Unit – 5

OTHER TYPES OF ENERGY

Energy Conversion from Hydrogen and fuel cells, Geo thermal energy Resources, types of wells, methods of harnessing the energy, potential in India. OTEC, Principles utilization, setting of OTEC plants, thermodynamic cycles. Tida and Wave energy: Potential and conversion techniques, mini-hydel power plants and their economics.

5

OTHER TYPES OF ENERGY

5.1. INTRODUCTION TO HYDROGEN

Generally, hydrogen is considered as the fuel for the future with reduced pollution problems due to decrease in availability of fossil fuels. Hydrogen is the most abundant element in the Universe but it is rarely found in its uncombined form on the earth. When combusted (oxidized), it creates only water vapour and heat as by-products. The exhaust is free from carbon dioxide. While no transportation distribution system currently exists for hydrogen transportation use, the ability to create the fuel from a variety of resources including natural gas and its clean-burning properties make it a desirable alternative fuel and worthy of consideration. Though some automakers are testing hydrogen-burning cars, they are not currently feasible or economical. Research shows that the greatest potential use for hydrogen as a transportation fuel is in fuel cells.

Hydrogen is a secondary energy carrier similar to electricity. But it involves some issues in production, storage and transport, usage of hydrogen as energy source, safety, economic and management.

As *Jule Verne* predicted "*Water would be one day as a fuel furnishing, in-exhaustible source of energy*". It is coming true in the formation of hydrogen. Hydrogen is user friendly and eco-friendly fuel.

5.1.1. Hydrogen as an Energy Source

Hydrogen is the lightest element which may someday replace heavier compounds as a source of energy for many applications. Although low-cost technology to allow this odorless, colorless, diffuse gas to be collected, hydrogen's potential to be a clean energy source has some hope about a future "hydrogen economy" which would not rely on fossil fuels.

Finding sources of hydrogen fuel is harder than the people think. Hydrogen is a versatile material as a fuel. But it is reactive with chemicals. Therefore, it is not freely available as a separate compound. It must be extracted from other compounds. It is considered as a secondary source of energy because another form of energy is needed to produce the hydrogen fuel. The primary sources of energy to produce hydrogen are natural gas, water, coal or oil. These sources go through different types of processes that allow hydrogen fuel to be made.

Natural gas and methanol provide much of the raw material for hydrogen today. Another major source is water (H_2O). The hydrogen and oxygen in water can be dissociated with an electric current in a process called *electrolysis*.

$$H_2 + \frac{1}{2}O_2 \Rightarrow H_2O + \text{Energy}$$

5.1.2. Hydrogen as a Fuel

Hydrogen has the highest energy content per unit weight of any known fuel 120.7 *kJ/g*. It burns cleanly. When hydrogen is burnt with oxygen, only byproducts are heat and water. When burnt with air which is 79% nitrogen (on a volumetric basis), some oxides of nitrogen are formed.

Hydrogen in its liquid form has been used as a fuel in space vehicles for years. Hydrogen has high combustion energy per *kg* relative to other fuels which means hydrogen is more efficient on a weight basis than fuels currently used in air or ground transportation. This weight factor makes hydrogen an attractive fuel.

Hydrogen fuel can be used in applications requiring electricity or gas and it can link the fossil-based energy supply today with the renewable energy tomorrow.

Advantages of using hydrogen as fuel:

1. Hydrogen combustion produces only water as a by-product. Hydrogen generates energy without releasing greenhouse gasses or pollutant particles.
2. The only pollution-free source of hydrogen is water which is also the most abundantly available. A simple process called *electrolysis* can liberate hydrogen from water.
3. Hydrogen has higher energy density than petroleum-based fuels. It means, it supplies more energy per volume than gasoline, diesel or kerosene.
4. Hydrogen has the potential to run a fuel-cell engine with greater efficiency over an internal combustion engine.

Disadvantages of using hydrogen as fuel:

1. Heavy and bulky fuel storage both in vehicle and at the service station. Hydrogen can be stored either as a cryogenic liquid or as a compressed gas. If stored as a liquid, it would have to be kept under pressure at very low temperature. It would require a thermally super-insulated fuel tank. Storing in a gas phase would require a heavy pressure vessel with limited capacity.
2. It is difficult to refuel.
3. Fuel cost would be high at present-day technology and availability.
4. NOx emissions are high because of high flame temperature.

5.1.3. Hydrogen Production

About 95% of the hydrogen is produced by steam reforming of natural gas today. Remaining is high-purity hydrogen from water electrolysis by using electricity mainly generated by burning fossil fuels. Some of the specific technologies used to produce hydrogen are as follows:

(a) *Electrolysis* uses electrical current to split water into hydrogen at the cathode (+) and oxygen at the anode (-).

(b) *Steam reforming* converts methane (and other hydrocarbons in natural gas) into hydrogen and carbon monoxide by reaction with steam over a nickel catalyst.

(c) *Steam electrolysis* (a variation on conventional electrolysis) uses heat instead of electricity to provide some of the energy needed to split water in making the process more energy efficient.

(d) *Thermochemical water splitting* uses chemicals and heat in multiple steps to split water into its component parts.

(e) *Photo-electrochemical systems* use semiconducting materials such as photovoltaics to split water using only sunlight.

(f) *Photo-biological systems* use microorganisms to split water using sunlight.

(g) *Biological systems* use microbes to break down a variety of biomass feed stocks into hydrogen.

(h) *Thermal water splitting* uses a very high temperature approximately 1000°C to split water.

(i) *Gasification* uses heat to break down biomass or coal into a gas from which pure hydrogen can be generated.

5.1.3.1. Hydrogen production by electrolysis process

Electrolysis is the process splitting water into hydrogen and oxygen by passing electric current. The electrolysis cell consists of two electrodes such as flat metal and carbon plates. These two plates are immersed in an aqueous solution named as *electrolyte*. Among two plates, one plate acts an anode and other one acts a cathode. DC power supply is connected between anode and cathode. Due to the flow of electric current, the electrolyte solution is decomposed into hydrogen gas released at cathode and oxygen gas released at anode. Potassium hydroxide is mixed with electrolyte to enhance the electrolysis process by increasing the conductivity. If the electrolysis process is done at normal temperature and pressure, a voltage of 1.23*V* is sufficient to decompose water into hydrogen and oxygen.

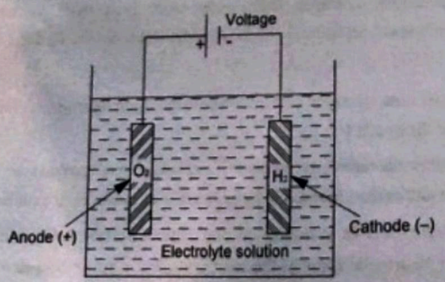


Figure 5.1 A simple electrolyte cell

Sometimes, the supply is increased as per the area of electrode to decompose the water. Therefore, the rate of hydrogen production is directly proportional to the supply voltage with higher current density. So, the maximum efficiency of the electrolysis process is up to 60 to 70%. The efficiency of electrolysis can be further increased by using platinum catalyst and diaphragm to prevent electronic contact.

The advantages of operating electrolyser at high pressures are as follows:

(i) Reduction in specific power consumption

(ii) Delivery of gas to eliminate the cost gas compressors

(iii) Reduction in the size of electrolysis cells.

5.1.3.2. Hydrogen production by fossil fuel methods

Generally, a mixture of carbon monoxide and hydrogen is formed in the first stage of hydrogen production using fossil fuel such as natural gas, petroleum product or coal. So, this mixture can be used as a synthesis gas or water gas. The same procedure is used in steam reforming of methane, light liquid hydrocarbon and partial oxidation of a heavier hydrocarbon with high temperature steam. The main thing in all cases is the production of hydrogen from hydrocarbon.

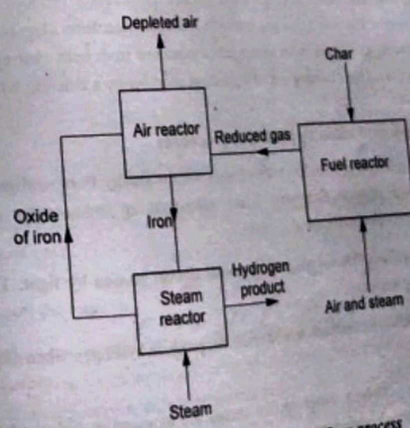


Figure 5.2 Hydrogen production by Iron process

The gas mixture is reacted with water and reacts with steam to remove carbon monoxide. During reaction, the carbon monoxide is converted into carbon dioxide with the formation of hydrogen.

$$CO + H_2O \Rightarrow CO_2 + H_2 + \text{Energy}$$

The acid gas of carbon dioxide can be absorbed by alkaline solution. A small amount of carbon monoxide and carbon dioxide will remain in hydrogen. But they can be easily converted into methane and separated by cooling process at moderately low temperature.

Many processes are used to convert coal into gaseous liquid hydrocarbon fuels. At the same time, these fuels should be rich in hydrogen gas. The coal or char is first reacted with steam and sufficient amount of oxygen to produce hydrocarbon. Then it is converted into hydrogen using an above discussed method.

During production of hydrocarbon, sometimes, air is used instead of pure oxygen to make the process more economical.

During reaction of coal with steam at 815°C at *7MPa*, the pure hydrogen gas and solid iron oxide (FeO) are produced in a separation chamber. The chemical reaction is given below.

$$Fe + H_2O \Rightarrow FeO + H_2$$

The solid iron is collected in a separate vessel and it is reused to produce hydrocarbons by reacting with steam. The iron oxide gas is sent to hydrogen separation chamber. The sufficient amount of reducing gas in the form hydrocarbon produced from both char-air-steam process and oxidation of solid iron coming out of separation chamber by a reaction with steam.

5.1.3.3. Hydrogen production by photolytic processes

Photolytic hydrogen production technologies use the energy from sunlight to split water into hydrogen and oxygen. Emerging direct water-splitting technologies include photo-biological and photo-electrochemical systems.

Photolytic methods: Photolysis is a chemical change caused by light. Two photolytic processes are being explored.

(a) Biophotolysis methods where microbes produce hydrogen when exposed to light, and

(b) Photo-electrolysis where special metals are exposed to light and submersed in water which generates enough electricity to generate hydrogen by splitting the water.

5.1.3.4. Hydrogen production by thermolysis of water

When primary energy is available in the form of heat (solar thermal), it is more logical to produce hydrogen by splitting water directly from heat energy using thermolysis. It is more efficient than conversion of heat, first to electricity and then producing hydrogen through electrolysis. The efficient of thermal plant is in the range of 32-38% and electrolysis is 80%. The overall efficiency through thermal-electrical-hydrogen route will be 25-30%.

Direct thermal decomposition of water is possible but it needs a minimum temperature of 2500°C. Because of temperature limitations of conversion process equipment, direct single step water decomposition cannot be achieved. However, sequential chemical reactions at substantially lower temperature can be devised to split water into H_2 and O_2. In reaction series, water is taken up at one stage and H_2 and O_2 are produced in different stages. The energy is supplied as heat at one or more stages and partly released at some stage in the cycle. Apart from decomposition of water, all other materials are recovered when the cycle is completed. Therefore, the method is known as *thermo-chemical cycle*.

