move to the external circuit. The remaining positive hydrogen ions move from the anode into the electrolyte through porous cell walls. The oxidant (oxygen) is fed into the cathode side, where it is reduced by the electrons coming from anode through external circuit. The remaining negative oxygen ions enter the electrolyte from the porous wall of cathode. The negative oxygen ions and positive hydrogen ions combine to form water. The electrochemical reactions are as follow:

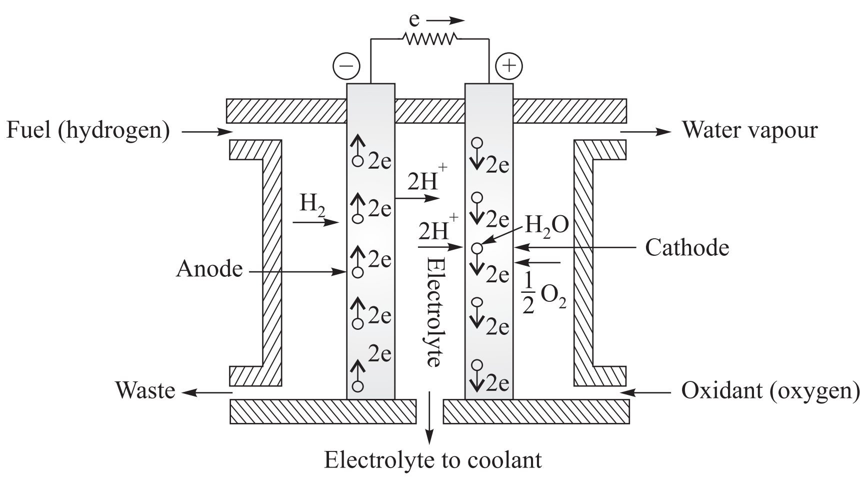


Figure 7.1 A hydrogen–oxygen or phosphoric acid and fuel cell.

(i) Anode

$$2H_2 \longrightarrow 4H^+ + 4e$$

(ii) Cathode

$$O_2 + 4e \longrightarrow 2O^{2-}$$

(iii) Electrolyte

$$4H^+ + 2O^{2-} \longrightarrow 2H_2O$$

7.3.2 Efficiency of Fuel Cell

- **Derive an expression for the efficiency of a fuel cell.**

or

- **Show that a hydrogen–oxygen fuel has mere efficiency of 83%.**

or

- **Why heat has to be removed from a fuel cell?**

Electrochemical reactions take place in a fuel cell in which reactants (fuel and oxidant) are converted into work (electric output) by a steady flow process. The energy equation in steady flow condition by first law of thermodynamics is as follow:

$$\Delta Q = \Delta W + \Delta(\text{KE}) + \Delta(\text{PE}) + \Delta H$$

where ΔQ is the heat transfer
ΔW is the work done
ΔKE is the change in kinetic energy
ΔPE is the change in potential energy and
ΔH is the change in enthalpy.

If $\Delta\text{KE} = \Delta\text{PE} = 0$, then steady flow equation is as follow:

$$\Delta Q = \Delta W + \Delta H$$

For maximum work output, the process has to be reversible. For reversible process,

$$\Delta Q = T \times \Delta S$$

Hence, $$\Delta W = \Delta W_{max} \text{ when } \Delta Q = T \times \Delta S$$

$$\therefore \quad \Delta W_{max} = -(\Delta H - T \times \Delta S) \tag{7.1}$$

But Gibbs free energy is given by the following equation:

$$G = H - TS$$

On differentiation, we get

$$\Delta G = \Delta H - (T \cdot \Delta S - S \cdot \Delta T)$$

As temperature remains unchanged in the fuel cell, $\Delta T = 0$

$$\therefore \quad \Delta G = \Delta H - T \cdot \Delta S \tag{7.2}$$

From Eqs. (7.1) and (7.2), we have

$$\Delta W_{max} = -\Delta G$$

The efficiency of fuel cell in steady flow condition is given by

$$\eta = \frac{\text{Work output}}{\text{Change of enthalpy}}$$

$$= \frac{\Delta W_{max}}{-\Delta H}$$

$$= \frac{\Delta G}{-\Delta H} \tag{7.3}$$

The Gibbs free energy is related to electromotive force (E) that drives the electrons through external circuit, which is given by the following equation:

$$E = \frac{-\Delta G}{n \cdot F}$$

where F is Faraday's constant (96,500 coulomb/gm mole) and n is the number of electrons transferred per molecule of the reactant.

Putting the value of ΔG in Eq. (7.3), we have

$$\eta = \frac{nFE}{\Delta H}$$

In case of hydrogen–oxygen fuel cell we have

$$\Delta G = -2{,}37{,}191 \text{ kJ/(kg mole)}$$

and $$\Delta H = -2{,}85{,}838 \text{ kJ/kg.}$$

Putting these values in the efficiency relation, we obtain

$$\eta = \frac{\Delta G}{\Delta H} = \frac{2{,}37{,}191}{2{,}85{,}838} = 83\%$$

As fuel cell has the maximum efficiency of 83%, 17% enthalpy of reactants is wasted as heat energy, resulting in the temperature rise of the fuel cell. The maximum output of work is possible in isothermal condition of the reactants, and hence heat has to be removed to maintain the efficiency of conversion of enthalpy of the reactants into electrical energy by the cell. The heat can be removed either by passing excessive air at positive electrode or by circulating the heated electrolyte through any cooling heat exchanger.

- **Find electromotive force generated in a hydrogen–oxygen fuel cell. Assume change of Gibbs free energy for the chemical reaction at 25°C as 237.3 × 10^3 J/(gm mole) of hydrogen.**

The reaction in the fuel cell is as follows:

$$H_2 + \frac{1}{2} O_2 = H_2O$$

Hence, $$n = 2 \text{ and } \Delta G = 237.3 \times 10^3 \text{ J/(gm mole)}$$

Now electromotive force of fuel cell is

$$\Rightarrow \qquad E = \frac{\Delta G}{nF}$$

where F is Faraday's constant (96,500 coulomb/gm mole)

$$\therefore \qquad E = \frac{237.3 \times 10^3}{2 \times 96{,}500} = 1.23 \text{ V}$$

- **For a hydrogen–oxygen fuel cell, find the following:**
  - **(i) Cell efficiency**
  - **(ii) Electrical work output per mole of hydrogen consumed and per mole of water produced**
  - **(iii) Heat transfer to the surroundings**

  The cell operates at 25°C. Assume

  $$\Delta H_{25°C} = -286 \times 10^3 \text{ kJ/(gm mole)}$$

  and $$\Delta G_{25°C} = -237.3 \times 10^3 \text{ kJ/(kg mole).}$$

The reaction is as follows:

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

Hence $n = 2$, and the efficiency is given by

$$\eta = \frac{\Delta G}{\Delta H} = \frac{237.3 \times 10^3}{286 \times 10^3}$$

$$= 83\%$$

Electrical work output per mole is given by

$$\Delta W = nFE$$

But $$E = \frac{\Delta G}{nF}$$

or $$\Delta W = \Delta G$$

$$= 237.4 \times 10^3 \text{ kJ/(kg mole) of } H_2$$

As 1 mole of H_2O is generated for each mole of H_2.

$$\Delta W \text{ per mole of water} = \Delta W \text{ per mole of } H_2$$

$$= 237.4 \times 10^3 \text{ kJ/(kg mol) } H_2O$$

Heat transfer to surrounding is given by

$$\begin{aligned}\Delta Q &= \Delta H - \Delta W \\ &= \Delta H - \Delta G \\ &= -286 \times 10^3 + 237.3 \times 10^3 \\ &= -48.7 \times 10^3 \text{ kJ/(kg mole)}\end{aligned}$$

7.3.3 Types of Fuel Cells

- **List five types of fuel cells.**

or

- **Explain various types of fuel cells.**

or

- **What are the different types of fuel cells?**

or

- **How are fuel cells classified?**

or

- **Discuss various types of fuel cells.**

The fuel cells can be classified based on their electrolyte, fuel and oxidant, application, nature of electrolyte, operating temperature, physical state of fuel and physical state of electrolyte. According to the type of electrolyte, the fuel cells can be phosphoric acid fuel cell (PAFC), alkaline fuel cell (AFC), polymer electrolyte membrane fuel cell (PEMFC), molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC).