The efficiency of conversion from heat energy to hydrogen is better than its conversion through electrolysis route only when the upper temperature of 950°C the efficiency of conversion is about 700°C. For the upper temperature of 950°C, the efficiency of conversion is 50%. It is a remarked improvement over the possible one through electrolysis route. One of the cycles is given below.

$$2CrCl_2 + 2HCl \xrightarrow{325^\circ C} 2CrCl_3 + H_2$$

$$2CrCl_3 \xrightarrow{875^\circ C} 2CrCl_2 + Cl_2$$

$$H_2O + Cl_2 \xrightarrow{850^\circ C} 2HCl + \frac{1}{2}O_2$$

At present, no commercial process for thermal splitting of water using thermo-chemical cycle is in operation.

5.1.4. Hydrogen Storage

Hydrogen is an ultra-light gas that occupies a substantial volume under standard conditions of pressure, i.e., atmospheric pressure. One liter of this gas weighs only 90 mg under normal atmospheric pressure, which means that it is 11 times lighter than the air. A volume of around 11 m^3 (which is the volume of the trunk of a large utility or commercial vehicle) is needed to store just 1 kg of hydrogen, which is the quantity needed to drive 100 km. In order to store and transport hydrogen efficiently, this volume must be significantly reduced.

Hydrogen is stored to increase its utilization where required to use. Few gas industries store hydrogen in small pipe lines to some extent but large storage is not possible with pipe lines. At the same time, storing hydrogen is not easy. So, it is stored in other forms. The five modes are applied to store produced hydrogen such as

(i) Compressed gas storage
(ii) Liquid storage
(iii) Line pack storage system
(iv) Underground storage
(v) Storage as metal hydrides
(vi) Carbon adsorption
(vii) Microspheres

The type of storage of hydrogen is selected on the application fields. Both gaseous and liquid storages are possible methods. Gaseous hydrogen storage method is applied for large volume storage but liquid storage is selected to small volume of hydrogen storage.

5.1.4.1. Compressed gas storage

Hydrogen can be stored in cylinders under high pressures. Compressed hydrogen is the gaseous state of the element hydrogen which is kept under pressure. The easiest way to decrease the volume of a gas, at constant temperatures, is to increase its pressure. At 700 bar, which is 700 times normal atmospheric pressure, hydrogen has a density of 42 kg/m^3, compared with 0.090 kg/m^3 under normal pressure and temperature conditions. At this pressure, 5 kg of hydrogen can be stored in a 125-liter tank.

Compressed hydrogen in hydrogen tanks at 350 bar and 700 bar is used for in hydrogen vehicles. This method is expensive due to the use of large quantities of steel to make the storage system. Compressed storage usually supplies small amount of hydrogen. Advances in compression technologies are also required to improve the efficiency and reduce the cost of producing high-pressure hydrogen. Issues with compressed hydrogen gas tanks revolve around high pressure, weight, volume, conformability and cost.

5.1.4.2. Liquid storage

The energy density of hydrogen is improved by storing in a liquid state. Liquid hydrogen (LH_2) tanks can store more hydrogen in a given volume than compressed gas tanks. Hydrogen

turns into a liquid when it is cooled to a temperature below −250°C. The volumetric pressure is 700 bar gas tanks. At −252.8°C and 1.013 bar, liquid hydrogen has a density of close to 71 kg/m^3. At this pressure, 5 kg of hydrogen can be stored in a 75-liter tank. In order to maintain liquid hydrogen at this temperature, tanks must be perfectly isolated.

The issues with liquid hydrogen (LH_2) tanks are hydrogen boil-off, the energy required for hydrogen liquefaction, volume, weight, and tank cost. The energy requirement for hydrogen liquefaction is high. Typically 30% of the heating value of hydrogen is required for liquefaction. Storing hydrogen in the liquid form is an option for just a limited number of applications so far, in high-tech areas such as space travel. For example, the tanks on the Ariane launcher, designed and manufactured by Air Liquide, contain 28 tons of liquid hydrogen that will provide fuel to the central engine. Liquid tanks are being demonstrated in hydrogen-powered vehicles and a hybrid tank concept combining both high-pressure gaseous and cryogenic storage is studied.

5.1.4.3. Underground storage

Underground hydrogen storage is the way to store in underground caverns, salt domes and depleted oil and gas fields. Large quantities of gaseous hydrogen have been stored in underground caverns for many years without any difficulties. The storage of large quantities of hydrogen underground can function as grid energy storage which is essential for the hydrogen economy.

5.1.4.4. Storage as metal hydride

The methods used to store hydrogen in the solid form involve techniques that bring into play the mechanisms of absorption or adsorption of hydrogen by a material. Hydrogen can be stored at high densities in reversible metal hydries. Whenever it is needed, it can be released by heating the hydride and original metal or alloy is recovered for further recycling. The pressure of gas released by heating depends mainly on temperature. At fixed temperature, the pressure remains constant until the hydrogen content is alnost exhausted. Metal hydrides offer the advantage of lower pressure storage, comfortable shape and reasonable volumetric store efficeicny. At the same time, they have weight penalties aand thermal management issues. It is also very safe. In case of sudden breakdown of storage, the gas remains in hydride and does not escape. It is very much suitable as a storage medium. So, the metla hydride should have the following properties.

(i) The metal should be inexpensive.

(ii) The hydride should contain a large amount of hydrogen per unit volume and per unit mass.

(iii) Formation of hydride from metal by reaction with hydrogen should be easy and the hydride should be stable at room temperature.

(iv) The gas should be released from hydride at significant pressure and moderately high temperature (below 100°C).

The reactions with three promising hydrides of alloys are given below. .

(i) Lanthanum-Nickel:

$$LaNi_5 + 3H_2 \underset{}{\overset{\text{Charge}}{\rightleftharpoons}} (LaNi_5)H_6 + \text{Heat}$$

(ii) Iron-Titanium:

$$FeTi + H_2 \overset{\text{Charge}}{\rightleftharpoons} (FeTi)H_2 + \text{Heat}$$

(iii) Magnesium Nickel:

$$Mg_2Ni + 2H_2 \overset{\text{Charge}}{\rightleftharpoons} (Mg_2Ni)H_4 + \text{Heat}$$

These hydrides contain more hydrogen then an equal volume. $(LaNi_5)H_6$ contains 1.35% of hydrogen by weight, $(FeTi)H_2$ contains 1.9% and $(Mg_2Ni)H_4$ contains 3.6%. Due to heavy weight, hydride storage is not suitable for mobile storage such as vehicles. Some complex-based reversible hydrides such as alamates have recently shown improved weight performances over metal hydrides along with modest temperatures for hydrogen recovery.

Complex metal hydrides such as Alanate (AlH_4) materials have the potential for higher gravimetric hydrogen capacities in the operational window than simple metal hydrides. Alanates can store and release hydrogen reversibly when catalyzed with titanium dopants. The chemical reactions are given by

$$NaAlH_4 \Rightarrow 1/3\ Na_3AlH_6 + 2/3Al + H_2$$

$$Na_3AlH_6 \Rightarrow 3NaH + Al + 3/2H_2$$

Issues with complex metal hydrides include low hydrogen capacity, slow uptake and release kinetics and cost.

Batteries are the most common application for hydrogen storage alloys. These hydride-forming alloys are M in Ni-MH (nickel-metal hydride) batteries as the negative electrode in

the battery cell. Once a negative electrode is fabricated, it must be activated or charged with hydrogen. Then, during the battery's lifetime, it proceeds through many hydriding / dehydriding cycles.

5.1.4.5. Challenges in hydrogen storage

The following are key challenges for commercialization of fuel cell and hydrogen infrastructure technologies:

1. ***Weight and volume:***

The weight and volume of hydrogen storage systems are too high.

2. ***Efficiency:***

Energy efficiency is a challenge for all hydrogen storage approaches. The energy required to get hydrogen in and out is an issue for reversible solid-state materials. The energy associated with compression and liquefaction must be considered for compressed and liquid hydrogen technologies.

3. ***Refueling time:***

Refueling times are too long. There is a need to develop hydrogen storage systems with refueling times of less than three minutes over the lifetime of system.

4. ***Hydrogen production and delivery:***

The high cost of hydrogen production, low availability of the hydrogen production systems, and the challenge of providing safe production and delivery systems are early penetration barriers.

5. ***Public acceptance:***

Education of the general public, training personnel in the handling and maintenance of hydrogen system components, adoption of codes and standards, and development of certified procedures and training manuals for fuel cells and safety will foster hydrogen's acceptance as a fuel.

6. ***Codes and standards:***

Applicable codes and standards for hydrogen storage systems and interface technologies have not been established which will facilitate implementation/commercialization and assure safety and public acceptance. Standardized hardware and operating procedures, and applicable codes and standards are required.

5.1.5. Energy Conversion from Hydrogen

Hydrogen can be converted into useful forms of energy in different ways. Some of hydrogen conversion technologies are unique to hydrogen but all technologies are more efficient and less polluting than conversion of conventional fuels. The main hydrogen energy conversion technologies are as follows.

(i) Combustion in internal combustion engines

(ii) Direct steam generation by hydrogen or oxygen combustion

(iii) Catalytic combustion

(iv) Electrochemical conversion in fuel cells and

(v) Metal hydride technologies.

5.1.5.1. Combustion in internal combustion engines

Hydrogen is a very good fuel for internal combustion engines. Hydrogen powered internal combustion engines are 20% more efficient than comparable gasoline engines. The ideal thermal efficiency of an internal combustion engine can be calculated by

$$\eta = 1 - \frac{1}{r^{\gamma-1}}$$

where r = Compression ratio and γ = Ratio of specific heats.

From above equation, it can be understood that the thermal efficiency can be improved by increasing either the compression ratio or the specific heat ratio. In hydrogen engines, both ratios are higher than in a comparable gasoline engine due to hydrogen's lower self-ignition temperature and ability to burn in lean mixtures. Nevertheless, the use of hydrogen in internal combustion engines leads to the loss of power due to lower energy content in a stoichiometric mixture in the engine's cylinder. The power output of a hydrogen engine can be improved by using more advanced fuel injection techniques or liquid hydrogen.

One of the most important advantages of hydrogen as a fuel for internal combustion engines is, hydrogen engines release by far fewer pollutants than comparable gasoline engines. Basically, the only products of hydrogen combustion in air are water vapor and small amounts of nitrogen oxides. Hydrogen has a wide flammability range in air. Therefore, high excess air is utilized more effectively. The formation of nitrogen oxides in hydrogen or air combustion can be minimized with excess air.

The low ignition energy and fast flame propagation of hydrogen has led to problems of pre-ignition and backfire. These problems have been overcome by adding hydrogen to the air mixture at the point where and when the conditions for pre-ignition are less likely to deliver the fuel and air separately to the combustion chamber and injecting hydrogen under pressure into the combustion chamber before the piston is at the Top Dead Center (TDC) and after the intake air valve has been closed. Both water injection and exhaust gas recirculation techniques are also used in hydrogen engines to help control premature ignition. The most effective method of reducing the preignition and knocking problems is the redesign of the combustion chamber and coolant systems to accommodate hydrogen's unique combustion properties.