According to the types of fuel and oxidant used in the fuel cell, the fuel cells can be hydrogen–oxygen fuel cell, hydrogen-air fuel cell, ammonia-air fuel cell, synthetic gas-air fuel cell, hydrocarbon (gas)-air fuel cell and hydrocarbon (liquid)-air fuel cell.

According to the types of application, fuel cells can be space application fuel cell, vehicle propulsion fuel cell, submarine propulsion fuel cell, commercial fuel cells and fuel cell for defence applications.

On the basis of the nature of electrolyte, fuel cell can be acidic, alkaline and neutral.

On the basis of the operating temperature, fuel cells can be low temperature (below 150°C), medium temperature (150–200°C), high temperature (250–800°C) and very high temperature (800–1100°C) fuel cell.

As per the physical state of fuel, the fuel cell can be gaseous, liquid and solid fuel cell.

As per the physical state of electrolyte, fuel cells can be solid matter, aqueous and non-aqueous electrolyte fuel cell.

Phosphoric acid or hydrogen–oxygen fuel cell

It includes the following (Figure 7.2):

(i) **Fuel:** hydrogen

(ii) **Oxidant:** oxygen

(iii) **Electrolyte:** phosphoric acid
(iv) **Electrodes:** porous nickel
(v) **Reactions**

$$H_2 \longrightarrow 2H^+ + 2e^- \quad \text{(anode)}$$

$$2H^+ + \frac{1}{2}O_2 + 2e^- \longrightarrow H_2O \quad \text{(cathode)}$$

(vi) **Output:** 1.23 V at 25%
(vii) **Efficiency:** 83%

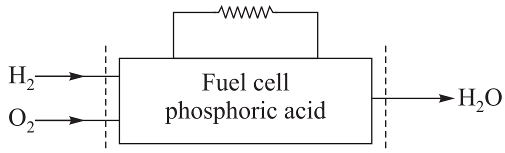


Figure 7.2 A hydrogen–oxygen or phosphoric acid fuel cell.

Alkaline fuel cell

It includes the following (Figure 7.3):

(i) **Fuel:** hydrogen or hydrogen-rich gas
(ii) **Oxidant:** oxygen or air
(iii) **Electrodes:** porous nickel
(iv) **Electrolyte:** KOH (40%)
(v) **Reactions**

$$\frac{1}{2}O_2 + H_2O + 2e \longrightarrow 2OH^- \quad \text{(cathode)}$$

$$H_2 + 2OH^- \longrightarrow 2H_2O + 2e \quad \text{(anode)}$$

(vi) **Output:** 1.23 V at 90°C

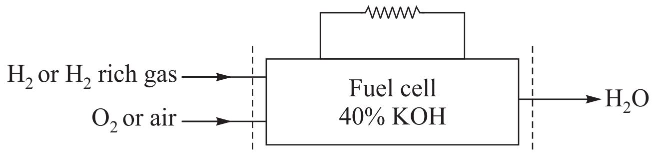


Figure 7.3 Alkaline fuel cell.

Polymer electrolyte or proton exchange membrane fuel cell

It is also called solid polymer fuel cell (SPFC). It includes the following (Figure 7.4):

(i) **Fuel:** hydrogen
(ii) **Oxidant:** oxygen

(iii) **Electrodes:** deposited platinum layers
(iv) **Electrolyte:** proton conducting polymer membrane
(v) **Reaction**

$$H_2 \longrightarrow 2H^+ + 2e^- \quad \text{(anode)}$$

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \longrightarrow H_2O \quad \text{(cathode)}$$

(vi) **Output:** 1.23 V at 25°C.

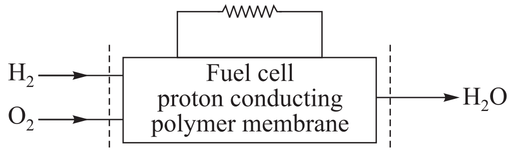


Figure 7.4 Polymer electrolyte membrance fuel cell or proton exchange membrane fuel cell.