5.1.5.2. Direct steam generation by hydrogen or oxygen combustion

Hydrogen combusted with pure oxygen results in pure steam which can be written as

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

Above chemical reaction produces the temperature in the flame zone above 3000°C. Therefore, additional water has to be supplied. So, the steam temperature can be regulated at a desired level. Both saturated and superheated vapor can be produced.

The German Aerospace Research Establishment (DLR) has developed a compact hydrogen and oxygen steam generator. The steam generator consists of ignition, combustion and evaporation chambers. In the ignition chamber, a combustible mixture of hydrogen and oxygen at a low oxidant and fuel ratio is ignited by means of a spark-plug. The rest of oxygen is added in the combustion chamber to adjust the oxidant and fuel ratio exactly to the stoichiometric proportion. Water is also injected in the combustion chamber after passing through the double walls of the combustion chamber. The evaporation chamber serves to homogenize the steam. The steam's temperature is monitored and controlled. Such a device is close to 100% efficient since there are no emissions other than steam and little or no thermal losses.

5.1.5.3. Catalytic combustion of hydrogen

Hydrogen and oxygen in the presence of a suitable catalyst can be combined at temperatures significantly lower than flame combustion. This principle is used to design catalytic burners and heaters. Catalytic burners need more surface area than conventional flame burners. Therefore, the catalyst is dispersed in a porous structure. The reaction rate and temperature can be easily controlled by controlling the hydrogen flow rate. The reaction takes place in a reaction zone of the porous catalytic sintered metal cylinders or plates in which hydrogen and oxygen are mixed by diffusion from opposite sides. A combustible mixture is formed only in the reaction zone and assisted with (platinum) catalyst to burn at low temperatures as shown in Figure 5.3. The only product of catalytic combustion of hydrogen is water vapor. Due to low temperatures, there are no nitrogen oxides formed. The reaction cannot drift into the hydrogen supply since there is no flame and hydrogen concentration is above the higher flammable limit.

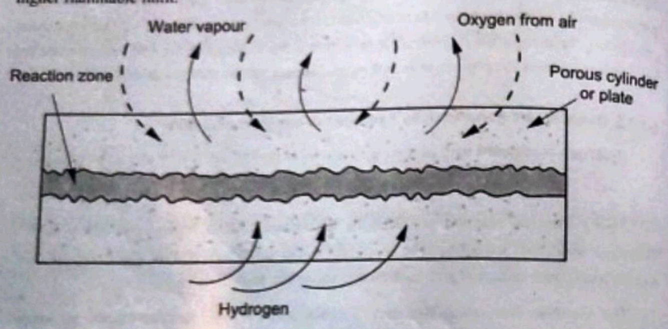


Figure 5.3 Schematic representation of catalytic burner

Possible applications of catalytic burners are in household appliances such as cooking ranges and space heaters. The same principle is also used in hydrogen sensors.

5.1.5.4. Electrochemical electricity generation (Hydrogen fuel cells)

Hydrogen can be combined with oxygen without combustion in an electrochemical reaction (reverse of electrolysis) and produce electricity (DC). The device where such a reaction takes place is called *electrochemical fuel cell.*

Depending on the type of the electrolyte used, there are several types of fuel cells. Detailed discussion of concept and various types of fuel cells are discussed in Chapters **5.2.3.1-5.2.3.7**.

5.1.5.5. Metal hydrides applications

Forming metal hydrides can be used in both hydrogen storage and various energy conversions. When a hydride is formed by the chemical combination of hydrogen with a metal, an element or an alloy, heat is generated by exothermic process. In the metal hydride process,

heat will be supplied. These processes can be represented by the following chemical reactions below.

Charging or absorption: $M + xH_2 \Rightarrow MH_{2x} + Heat$

Discharging or desorption: $MH_{2x} + Heat \Rightarrow M + xH_2$

where *M* represents the hydriding substance such as a metal, an element or an alloy. The rate of these reactions increases with increase in the surface area. Therefore, the hydriding substances are used in powdered form to speed up the reactions.

Elements or metals with unfilled shells or subshells are suitable hydriding substances. Metal and hydrogen atoms form chemical compounds by sharing their electrons in the unfilled subshells of the metal atom. For example, for a given temperature, the charging or absorption process and the discharging or desorption process takes place at the same constant pressure though there is a hysteresis effect and the pressure is not absolutely constant for a given temperature charging pressures are higher than the discharging pressures. The heat generated during the charging process and the heat required for discharging are the functions of the hydriding substance, hydrogen pressure and heat supplied or heat extracted temperature. Using different metals and by forming different alloys, different hydriding characteristics can be obtained. For examples, waste heat storage, electricity generation, pumping, hydrogen purification and isotope separation applications, it is possible to find hydriding substances.

5.1.6. Applications of Hydrogen Energy

Hydrogen energy is used in many areas of industrial fields and domestic purposes such as residential uses, industrial uses, alternate transport fuel, alternate fuel for aircraft and power generation.

Hydrogen can be used in combustion-based power generation such as gas turbine using hydrogen alone or mixed with natural gas. Such applications are proposed for stationary power generation including backup power units, stand-alone power plants, distributed generation for buildings and cogeneration. Alternatively, hydrogen may be obtained from steam reforming of natural gas and used in to generate electricity.

Portable applications for fuel cell-based generation include consumer electronics, business machinery and recreational devices. These portable power applications range from 25 *W* for portable electronics to 10 *kW* system for critical commercial and medical functions and on site power generation for individual homes and office buildings.

Electricity used in domestic appliances such as lights and refrigerators can be operated by fuel cells, radiant space heater, domestic cooking and hydrogen stove in which hydrogen energy is stored. In industrial sectors, it is used as an agent to remove oxygen by oxidizing process and the use of natural gas can be replaced by hydrogen.

There have only been a small number of prototype hydrogen vehicles made. Most of these have been experimental vehicles made by car manufacturers. Hydrogen is also used in fuel cells. Hydrogen-fuel engines are used in air craft applications with increased efficiency. If the hydrogen is used in air craft fields, it will reduce the use of lubricating oils. Hydrogenated fuel cells are used in light applications because of the portable size of it.

Further applications of hydrogen energy are listed below:

1. A fuel in H_2-O_2 fuel cell system
2. Manufacturing synthetic Ammonia, synthetic Methanol and synthetic Urea or ammonium nitrate.
3. An aviation fuel by hydrogenation process.
4. Welding process.
5. Chemical reduction and various heating process.
6. A coolant in large generators and motors.
7. Processing natural gas, coal and Ammonia.
8. Used in the manufacturing of Tungsten filaments for lamps.
9. An alternate fuel in transport and energy carrier.

5.2. FUEL CELL

Fuel cell technology is over 150 years old. The first fuel cell was demonstrated by *Sir William Grove* in 1839. Grove used porous platinum electrodes and sulfuric acid as the electrolyte bath. *William White Jaques* later substituted phosphoric acid in the electrolyte bath and was the person who coined the term "fuel cell."

A significant fuel cell research was done in Germany during 1920's which laid the groundwork for subsequent development of carbonate cycle and solid oxide fuel cells. In 1960s, NASA began using alkaline fuel cells to provide onboard electrical power for spacecraft.

A fuel cell produces electricity directly from the reaction between hydrogen (derived from a hydrogen-containing fuel or produced from the electrolysis of water) and oxygen from air. In

a fuel cell, the liquid is oxidized but the resulting energy takes in the form of electricity. When powered by pure hydrogen, by-products of the reaction are heat and water.

Fuel cells have the potential to revolutionize the way we power our nation, offering cleaner, more-efficient alternatives to the combustion of gasoline and other fossil fuels.

The amount of power produced by a fuel cell depends on several factors including fuel cell type, cell size, the temperature at which it operates and the pressure at which the gases are supplied to the cell.

A single fuel cell produces enough electricity for only small applications. Therefore, to provide the power needed for most applications, individual fuel cells are combined in series into a fuel cell stack. A typical fuel cell stack may consist of hundreds of fuel cells.

5.2.1. Working Principle of a Fuel Cell

A fuel cell is an electrochemical device in which the chemical energy of a conventional fuel is directly converted into low voltage DC electrical energy. One of the main advantages of such device is that Carnot limitation on efficiency does not apply because the conversion can be carried out isothermally. A fuel cell is frequently described as a primary battery in which the fuel and oxidizer are stored in the battery and fed to it as needed.

Figure 5.4 shows a schematic diagram of a fuel cell. The fuel gas diffuses through the anode and it is oxidized. Therefore, it releases electrons to the external circuit. The oxidized fuel diffuses through the cathode and it is reduced by electrons coming from anode by the way of external circuit.

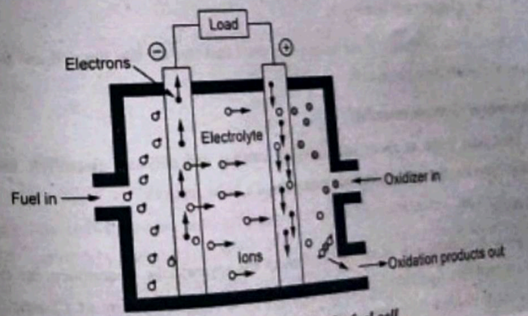


Figure 5.4 Schematic of a fuel cell

The fuel cell is a device which keeps the fuel molecules from mixing with the oxidizer molecules in permitting the transfer of electron by a metallic path that may contain a load of available fuels. Hydrogen has so far given the most promising results, although cells consuming coal, oil or natural gas would be economically much more useful for large scale applications.

Some of the possible reactions are given by

Hydrogen/oxygen 1.23 *V*	$2H_2 + O_2 \Rightarrow 2H_2O$
Nitrogen 1.56 *V*	$N_2H_4 + O \Rightarrow 2H_2O + N_2$
Carbon (Coal) 1.02 *V*	$C + O_2 \Rightarrow CO_2$
Methane 1.05 *V*	$CH_4 + 2O_2 \Rightarrow CO_2 + 2H_2O$

5.2.2. Construction of a Fuel Cell

A fuel cell power system has many components but its heart is the fuel cell stack which is made of many thin flat cells layered together. Although the term *fuel cell* is often used to describe the entire stack strictly speaking, it refers only the individual cells. Each cell produces electricity and the output of all cells is combined to get more power.

Polymer Electrolyte Membrane (PEM) fuel cells are the current focus of research for many of the fuel cell based power generation applications. PEM fuel cells are made from several layers of different materials as shown in the Figure 5.6 on Page 5.23. The three key layers in a PEM fuel cell include the following:

- Membrane electrode assembly
- Catalyst and Hardware.

Other layers of materials are designed to draw fuel and air into the cell and to conduct electrical current through the cell.

1. Membrane electrode assembly:

Electrodes (such as anode and cathode), catalyst and polymer electrolyte membrane together form the membrane electrode assembly of a PEM fuel cell.

(a) Anode:

Anode is negative side of the fuel cell which has several jobs. It conducts the electrons which are bred from hydrogen molecules in order to use in an external circuit. Channels etched into the anode disperse the hydrogen gas equally over the surface of catalyst.

(b) Cathode:

Cathode is positive side of the fuel cell also containing channels which distribute oxygen to the surface of catalyst. It conducts electrons back from the external circuit to the catalyst where they can recombine with the hydrogen ions and oxygen to form water.

(c) Polymer electrolyte membrane:

Polymer Electrolyte Membrane (PEM) is a specially treated material which looks similar to ordinary kitchen plastic wrap which conducts only positively charged ions and blocks electrons. PEM is the key to the fuel cell technology. It will permit only the necessary ions to pass between anode and cathode. Other substances passing through the electrolyte will disrupt the chemical reaction.

2. Catalyst:

All electrochemical reactions in the fuel cell consist of two separate reactions such as an oxidation half-reaction at the anode and a reduction in half-reaction at the cathode. Normally, two half-reactions will occur very slowly at low operating temperature of a PEM fuel cell. So, each of the electrode is coated at one side with a catalyst layer which speeds up the reaction of oxygen and hydrogen. It is usually made of platinum powder very thin coated onto carbon paper or cloth. The catalyst is rough and porous to expose the maximum surface area of the platinum to the hydrogen or oxygen. The platinum-coated side of the catalyst faces PEM. Platinum-group metals are critical to catalytic reactions in the fuel cell but they are very expensive.

3. Chemistry of a fuel cell:

Anode side:

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

Cathode side:

$$O_2 + 4H^+ + 4e^- \Rightarrow 2H_2O$$

Net reaction:

$$2H_2 + O_2 \Rightarrow 2H_2O$$

The pressurized hydrogen gas (H_2) enters the fuel cell at anode side. This gas is forced through the catalyst by the pressure. When a H_2 molecule comes in contact with the platinum on the catalyst, it splits into two H^+ ions and two electrons (e^-). The electrons are conducted through the anode where they make their way through the external circuit and return to the cathode side of fuel cell.

Meanwhile, on the cathode side of the fuel cell, oxygen gas (O_2) is forced through the catalyst where it forms two oxygen atoms. Each of these atoms has a strong negative charge. This negative charge attracts two H^+ ions through the membrane where they combine with an oxygen atom and two of electrons from the external circuit to form a water molecule (H_2O).

This reaction in a single fuel cell produces only about 0.7 *V*. To obtain this voltage up to a reasonable level, many separate fuel cells must be combined to form a fuel-cell stack.

4. Hardware:

The backing layers, flow fields and current collectors are designed to maximize the current from a membrane/electrode assembly. The backing layers are one next to anode and the other next to cathode is usually made of a porous carbon paper or carbon cloth about thickness of 4 to 12 sheets of paper. The backing layers have to be made of a material which can conduct electrons that leave anode and enter cathode. The porous nature of the backing material ensures the effective diffusion of each reactant gas to the catalyst on the membrane/electrode assembly. The gas spreads out as it diffuses so that it will be in contact with the entire surface area of the catalyzed membrane when it penetrates backing.

The backing layers also help in managing water in the fuel cell. Too little or too much water can cause the cell to stop operating. Water can build up in flow channels of plates or can clog the pores in the carbon cloth preventing reactive gases from reaching electrodes.

Each plate also acts as a current collector. Electrons produced by the oxidation of hydrogen must:

1. be conducted through the anode and next, through the backing layer along the length of the stack and through the plate before they can exit the cell.
2. travel through an external circuit, and
3. re-enter the cell at cathode plate. With the addition of flow fields and current collectors, PEM fuel cell completes only a load-containing external circuit such as an electric motor which requires electric current.

5.2.3. Types of Fuel Cells

Fuel cells can be classified in several ways as follows:

(i) Based on the type of electrolyte:

(a) Polymer Electrolyte Membrane (PEM) fuel cell

(b) Direct methanol fuel cell

(c) Alkaline fuel cell

(d) Phosphoric acid fuel cell

(e) Molten carbonate fuel cell

(f) Solid oxide fuel cell

(g) Regenerative fuel cell.

(ii) Based on the types of the fuel and oxidant:

(a) Hydrogen (pure) - oxygen (pure) fuel cell

(b) Hydrogen rich gas - air fuel cell

(c) Hydrazine-Oxygen/hydrogen peroxide fuel cell

(d) Ammonia-air fuel cell

(e) Synthesis gas-air fuel cell

(f) Hydrocarbon (gas) -air fuel cell

(g) Hydrocarbon (liquid) -air fuel cell.

(iii) Based on the operating temperature:

(a) Low temperature fuel cell (below 150°C)

(b) Medium temperature fuel cell (150 - 250°C)

(c) High temperature fuel cell (250 - 800°C)

(d) Very high temperature fuel cell (800 - 1100°C).

(iv) Based on application:

(a) Fuel cell for space applications

(b) Fuel cell for vehicle propulsion applications

(c) Fuel cell for submarine applications

(d) Fuel cell for defense applications

(e) Fuel cell for commercial applications.

(v) Based on the chemical nature of electrolyte:

(a) Acid electrode type fuel cell

(b) Alkaline electrode type fuel cell

(c) Neutral electrode type fuel cell.

5.2.3.1. Hydrogen-Oxygen Cell

The hydrogen-oxygen fuel cell is shown in Figure 5.5. It is a typical type of fuel cell. It has three chambers separated by two porous electrodes, anode and cathode. The middle chamber between electrodes is filled with a strong solution of potassium hydroxide. The surfaces of electrodes are chemically treated to repel the electrolyte so that there is minimum leakage of potassium hydroxide into outer chambers. The gases diffuse through electrodes undergoing reactions as shown below:

Anode: $2\,H_2 + 4\,(OH)^- \Rightarrow 4\,H_2O + 4\,e^-$

Cathode: $O_2 + 2\,H_2O + 4\,e^- \Rightarrow 4\,(OH)^-$

$4\,KOH \Rightarrow 4\,K^+ + 4\,(OH)^-$

Cell reaction: $2H_2 + O_2 \Rightarrow 2\,H_2O$

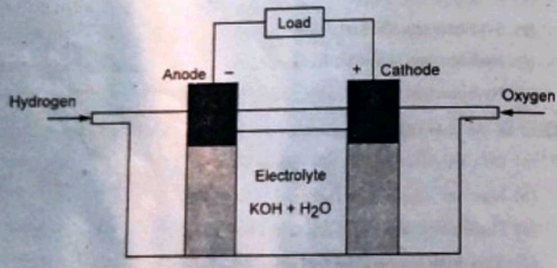


Figure 5.5 Hydrogen-oxygen fuel cell

The water formed is drawn off from the side. The electrolyte provides the OH^- ions needed for the reaction and it remains unchanged at the end since these ions are regenerated. The electrons liberated at the anode find their way to move to the cathode through the external circuit. This transfer is equivalent to the flow of a current from cathode to anode. Such cells when properly designed and operated have an open circuit voltage of about 1.1 *V*. The electrolyte fuel efficiencies are as high as 60% - 70%.

There are two types of hydrogen fuel cells:

(i) Low temperature cell, and

(ii) High pressure cell.

Low temperature cell is operated at 90°C and less pressurized up to 4 atmospheric pressure. In the case of high pressure cell, pressure and temperature are 45 atmospheric pressure and 300°C respectively. Gases should be free from carbon dioxide. Otherwise, the gas will react with potassium hydroxide and produce potassium carbonate. This type of fuel cell is mainly suited for low voltage and high current applications.

5.2.3.2. Polymer Electrolyte Membrane (PEM) Fuel Cells

Polymer Electrolyte Membrane (PEM) fuel cells also called *proton exchange membrane fuel cells* deliver high power density and offer the advantages of low weight and volume when compared to other fuel cells.

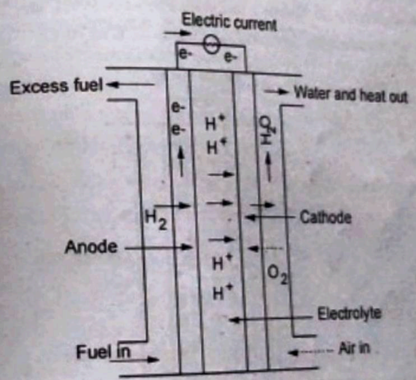


Figure 5.6 Polymer electrolyte membrane fuel cell

PEM fuel cells use a solid polymer as an electrolyte and porous carbon electrodes containing a platinum catalyst. They need only hydrogen, oxygen from air and water to operate. It does not require corrosive fluids similar to some other fuel cells. They are typically fueled with pure hydrogen supplied from storage tanks or onboard reformers.

Polymer electrolyte membrane fuel cells operate at relatively low temperature around 80°C. Low temperature operation allows them to start quickly (less warm-up time) and it results less wear on system components thereby resulting better durability. However, it requires a noble-metal catalyst (platinum) which is used to separate hydrogen electrons and protons. It is added with the system cost.

The platinum catalyst is also extremely sensitive to CO poisoning making it necessary to employ an additional reactor to reduce CO in the fuel gas if hydrogen is derived from an alcohol or hydrocarbon fuel. It is also added with the cost. PEM fuel cells are primarily used for the transport applications and some stationary applications.

5.2.3.3. Alkaline Fuel Cells

Alkaline Fuel Cells (AFCs) were one of the first fuel cell technologies developed and they were the first type widely used in US. A space program is to produce electrical energy and water onboard spacecraft. These fuel cells use a solution of potassium hydroxide (KOH) in water as the electrolyte using a variety of non-precious metals as a catalyst at anode and cathode. High-temperature AFCs operate at temperature between 100°*C* and 250°*C*. However, newer AFC designs operate at low temperature of roughly 23°*C* to 70°*C*.

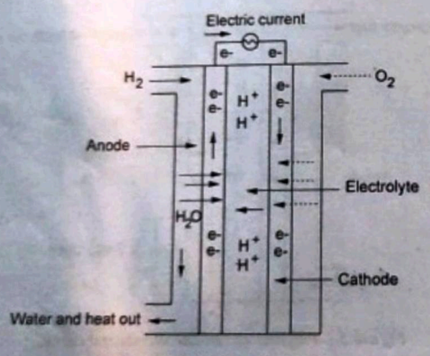


Figure 5.7 Alkaline fuel cell

The operation and movements of charge carriers is shown in Figure 5.7. At positive electrode oxygen, water (from electrolyte) and returning electrons from the external load combine to produce OH^- ions.

$$1/2\,O_2 + H_2O + 2\,e^- \Rightarrow 2\,OH^-$$

These OH^- ions migrate from positive to negative electrode through electrolyte. On reaching positive electrode these OH^- ions combine with H_2 to produce water. AFC's high

performance is due to the rate at which the chemical reactions take place in the cell. They have also demonstrated the efficiency of 60% in space applications.

The disadvantage of this fuel cell type is that it is easily poisoned by carbon dioxide (CO_2). Even small amount of CO_2 in the air can affect this cell's operation. So, it should purify both hydrogen and oxygen used in the cell. This purification process is costly. The susceptibility to poisoning also affects the cell's lifetime further adding to cost.