Molten carbonate fuel cell

The cell includes the following (Figure 7.5):

(i) **Fuel:** synthetic gas (H_2 + CO)
(ii) **Oxidant:** air
(iii) **Electrodes:** nickel (anode) and silver (cathode)
(iv) **Electrolyte:** molten carbonate (sodium bicarbonate)
(v) **Reaction:**

$$H_2 + CO_3^{2-} \longrightarrow H_2O + CO_2 + 2e^- \quad \text{(anode)}$$

$$CO + CO_3^{2-} \longrightarrow 2CO_2 + 2e^- \quad \text{(anode)}$$

$$O_2 + 2CO_2 + 4e^- \longrightarrow 2CO_2 \quad \text{(cathode)}$$

(vi) **Output:** 1 V at 700°C

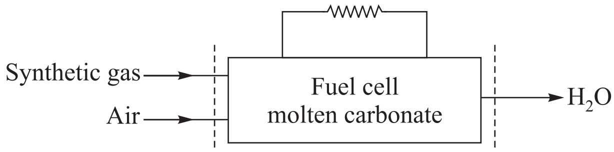


Figure 7.5 Molten carbonate fuel cell.

Solid oxide fuel cell

It includes the following (Figure 7.6):

(i) **Fuel:** synthetic gas (H_2 + CO)
(ii) **Oxidant:** air

(iii) **Electrodes:** porous platinum ceramic
(iv) **Electrolyte:** ceramic (zirconium oxide) conducting oxygen ions
(v) **Reaction:**

$$H_2 + O^{2-} \longrightarrow H_2O + 2e^- \quad \text{(anode)}$$

$$CO + O^{2-} \longrightarrow CO_2 + 2e^- \quad \text{(anode)}$$

$$O_2 + 4e \longrightarrow 2O^{2-} \quad \text{(cathode)}$$

(vi) **Output:** 1 V at 800–1000°C

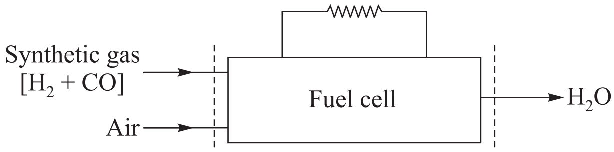


Figure 7.6 Solid oxide fuel cell.

Regenerative cell

In a regenerative fuel cell, the reactants are regenerated from the products and the regenerated reactants are recycled into fuel cell. The regenerative fuel cell has the efficiency of 5–20%.

7.3.4 Polymer Electrolyte Membrane Fuel Cell

- **Write the desired properties of an ideal ion exchange membrane electrolyte.**

or

- **Explain the working of a polymer electrolyte or photon exchange membrane fuel cell.**

The fuel cell uses a membrane of organic materials such as polystyrene sulphonic acid as electrolyte. The membrane has property to allow H^+ ions to pass through it. The desired properties of membrane are as follow:

(i) High ionic (H^+) conductivity
(ii) Non-permeable to reactant gases such as oxygen and hydrogen
(iii) High resistance to dehydration
(iv) Lesser tendency to electroosmosis
(v) High amount of mechanical stability

The fuel cell consists of a thin layer of electrolyte membrane which has platinum deposited on its each surface to act as electrodes (anode and cathode). H_2 enters and interact with anode. The gas is converted into H^+ ions and electrons are liberated: The reaction is given by

$$H_2 \longrightarrow 2H^+ + 2e^-$$

Hydrogen ions formed at anode are transported to cathode through photon exchange membrane and electrons are forced through the outer circuit to cathode. At cathode, ions, electrons and oxygen gas interact to produce water (Figure 7.7). The reaction is

$$2H^- + 2e^- + \frac{1}{2}O_2 \longrightarrow H_2O$$

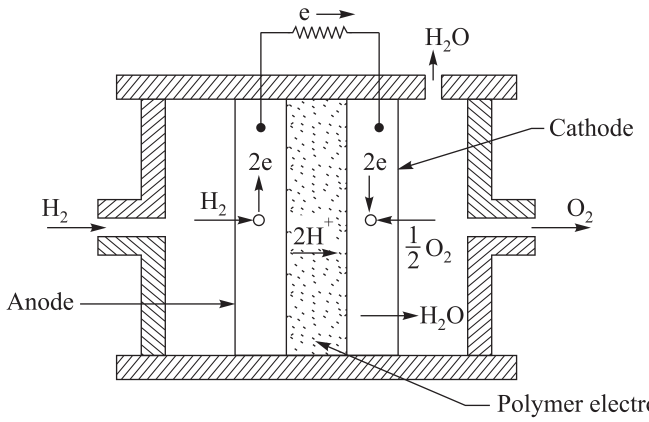


Figure 7.7 Polymer electrolyte or photon exchange membrane fuel cell.