5.2.3.4. Phosphoric Acid Fuel Cells (PAFCs)

Phosphoric Acid Fuel Cells (PAFCs) use liquid phosphoric acid as an electrolyte. The acid is contained in a Teflon-bonded silicon carbide matrix and porous carbon or nickel electrodes containing a platinum catalyst. Pure hydrogen or hydrogen rich gas is supplied at negative electrode and oxygen or air is supplied at positive electrode. The pores provide an opportunity to gas, electrolyte and electrode to come into contact for electrochemical reaction. The reaction is normally very slow and a catalyst is required in the electrode to accelerate the reaction. The chemical reactions take place in the cell shown in Figure 5.8.

At the negative electrode, hydrogen gas is converted to hydrogen ions (H^+) and an equal number of electrons (e^-). Thus the chemical is reaction is given by

$$H_2 \Rightarrow 2\,H^+ + 2\,e^-$$

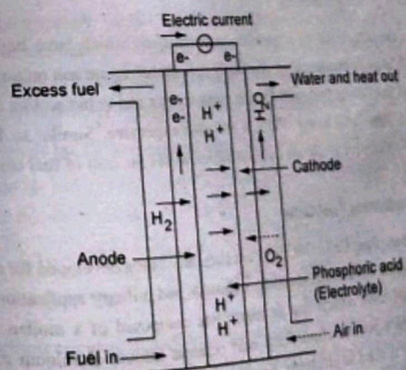


Figure 5.8 Phosphoric acid fuel cell

The electrons originating at negative electrode flow through the external load to positive electrode. Also, the H^+ ions migrate from negative electrode towards positive electrode through the electrolyte. On reaching the positive electrode they interact with O_2 to produce water. Thus the chemical is reaction is given by

$$\tfrac{1}{2} O_2 + 2H^+ + 2e^- \Rightarrow H_2O$$

Combining above equations indicates that a fuel cell combines H_2 and O_2 to produce water and electrical energy. The overall reaction is therefore

$$H_2 + 1/2\, O_2 \Rightarrow H_2O$$

Platinum serves as the best catalyst for both electrodes and used for premium fuel cells. In general, a less expensive material such as nickel (for negative electrode) and silver (for positive electrode) is used wherever possible. Thus finely divided platinum or nickel/silver deposited on the outer surface of electrodes is used as catalyst.

The operating temperature of PAFC is 150-200°C. At atmospheric pressure it produces an ideal emf of 1.23 *V* at 25°C, which reduces to 1.15 *V* at 200°C. The actual value is always less than this and decreases with current.

Usually, PAFC is considered as the "first generation" of modern fuel cells. It is one of the most grown-up cell types and currently used over 200 units. This type of fuel cell is typically used for stationary power generation.

PAFCs are more tolerant of impurities in fossil fuels which have been reformed into hydrogen than PEM cells because they are easily "poisoned" by carbon monoxide. PAFCs are also less powerful than other fuel cells for the same weight and volume. As a result, these fuel cells are typically large and heavy. PAFCs are also expensive. Similar to PEM fuel cells, PAFCs require an expensive platinum catalyst which raises the cost of fuel cell.

5.2.3.5. Molten Carbonate Fuel Cells

Molten Carbonate Fuel Cells (MCFCs) are currently being developed for natural gas and coal-based power plants for electrical utility, industrial and military applications. MCFCs are high-temperature fuel cells which use an electrolyte composed of a molten carbonate salt mixture suspended in a porous chemically inert ceramic lithium aluminum oxide ($LiAlO_2$) matrix. Porous nickel is used as electrode. Since they operate at extremely high temperature of 650°C and above, non-precious metals can be used as catalysts at the anode and cathode which reduces its cost.

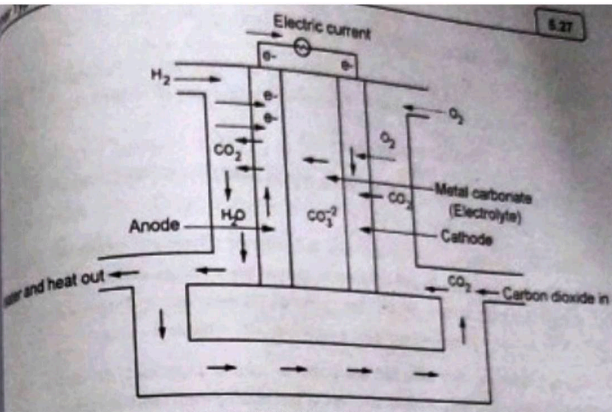


Figure 5.9 Molten carbonate fuel cell

A special feature of these cells is that during operation they oxidize hydrogen to water and carbon monoxide (present in fuel) to carbon dioxide. Hence, gaseous mixtures of hydrogen and carbon monoxide (synthesis gas), which are relatively inexpensive to manufacture can also be used. This feature allows to use of a variety of fossil fuels including coal (gasified). These fuels are first converted to get H_2 and CO and desulphurized to prevent poisoning of electrodes.

The discharges mainly consisting of steam, carbon dioxide and nitrogen from spent oxidant (air) are at a temperature exceeding 540°C. These hot gases could be used to provide industrial process heat or to generate additional power employing waste heat boiler and steam turbine. The overall efficiency of fuel would thus be increased substantially.

The operation of MCFC is explained with the help of a diagram shown in Figure 5.9. At the fuel electrode H_2 and CO react with CO_3^{-} ions present in the electrolyte and release two electrons each to the electrode as given below:

$$H_2 + CO_3^{--} \Rightarrow H_2O + CO_2 + 2e^-$$

$$CO + CO_3^{--} \Rightarrow 2CO_2 + 2e^-$$

These electrons circulate through external resistance, forming load current, and reach the oxidant electrode. The CO_2 produced at fuel electrode is circulated through an external path to oxidant electrode, where it combines with O_2 and returning electron through external path to produce CO_3^{--}.

$$O_2 + 2CO_2 + 4e^- \Rightarrow 2CO_3^{--}$$

The CO_3^{--} ions thus produced, are responsible for transportation of charge from positive to negative electrode within electrolyte. The overall reaction may be written as:

$$H_2 + CO + O_2 \Rightarrow H_2O + CO_2$$

The theoretical value of emf at no load is approximately 1 *V* at 700°C. But actual value is always less (0.7*V*).

Dissimilar to alkaline, phosphoric acid and polymer electrolyte membrane fuel cells, MCFCs do not require an external reformer to convert more energy-dense fuel to hydrogen. Due to high temperature, these MCFCs are operated to convert into hydrogen within the fuel cell itself by a process called *internal reforming* which also reduces the cost.

Molten carbonate fuel cells are not prone to carbon monoxide or carbon dioxide "poisoning". They can even use carbon dioxides as fuel making them more attractive for fueling with gases made from coal because they are more resistant to impurities than other fuel cell types.

The primary disadvantage of current MCFC technology is durability. High temperatures are preferred to operate these cells to avoid component breakdown and the corrosive electrolyte is used to reduce the corrosion because the corrosion affects the cell life. Scientists are currently exploring corrosion-resistant materials for components as well as fuel cell designs which increase the cell life without decreasing its performance.

5.2.3.6. Solid Oxide Fuel Cells

Solid Oxide Fuel Cells (SOFCs) use hard and non-porous ceramic compound as the electrolyte. For example, zirconium oxide containing a small amount of other oxide to stabilize the crystal structure has been used as an electrode. The material is able to conduct O^{--} ions at high temperature. The negative electrode is made of porous nickel and positive electrode employs metal oxide e.g. indium oxide. Since the electrolyte is a solid, cells do not have to be constructed in the plate similar to the configuration of typical other fuel cell types. The efficiency of SOFCs is expected around 50-60% in converting fuel to electricity. These cells can be used where the system wants to capture and utilize the system's waste heat (co-generation). The overall fuel efficiency is around 80-85%. Figure 5.10 illustrates the construction details and electron flow of the SOFC.

SOFCs operate at high temperature range of 600 - 1,000°C. High temperature operation removes the need for precious metal catalyst thereby reducing its cost. It also allows SOFCs to reform fuels internally which enables the use of a variety of fuels and it reduces the cost associated with adding a reformer to the system. The output voltage at full load is about 0.63*V*.

At the fuel electrode H_2 and CO react with O^{--} ions present in the electrolyte to produce H_2O and CO_2. The two electrons released per ion flow through external path to constitute load current. Similar to metal oxide fuel cell, the heat of discharge can be utilized as process heat. The reactions at the electrodes are:

Anode: $H_2 + O^{--} \Rightarrow H_2O + 2e^-$

and $CO + O^{--} \Rightarrow CO_2 + 2e^-$

Cathode: $O_2 + 4e^- \Rightarrow 2O^{--}$

The overall reaction: $H_2 + CO + O_2 \Rightarrow H_2O + CO_2$

SOFCs are also the most sulphur-resistant fuel cell type. They can tolerate several orders of magnitude more sulphur than other cell types. In addition, they are not poisoned by carbon monoxide (CO) which can even be used as fuel. It allows SOFCs to use gases made from coal.

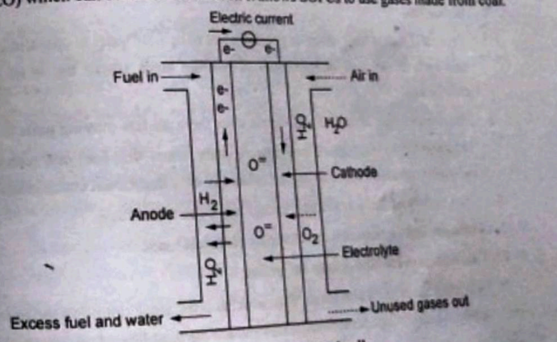


Figure 5.10 Solid oxide fuel cell

High-temperature operation is the main disadvantage of this cell. It results a slow start-up and it requires significant thermal shielding to retain heat and protect personnel which may be acceptable for utility applications but it is not for transportation and small portable applications.

5.2.3.7. Hybrid Fuel Cells

In a hybrid fuel cell system, high-temperature fuel cells are coupled with other power generation systems such as gas turbine and reciprocating engine or other type of fuel cell. The hybrid arrangement allows the rejected thermal energy and residual fuel from a high-temperature fuel cell used to drive a gas turbine. Hybrid systems can maintain extremely low emissions while achieving the fuel efficiency far beyond the reach of one technology alone.

5.2.4. Advantages and Disadvantages of Fuel Cells

Advantages of fuel cells:

1. Fuel cells eliminate pollution caused by burning fossil fuels; the only by-product is water.
2. Fuel cells do not need conventional fuels such as oil or gas and can therefore eliminate economic dependence on politically unstable countries.
3. Fuel cells can achieve high efficiencies in energy conversion terms, especially where the waste heat from the cell is utilised in cogeneration situation.
4. Installation of smaller stationary fuel cells leads to a more stabilized and decentralized power grid.
5. Fuel cells, due to their nature of operation, are extremely quiet in operation. This allows fuel cells to be used in residential or built-up areas where the noise pollution is undesirable.
6. The maintenance of fuel cells is simple since there are few moving parts in the system.
7. The absence of combustion and moving parts means that fuel cell technologies are expected to provide much improved reliability over traditional combustion engines.
8. Use a variety of fuels, renewable energy and clean fossil fuels.
9. Fuel cells can be responsive to changing electrical loads.
10. Fuel cells provide high quality DC power.
11. Operating times are much longer than with batteries, since doubling the operating time needs only doubling the amount of fuel and not the doubling of the capacity of the unit itself.