The cell produces emf of 1.23 V at 25°C. It can operate at the temperature range of 40–60°C.

7.3.5 Alkaline Fuel Cell

- **Explain the principle of operation of an alkaline fuel cell.**

or

- **Why the fuel of alkaline fuel cell has to be free from carbon dioxide?**

The principle of working of alkaline fuel cell is the same as that of a phosphoric acid or hydrogen–oxygen fuel cell. It uses H_2 or H_2 rich gas as the fuel and oxygen or air as the oxidant. 40% aqueous KOH solution is used as the electrolyte. The hydrogen gas at anode is oxidised, resulting in the liberation of electrons. Electrons are forced through external circuit to cathode. At cathode, oxygen gas, water and electrons combine to produce OH^- ions. The reaction is given as follows:

$$\frac{1}{2}O_2 + H_2O + 2e^- \longrightarrow 2OH^-$$

These OH^- ions move from cathode to anode through the electrolyte, where these combine with hydrogen gas to produce water. The reaction is as follows:

$$H_2 + 2OH^- \longrightarrow 2H_2O + 2e^-$$

The alkaline fuel cell is shown in Figure 7.8. It has porous electrodes of nickel separated by the electrolyte consisting of a solution of KOH (40%) which also helps in preventing the reactants (hydrogen and oxygen) from directly interacting with each other.

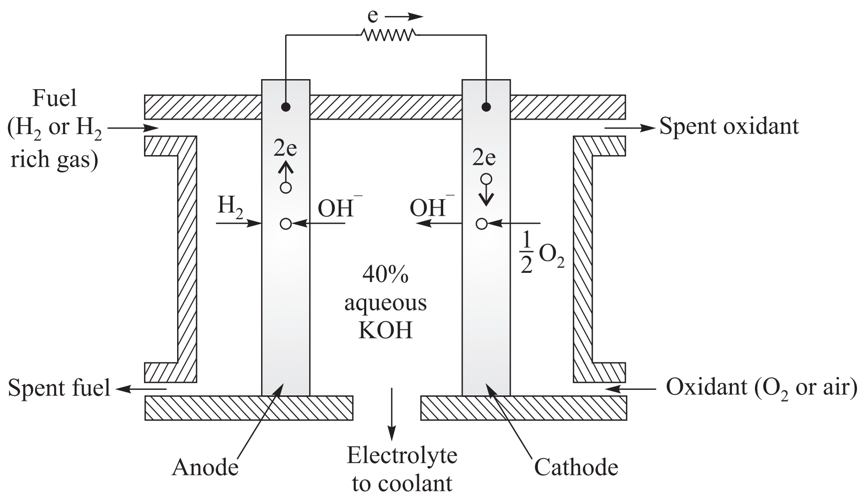


Figure 7.8 Alkaline fuel cell.

The fuel used for the alkaline fuel cell has to be free from carbon dioxide because carbon dioxide can combine with electrolyte (potassium hydroxide) to form potassium carbonate. The potassium carbonate increases the resistance to motion of OH^- ions, thereby decreasing the output voltage of the cell.

If air is used as the oxidant in place of oxygen, the air must be free of carbon dioxide as the presence of carbon dioxide lowers the performance of cell.

7.3.6 Molten Carbonate Fuel Cell

- **Explain the working of molten carbonate fuel cell using appropriate diagram and write the various chemical reactions involved in this type of fuel cell.**

The molten carbonate fuel cell has a high operating temperature with molten carbonate mixture as electrolyte. It offers the prospect of the use of a variety of fossil fuels including coal. The special feature of these cells is that they can oxidise carbon monoxide to carbon dioxide as well as hydrogen to water during their operation. Hence, the cell can use inexpensive mixture of hydrogen and carbon monoxide, which is called synthetic gas. Also, the presence of carbon dioxide in fuel and air does not have any adverse effect on the working of the cell.

The carbonate of alkali metals (Na, K and Li) in molten state is used as the electrolyte. This necessity makes the cell to operate at a temperature above the melting point of carbonates (range of 600–700°C). The porous nickel and silver are used as the anode and the cathode electrode respectively which are separated by electrolyte held by a sponge-like ceramic matrix. The synthetic gas (H_2 + CO) is used as the fuel and air is used as the oxidant. The synthetic gas is passed through the anode, where the hydrogen and carbon monoxide are oxidised with CO_3^{2-} ions, thereby liberating electrons. The electrons move to cathode from the external circuit. At the cathode, oxygen gets reduced in the presence of carbon dioxide and electrons, thereby forming CO_3^{2-} ions. The reactions are as follows:

$$H_2 + CO_3^{2-} \longrightarrow H_2O + CO_2 + 2e^- \quad \text{(anode)}$$

$$CO + CO_3^{2-} \longrightarrow 2CO_2 + 2e^- \quad \text{(anode)}$$

$$O_2 + CO_2 + 4e^- \longrightarrow 2CO_3^{2-} \quad \text{(cathode)}$$

The emf generated by the cell is about 1 V at 700°C. Any fuel which can be converted into a mixture of hydrogen and carbon monoxide can be used. However, the mixture has to disulphurized as sulphur can poison the electrodes or reduce their effectiveness as a catalyst.

The discharge from the reactants consists of steam, carbon dioxide and nitrogen and the discharge has temperature of 540°C. This hot discharge can be used to generate power using waste heat boiler with steam turbine to run generator (Figure 7.9).

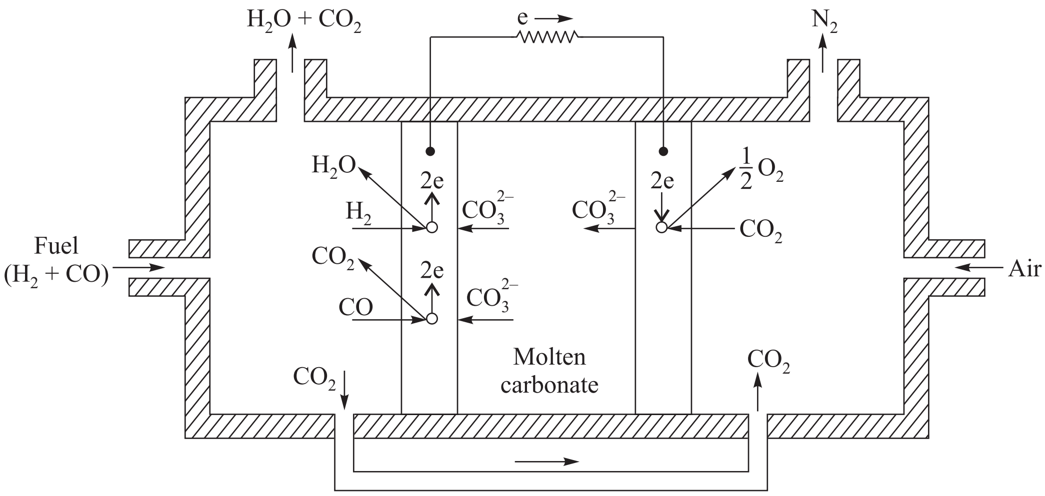


Figure 7.9 Molten carbonate fuel cell.

7.3.7 Solid Oxide or Ceramics Fuel Cell

- **Describe solid oxide fuel cell.**

It has been found that certain solid oxides or ceramics can be used as an electrolyte and these ceramics can conduct oxygen ions at a high temperature. Zirconium oxide is one such ceramic.