Disadvantages of fuel cells:

1. Initial cost is high. Fuel cells are currently very expensive to produce, since most units are hand-made.
2. Service life is low.

3. Operation requires repleisable fuel supply.
4. Some fuel cells use expensive materials.
5. Fuelling fuel cells is still a major problem since the production, transportation, distribution and storage of hydrogen is difficult.
6. Reforming hydrocarbons via reformer to produce hydrogen is technically challenging and not clearly environmentally friendly.
7. The technology is not yet fully developed and few products are available.
8. The refueling and the starting time of fuel cell vehicles are longer and the driving range is shorter than in a "normal" car.

5.2.5. Applications of Fuel Cells

Once fuel cells of reasonably low cost and long life become available, they will be preferred in large number of applications. Some of the potential applications are listed here:

1. Fuel cells have the potential to replace the internal combustion engine in vehicles. They can be used in transportation applications such as powering automobiles, submarines, spacecraft and other vehicles.
2. Fuel cells can be effectively used for load leveling. When the generation exceeds the demand, excess generated energy can be converted and stored as hydrogen by electrolysis of water. During peak load, when the demand exceeds the generation, the stored hydrogen would be used in fuel cells to meet additional demand.
3. Fuel cells using gasified coal as fuel can be used in central power stations. The efficiency of such plant would be higher due to direct energy conversion. Thus coal can be used more efficiently with reduced emissions.
4. Fuel cells are also suitable for dispersed generation. By locating the fuel cell near load centre, transmission and distribution cost would be reduced. They can also be used for stationary applications such as providing electricity to power homes and business.
5. Many portable devices can be powered by fuel cells such as laptop computers, mobile phones and other low power applications.
6. To meet the demand of isolated sites such as construction sites, military camps and small village community or hamlet, fuel cells are more suitable than diesel generator.
7. For remote and inaccessible locations fuel cells can be used unattended for a long period.

8. Emergency / auxiliary supply to critical loads such as hospitals, laboratory etc. can be better met using fuel cells as compared to diesel generator.

5.3. GEOTHERMAL ENERGY

The thermal energy contained in the interior of the earth is called *geothermal energy*. Volcanoes, geysers and hot springs are visible evidences of the large amount of heat lying in earth's interior. The geothermal energy is enormous and last for several millions of years. Hence, it is called renewable energy.

5.3.1. Basics of Geothermal Energy

Energy present as heat (*i.e.* Thermal energy) in the earth's crust. The more readily accessible heat is in the upper most (10 *km*) or the crust constitutes a potentially useful and almost inexhaustible source of energy. This heat is apparent from the increase in temperature of the earth with increase in depth below the surface. Although higher and lower temperatures occur, the average temperature at a depth of 10 *km* is 200°C.

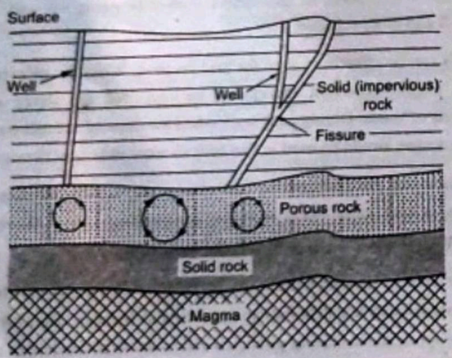


Figure 5.11 Typical geothermal field

The molten rock within the earth is called *magma*. It is commonly present at a depth of about 32 *km* on an average with the temperature of about 3000°C. In some places, anomalous geologic conditions cause the magma to be pushed up towards the surface where the heat of the magma is being conducted upward through an overlying rock layer. Figure 5.11 shows a typical geothermal field.

The hot magma near the bottom surface solidifies into igneous solid rock (B). The heat of magma is conducted upward to this igneous rock. Ground water which finds its way down to this rock through cracks is heated by the heat of rock or by mixing with hot gases and steam emerging from magma. The heat is transported from hot rocks by circulating movement. Then the heated water convectively rises upward into a porous and permeable reservoir above the solid rock. The reservoir is capped by a layer of impervious solid rock which traps hot water in the reservoir. The solid rock has fissures which act as vents of the giant underground boiler. The hot water or steam often escapes through fissures in the rock thereby forming hot springs and geysers fumaroles. To utilize the geothermal energy, wells are drilled either to intercept a fissure or more commonly into the formation containing water.

At any place on the planet, there is a normal temperature gradient of 30°C per *km* dug into the earth. Therefore, if 20,000 *feet* is dug on the earth, the temperature will be about 190°C above the surface temperature. This difference will be enough to produce electricity. However, no useful and economical technology has been developed to extract this large source of energy.

5.3.2. Geothermal Energy Resources

Basic kinds of geothermal sources are as follows:

1. Hydrothermal
   (a) Vapour dominated or dry steam fields
   (b) Liquid dominated system
   (c) Hot-water fields
2. Geopressured
3. Hot dry rock or Petrothermal
4. Magma resources
5. Volcanoes.

1. *Hydrothermal sources*:

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

2. Geopressured reservoirs:

Geothermal resource is hot water or brine trapped underground at the depth of about 2.4 *km* to 9.1 *km* with temperature at about 150°C. It is stored under pressure of about 1000 *bar* from the weight of overlying rock. This type of resource can be used for both heat and natural gas. Although it has a 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 combination of methane to generate electricity.

3. Hot dry rock or Petrothermal:

Hot dry rock or petrothermal resources consist of high-temperature rocks ranging from 90°C to 650°C. The rocks can be fractured and water may be circulated through the rocks to extract thermal energy. It is similar to Normal Geothermal Gradient (NGG) but the gradient is 40°C/*km* dug underground.

4. Molten magma:

Geothermal energy in the form of active volcanic vents occurs in many parts of the world. There is molten rock or magma present in these volcanic vents at temperature ranging from 700°C to 1600°C. Magma chambers have got huge got huge thermal energy compared to other geothermal resources. However, extracting thermal energy from volcanic vents is difficult. No technology exists to tap into heat reserves stored in magma.

Magma may be present at shallow depth at certain places. The heat can be easily extracted at these places.

5.3.3. Types of Wells

(i) Temperature gradient (TG) wells:

First wells are drilled and used to delineate the heat anomaly and to establish the geothermal gradient. It is not capable of being produced. TG wells are shallow which are less than 500 *m*. Mostly, it is often 150 *m* or less. Wells are drilled with light truck-mounted rotary or diamond core rigs.

First, a surface hole is drilled for small diameter. Blow Out Preventer (BOP) is not used during drilling. Surface casing is cemented or a conductor is driven. Small diameter tubing is run back to surface. Then, driven surface conductor is pulled. Also, cement is pumped through tubing back to surface and a wiper plug is pumped to displace cement in tubing. A valve is

installed to give an access to the tubing for survey tools. Tubing is filled with water with the top 10 *m* filled with vegetable oil or antifreeze agents.

(ii) Stratigraphic or Slim wells:

It is larger diameter than TG wells. It is normally drilled into the reservoir. Drilled is carried out using BOP equipment with light-medium range oilfield rigs. It is drilled during the intermediate exploration phase to establish resource viability. A conductor is cemented in place. Surface hole is drilled. Surface casing is set and cemented back to surface. A temporary wellhead is installed along with BOP equipment. An intermediate hole is drilled. Geophysical logs are run (SP, Gamma and Resistivity) and casing is set and cemented back to surface. The permanent wellhead is installed with a master wellhead valve. An open (uncased) hole is drilled. Geophysical logs are run (often including imaging logs) and a perforated liner is set on bottom. Finally, a flange with a small valve is installed on the wellhead for providing access to the wellbore for future logging.

(iii) Commercial grade wells:

Two primary categories of commercial wells are:

(i) Production well and

(ii) Injection well

It is designed to be very robust and long-lived.

5.3.4. Methods of Harnessing Geothermal Energy

Geothermal electricity can be harnessed mainly in many ways by using indirect methods which are discussed below:

5.3.4.1. Vapour dominated or dry steam geothermal power plant

Figure 5.12 and Figure 5.13 show a schematic of a vapour-dominated geothermal power system. Dry steam from wells is collected, filtered to remove abrasive particles and passed through turbines which drive electric generators in the usual manner. The essential difference between this system and a conventional steam turbine-generator system using fossil fuel is that the geothermal steam is supplied at a much lower temperature and pressure. The dry steam from the well (1) at perhaps 200°C is used. It is nearly saturated at the bottom of the well and it may have a shut off pressure about 35 *bar*.

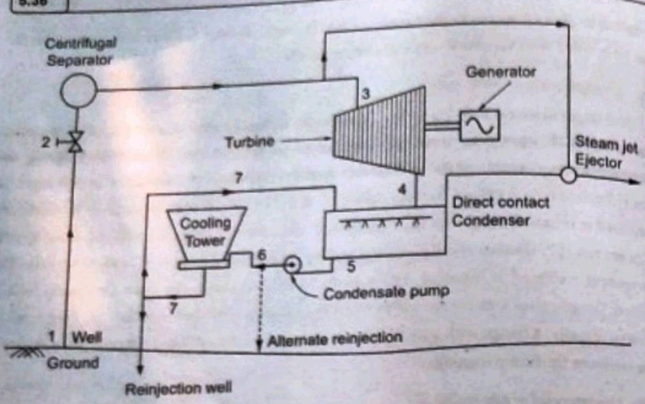


Figure 5.12 Vapour-dominated geothermal power plant

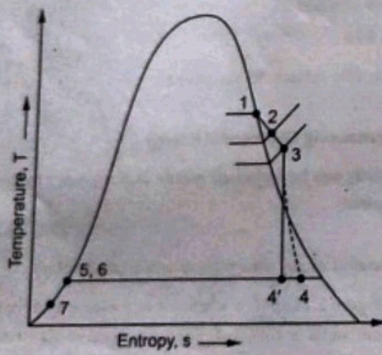


Figure 5.13 Vapour dominated system on Ts diagram

The pressure drop through the expansion valve (2) slightly superheats the steam. The steam after expansion in the turbine (3) enters the condenser at 4. The condensation of steam continuously increases the volume of cooling water. A part of this heat is lost by evaporation

in the cooling tower (6) and the remaining heat is injected deep into the ground (7) for disposal. The turbine exhaust steam at (4) mixes with the cooling water (7) coming from cooling tower. The mixture of cooling water coming from the cooling tower and turbine exhaust is saturated vapour at (5) and it is pumped to the cooling tower (6).

5.3.4.2. Liquid-dominated systems

In the liquid dominated reservoir, the water temperature is above the normal boiling point 100°C. However, it does not boil but it remains in liquid state because the water in the reservoir is under pressure. When the water comes to the surface, the pressure is reduced, then rapid boiling is occurred and the liquid water "flashes" into a mixture of hot water and steam. The steam can be separated and used to generate electric power or to provide space and process heat or it may be distilled to yield the purified water. For liquid-dominated systems, three methods which will be covered are as follows:

(a) Flashed-steam system

(b) Binary-cycle system

(c) Total flow system.

(i) Flashed-steam system:

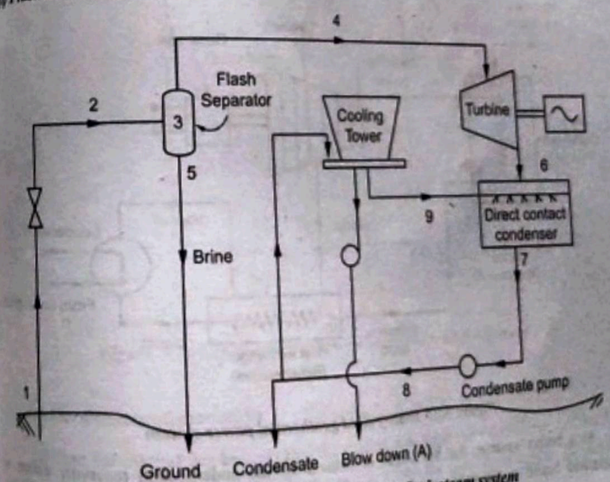


Figure 5.14 Liquid dominated single-flash steam system

The flashed-steam system is shown in Figure 5.14. Water from the under-ground reservoir at point (1) reaches the wellhead at point (2) at a lower pressure. It is throttled further in a flash separator resulting still low but it is slightly with higher quality at (3). This mixture is now separated into dry saturated steam at (4) and saturated brine at (5). Later, it is reinjected into the ground. The dry steam with a small friction of the total well discharge is expanded in a turbine to (6) and it is mixed with cooling water in a direct-contact condenser with the mixture at (7). It is then entered into a cooling tower similar to a vapour-dominated system. The condensate after the cooling water is recirculated to the condenser and reinjected into the ground. The power generation from such system can be made more economical by associating a chemical industry with the power plant to make use of the brine and gaseous effluent.

(ii) Liquid dominated binary cycle systems:

Liquid dominated systems are shown in Figure 5.15. In order to isolate the turbine from corrosive or erosive materials to accommodate higher concentration of non-condensable gases, the binary concept is considered. In the binary system, an organic fluid with a low boiling point such as isobutene and Freon-12 is usually recommended. Ammonia and propane may also be used. The working fluid is operated at higher pressure corresponding to the same water and heat-sink temperature.

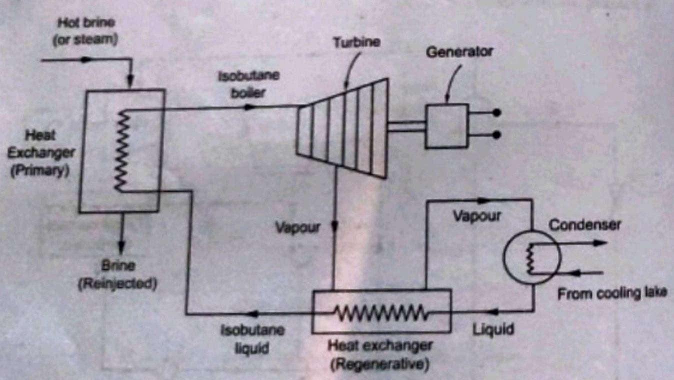


Figure 5.15 Binary fluid geothermal power system

In a binary system, the hot water or brine from the underground reservoir either as unflashed liquid or as steam producing by flashing is circulated through a primary heat

exchanger. In the heat exchanger, the hot brine transfers its heat to the organic fluid thus converting it to a superheated vapour. The vapour drives the turbine generator. The exhaust vapour from turbine is cooled in the regenerative heat exchanger and then it is condensed using condenser. The condenser is cooled by water from a natural source. The condensed liquid organic fluid is returned to the primary heat exchanger by a regenerative heat exchanger.

(c) Total flow system:

Working principle of a total flow concept is shown in Figure 5.16. The hot brine from geothermal well at (1) is throttled to (2) where it becomes a two-phase mixture of low quality. The two phases at this point are not separated but the full flow is expanded to (3) and then it is condensed to (4). Then, the brine is reinjected into the ground at (5). The other characteristic of total flow concept system is that it requires the use of a mixed phase expander powered by a two-phase mixture of low quality whereas the flashed steam system and vapour dominated systems rely on axial flow multistage steam turbines. The requirement of mixed phase expanders is to overcome losses associated with the impingement of liquid droplets on blades. They must also be able to withstand corrosive and erosive effects of significant quantities of dissolved solids in the brine.

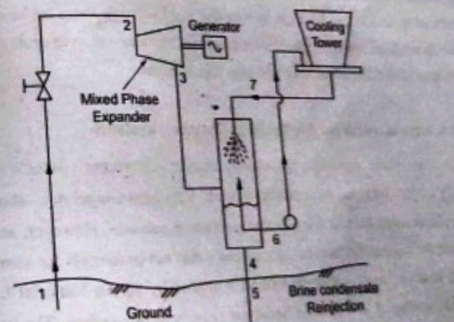


Figure 5.16 Schematic of a liquid-dominated total flow concept

5.3.4.3. Geopressured resources

Drilling for oil and gas has revealed the existence of reservoirs containing salt water at moderately high temperature and high pressure in a belt for 1200 m in length. Because of abnormally high pressures of water up to 1350 *atm* in the deepest layers, the reservoirs are referred as *geopressured*. A special feature of geopressured water (or brine) is their content of methane (natural gas). The energy value of the brine thus depends on their temperature. The solubility of methane in water at normal pressure is quite low but it is increased at high pressure of the geothermal reservoirs. Usually, the gas content of geopressured brine is 1.9 m^3 to 3.8 m^3.

5.3.4.4. Hot dry rock systems

Hot Dry Rock (HDR) system is a heated geological formation formed in the same way as hydrothermal resources but containing no water as the aquifers or fractures required to conduct water to the surface are not present. HDR reservoirs are instead man-made reservoirs in rocks that are artificially fractured and thus, any convenient volume of hot dry rock in the Earth's crust at accessible depth can become an artificial reservoir.

A pair of wells is drilled into the rock, terminating a hundred meters apart. Water is circulated down the injection well and through the HDR reservoir which acts as a heat exchanger. The fluid then returns to the surface through the production well and thus, transfers the heat to the surface as steam or hot water. The steam is ultimately used to generate electricity. Artificial reservoirs can be made by hydraulically fracturing these rocks and then circulating water through cracks. HDR systems are much more common than hydrothermal reservoirs and more accessible. Therefore, their potential is quite high.

5.3.4.5. Magma resources (Molten Rock-Chamber) systems

In some cases, especially the vicinity of relatively recent volcanic activity molten or partially molten rock occurs at moderate depth. Very high temperature above 650°C and the large volume make magma a substantial geothermal resource. However, an extraction of the heat from the molten rock will be difficult and it may not be feasible for some time. A concept of using heat exchange within the magma is studied by Sandia National Laboratories. Heat would be transferred to a suitable liquid and brought to the surface. The hot liquid could be used to produce a working fluid possibly steam to operate a turbine and electric generator. The liquid is then recirculated through the heat exchanger in the magma.

5.3.4.6. Hybrid (Geothermal Fossil Fuel) systems

The concept of hybrid geothermal fossil fuel systems utilizes relatively low temperature heat of geothermal sources in the low temperature end of a conventional cycle and high

temperature heat from fossil-fuel combustion in the high temperature end of the same cycle. The concept which combines the high efficiency of high temperature cycle with a natural source of heat for the part of heat addition reduces the consumption of the expensive and non-renewable fossil fuel.

The arrangements for hybrid plants are as follows:

1. Fossil superheat and 2. Geothermal preheat.

5.3.4.6.1. Fossil-superheat hybrid systems

In this system, the vapour dominated steam or vapour obtained from a flash separator in a high-temperature liquid-dominated system is superheated in a fossil-fired superheater. The schematic arrangement of fossil-superheat hybrid system cycle is shown in Figure 5.17. The cycle consists of a double flash geothermal steam system.

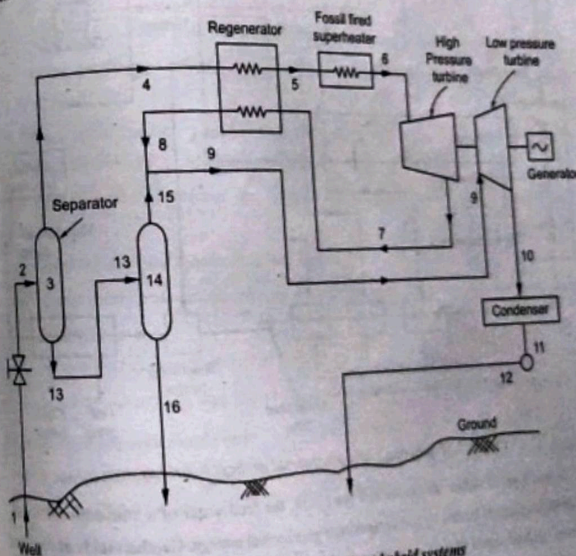


Figure 5.17 Fossil-superheat hybrid systems

From well (1), the geothermal source is collected and passed to separator (3). Steam produced at (4) in the first-stage flash separator is preheated from (4) to (5) in a regenerator by exhaust steam from high-pressure turbine at (7). It is then superheated by a fossil fuel-fired superheater to (6) and it expands in the high-pressure turbine to (7) at a pressure near the second stage steam separator. It then enters the regenerator and it leaves at (8) where it is mixed with the low-pressure steam produced in the second-stage flash separator at (15) and it produces steam at (9) which expands in the low-pressure turbine to (10). The condensate at (11) is pumped and reinjected into the ground at (12). The spent brine from the second stage evaporator is also reinjected into the ground at (16).

5.3.4.6.2. Geothermal-preheat hybrid system

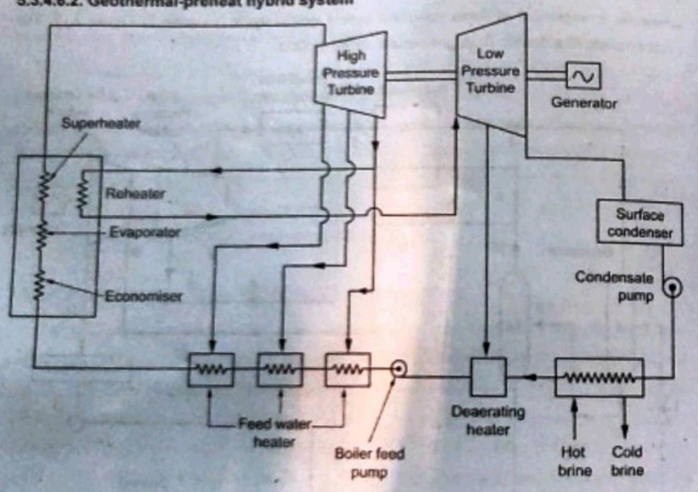


Figure 5.18 Schematic of a geothermal preheat hybrid system

In this type of system as shown in Figure 5.18, the feed water of a conventional fossil-fueled steam plant is heated by low temperature geothermal energy. Geothermal heat replaces some or all feed water heaters depending on its temperature. Geothermal heat heats the feed water throughout low temperature and prior to an open-type deaerating heater. It is followed by a boiler feed pump and three closed type feed water heaters with drains cascaded backward.