The fuel cell has porous nickel as anode electrode and indium oxide as cathode electrode. The operating temperature of the cell ranges from 600 to 1000°C. The fuel is a synthetic gas, that is, a mixture of hydrogen and carbon monoxide. At the anode, hydrogen and carbon monoxide react with oxygen ions present in the electrolyte to produce carbon dioxide and water. Hydrogen and carbon monoxide liberate electrons on oxidation. The liberated electrons flow through external circuit to cathode. At the cathode, oxygen is reduced by electrons to oxygen ions (Figure 7.10). The reactions are as follow:

$$H_2 + O^{2-} \longrightarrow H_2O + 2e^- \quad \text{(anode)}$$

$$CO + O^{2-} \longrightarrow CO_2 + 2e^- \quad \text{(anode)}$$

$$\frac{1}{2}O_2 + 2e^- \longrightarrow O^{2-} \quad \text{(cathode)}$$

The heat of discharge (spent fuel and oxidant) can be utilized as process heat or power generation. The output voltage at full load is about 0.63 V.

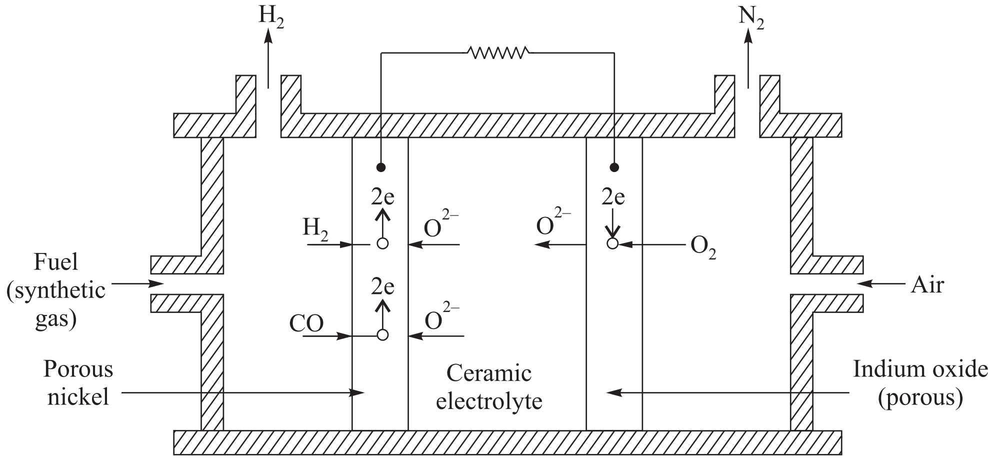


Figure 7.10 Sodium oxide fuel cell.

7.3.8 Regenerative Fuel Cell

- **Describe regenerative fuel cells.**

or

- **Write briefly on reversible cell.**

Regenerative or reversible fuel cell is a cell in which the reactants (fuel and oxidant) are regenerated from the products formed from the oxidation and reduction of fuel and oxidant respectively. It implies that the reactants are regenerated from its products so that these can be recycled into the fuel cell. Regeneration is carried out within or external to the fuel cell.

The regeneration can be carried out using chemical, electrical, thermal, radioactive and photochemical method.

In a regenerative fuel cell, reactants are converted into products with the removal of electrical work (W) and the products are converted into reactants in a regenerator at a higher temperature (T_H) (Figure 7.11). Hence, products can be considered as working fluid and fuel cell with regenerator forms a heat engine cycle, that is, heat engine performing cycle to give work output using heat supplied. The efficiency of regenerative fuel cell is, therefore, limited to Carnot engine efficiency. The efficiency of regenerative fuel cell is the product of efficiencies of a fuel cell and a regenerator. The efficiency of regenerative fuel cell is in the range of 5–20%.

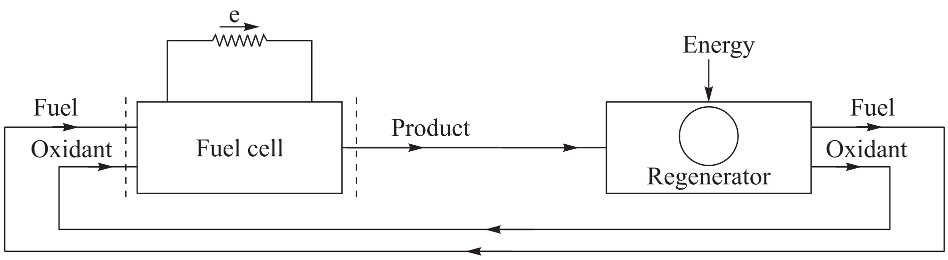


Figure 7.11 Regenerative fuel cell.

7.3.9 Performance Limiting Factors of Fuel Cell

• What are the various performance limiting factors of a fuel cell?

The performance limiting factors of a fuel cell are dependent on the following two requirements:

(i) reactivity (ii) invariance

Reactivity is required because electrodes of a fuel cell should have high electrode activity so that they can generate high current densities. To have high electrode activity, electrodes are made porous to increase the area of interface between reactants, electrolyte and electrodes. The output can also be increased by increasing pressure, raising temperature and using catalysts.

Invariance is required because a fuel cell remains unchanged in its performance as a convertor of reactants to electric energy throughout its working life. It means that its electrodes should keep on acting as a perfect catalyst without corrosion, poisoning or any degradation. Similarly, electrolyte should work without any degradation. The performance of the cell should remain invariant without any need for change of electrolyte and electrodes.

The requirements of reactivity and invariance are interrelated. Any attempt to increase reactivity with the help of a high temperature may cause the degradation of electrodes and electrolyte, thereby losing their invariance. On the other hand, when the fuel cell is operated at lower temperatures, the cell may be invariant, but it will have lesser reactivity, giving smaller electric output.

7.3.10 Losses of a Fuel Cell

• Explain briefly the losses of a fuel cell.

The losses that take place at the electrodes are generally attributed to some form of polarization. The polarization is the difference between the theoretical voltage output and the actual voltage output of a fuel cell. Electrode losses can result from chemical polarization, concentration polarization and resistance polarization. Chemical polarization depends on how ions are discharged at electrodes and the rate of which ions are discharged. Concentration polarization results in the loss of potential as reactions fail to maintain initial concentration at electrodes when current begins to flow. Resistance polarization results owing to the change in the conductivity of the electrolyte when ions move through it.

7.3.11 Advantages and Limitations of a Fuel Cell

- **What are the advantages of a fuel cell?**

or

- **What are the limitations of a fuel cell?**

The advantages of a fuel cell are as follows:

(i) It has a very high conversion efficiency.
(ii) It can be installed near the load point, thereby reducing the requirement of transmission lines.
(iii) It is noiseless and can operate quietly because of the absence of moving parts.
(iv) Fuel cells having hydrogen as fuel have water as waste product. Hence, fuel cells are non-polluting.
(v) Fuel cells operating at low temperature have discharge at a low temperature, thereby requiring no cooling to condense the discharge.
(vi) Fuel cells require lesser time for installation and operation.
(vii) Fuel cells need a lesser area for installation and operation.
(viii) As fuel cells are noiseless, they can be installed in residential areas.
(ix) Fuel cells can easily meet the varying load of customers.

Limitations of a fuel cell are as follows:

(i) Capital cost of fuel cell is high.
(ii) Heavy corrosion of electrodes causes low lifespan of a fuel cell.
(iii) Degradation of electrodes and electrolyte reduces the performance of a fuel cell.

7.3.12 Application of a Fuel Cell

- **What are the applications of a fuel cell?**

The applications of a fuel cell are as follows:

(i) Fuel cells can be employed for levelling of load in power plants. When power plant has lesser load, excess power can be converted into hydrogen and oxygen gases by electrolysis of water. The stored gases in hydrogen-oxygen fuel cells can be converted into power when load on power plant increases.
(ii) Fuel cell can use synthetic gas (a mixture of hydrogen and carbon monoxide) for conversion into electric power with high efficiency (about 70%).
(iii) Fuel cells are also suitable to be used for dispersed generation. The transmission and distribution cost can be reduced by operating fuel cells at different load centres.
(iv) Fuel cells can provide power at remote and inaccessible areas.
(v) Fuel cells can be used for propulsion of vehicles, spacecraft and submarines. Fuel cells are ideally suitable for electrical cars.
(vi) Emergency and critical supply such as to hospital can be met by fuel cells.
(vii) Fuel cells can replace batteries as an alternative power source.