...received heat from the steam bleeds from high-pressure stage of the turbine. No steam is ...d from the low pressure because the geothermal brine fulfills this function.

5.3.5. Advantages, Disadvantages and Applications of Geothermal Energy

Advantages of geothermal energy:

1. It is versatile in its use and reliable source of energy.
2. It is cheaper compared to energies obtained from other sources both zero fuels and fossil fuels.
3. It delivers a greater amount of net energy from its system than other alternative or conventional systems.
4. It has the highest annual load factor of 85% to 90% compared to 45% to 50% for fossil fuel plants.
5. It leads a minimum pollution compared to other conventional energy sources.
6. Using geothermal energy directly for heating applications can be upto 70% more efficient.
7. Once built, geothermal power station operating costs are small making geothermal generated electricity much cheaper.
8. Ground based geothermal heat pumps for heating and cooling can be used almost anywhere.
9. Geothermal plants require little land area.
10. Using geothermal energy directly for heating applications can be upto 70% more efficient.
11. Its availability is independent of weather.
12. It has an inherent storage feature and hence, no extra storage systems are necessary.

Disadvantages of geothermal energy:

1. Overall efficiency for power production is low about 15% when compared to 35-40% for fossil fuel plants.
2. The steam and hot water gushing out of the earth may contain H_2S, CO_2, NH_3 and radon gas, *etc*. These gases are to be removed by chemical action before they are discharged.
3. Drilling operation is noisy.

4. Large area is required for the exploitation of geo-thermal energy as much diffused.
5. Continuous extraction of heated ground water may lead to subsidence of land.
6. Corrosive and abrasive geothermal fluid reduces the life of plants.
7. Thermal energy cannot be distributed easily over long distance (longer than 30 *km*).
8. Initial capital and installation costs are high.

5.3.6. Applications of Geothermal Energy

1. It is used in generating electric power.
2. It is used in industrial process heat.
3. It is used in space heating for various kinds of buildings.
4. It is used in agricultural and related applications.

5.3.6.1. Direct use of geothermal energy

It is more appropriate for sources below 150°*C*. It is used for:

(i) Space heating
(ii) Air conditioning
(iii) Industrial processes
(iv) Drying
(v) Greenhouses
(vi) Aquaculture
(vii) Hot water
(viii) Resorts and pools
(ix) Melting snow.

Working principle of direct usage:

(i) Direct sources function by sending water down a well to be heated by the Earth's warmth.
(ii) Then a heat pump is used to take the heat from the underground water to the substance that heats the house as shown in Figure 5.19.
(iii) Then the cold water is injected back into the Earth.

Ground heat collectors:

This system uses horizontal loops filled with circulating water at a depth of 80 cm to 160 underground.

Borehole heat exchange:

This type uses one or two underground vertical loops that extend 150 m below the surface.

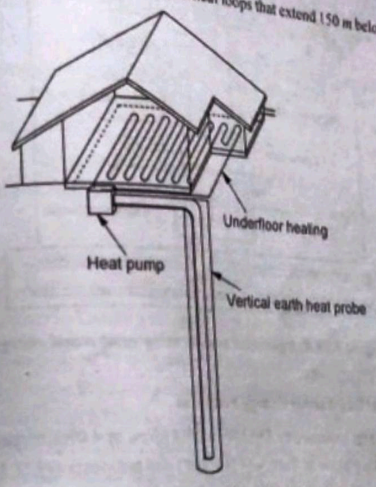


Figure 5.19 Direct use of geothermal energy

5.3.6.2. Refrigeration system using geothermal energy

It consists of evaporator, reversing valve, expansion valve, receiver, compressor, check valve, fan, hot water condenser and space heat condenser. Both evaporator and condenser are shell and tube heat exchangers. Long pipes buried in the ground carry water to and from a heat exchanger. The refrigerant absorbs heat from or rejects heat to the water. The cold refrigerant from ground loop enters the evaporator. Here, the temperature of refrigerant increases but the pressure remains same. Then it enters the compressor through where both pressure and temperature increase due to compression. The compressed refrigerant is condensed in the condenser and further expanded through expansion valve. It again enters the evaporator where the refrigerating effect is transferred to the space. This cycle is repeated.

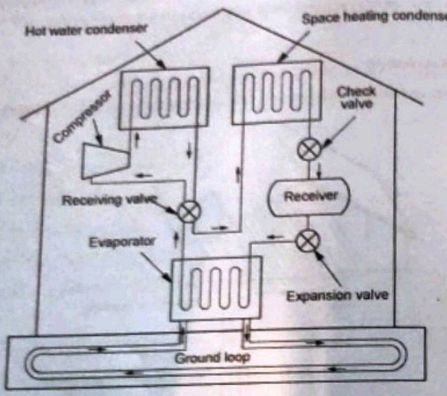


Figure 5.20 Refrigeration system using geothermal energy

5.3.7. International Geothermal Energy Potential

Geothermal energy increased by 539 *MW* in 2018 (grew by 4.0%), to reach 14.6 *GW*. Most of the expansion taking place in Turkey (+219 *MW*) and Indonesia (+137 *MW*), followed by the USA, Mexico and New Zealand. The US has the largest geothermal capacity with 3.8 *GW* (26% of the world total), followed by the Indonesia (1.946 *GW*), Philippines (1.928 *GW*), and Turky (1.283 *GW*).

In overall, the geothermal share of global power generation remains very small (0.3%), but in certain countries it plays a significant role, e.g. Kenya (over 40% of power), Iceland (over 25%), and New Zealand (18%).

5.3.8. Geothermal Energy Potential in India

Geothermal is energy generated from heat stored in the earth or the collection of absorbed heat derived from underground. Immense amounts of thermal energy are generated and stored in the Earth's core, mantle and crust. Geothermal energy is at present contributing about 14.5 *GW* over the world and India's small resources can augment the above percentage.

Geothermal energy is at present contributing about 10,000 *MW* over the world and India's small resources can augment the above percentage. The resource is little used at the moment but the Government has an ambitious plan to more than double the current total installed generating capacity.

Installation of a demonstration geothermal power plant of 300 *kW* capacity at Tattapani in Chhattisgarh is being taken up through National Hydro Power Corporation, India.

The Himalayan belt, Western and Eastern Ghats and Deccan Plateau are only a few of the locations with geothermal energy potential in India estimated to be over 10,600 *MW* according to 2007 research by the Geological Survey of India as per the latest reports of the international geothermal energy organisation.

According to the Ministry of New and Renewable Energy, geothermal resources in India have been mapped and a broad estimate suggests that there could be a 10 *GW* geothermal power potential (MNRE).

The government of Chhattisgarh decided in 2013 to build the country's first geothermal power plant at Tattapani in the Balrampur district. An agreement to establish the first geothermal power project in Ladakh was signed in 2021.

Further studies carried out by the geological survey of India have observed existence of about 340 hot springs in the hot country. These are distributed in seven geothermal provinces which are most productive in a 1500 *km* stretch of the Himalayas. These are also found along the west coast in Gujarat and Rajasthan and along a west south west-east-northeast line running from the west coast to the western border of Bangladesh (known as SONATA). The resource is little used at the moment but the Government has an ambitious plan to more than double the current total installed generating capacity by 2022.

5.3.9. Environmental Impact of Geothermal Energy

The thermal energy contained in the interior of the earth is called *geothermal energy*. Geothermal power plants have relatively little environmental impact. They burn no fuel to create electricity. These plants do create small amount of CO and sulphur compounds but geothermal emissions are smaller than fossil fuel power plants.

The most widely developed type of geothermal power plants known as *hydrothermal plants* are located near geologic *hot spots* where hot molten rock is close to the earth's crust and produces hot water.

In other regions enhanced geothermal systems or *hot dry rock geothermal*, it involves drilling into the earth's surface to reach deeper geothermal resources which can allow broader access to geothermal energy.

The environmental impacts of exploiting geothermal energy depend on the concrete situation. Environmental burdens can result from entrained pollutants (various salts, sulphur compounds, arsenic, and boron) and gases in the geothermal fluids. In modern geothermal facilities, the spent (cooled-down) fluids and their entrained pollutants are pumped back into the ground preferably to a point below the pay zone of the occurrence while the incidental gases are released to the atmosphere.

(i) Water quality and use:

Particularly, the extraction of geothermal fluids in dry-climate regions can negatively influence near-surface groundwater stories and hence, their utilization (potable water, irrigation) causes the groundwater table to recede.

Geothermal power plants have impacts on both water quality and consumption. Hot water is pumped from underground reservoirs. The pumped water contains high levels of sulfur, salt and other minerals. Most geothermal facilities have closed-loop water systems. So, the extracted water is pumped directly back into the geothermal reservoir after it has been used for heat or electricity production. In such systems, the water is contained within steel well casings cemented to the surrounding rock.

Sustained use of a particular geothermal reservoir can lead to gradual and extensive subsidence and frequent consequential damage to railroads, highways, power transmission lines and particularly the pipelines through which the geothermal fluids are pumped from the wells to the power plant or user.

(ii) Air emissions:

In closed-loop systems, the gases removed from the well are not exposed to the atmosphere and they are injected back into the ground after giving up their heat. So, air emissions are minimal. But in the case of open-loop systems, the geothermal fluid emits hydrogen sulfide, carbon dioxide, ammonia, methane and boron. Hydrogen sulfide has a distinctive *rotten egg* smell which is the most common emission.

Hydrogen sulfide changes into sulfur dioxide once released in the atmosphere. It forms the formation of small acidic particulates which is absorbed by bloodstream and cause heart and lung disease. Sulfur dioxide also causes acid rain which damages crops, forests, soils, acidifies lakes and streams.

Also, some geothermal plants also produce small amounts of mercury emissions which should be reduced using mercury filter technology. Scrubbers can reduce air emissions, but they produce a watery sludge composed of the captured materials such as sulfur, vanadium, silica compounds, chlorides, arsenic, mercury, nickel and other heavy metals. This toxic sludge must be disposed of at hazardous waste sites.

(iii) Land use:

The amount of land required by a geothermal plant depends on the properties of the resource reservoir, amount of power capacity, type of energy conversion system, type of cooling system, arrangement of wells and piping systems and substation, and auxiliary building needs. Many geothermal sites are located in remote and sensitive ecological areas to reduce the environmental impacts. Most geothermal facilities focus the risk of re-injection of wastewater back into geothermal reservoirs after the water's heat has been extracted.

(iv) Life-cycle global warming emissions:

In open-loop geothermal systems, 10% of the air emissions are carbon dioxide and smaller amount of methane emissions. They form a more potent global warming gas. In closed-loop systems, these gases are not released into the atmosphere but there are a still some emissions associated with plant construction and surrounding infrastructure.

5.4 OCEAN THERMAL ENERGY CONVERSION (OTEC)

Energy is available from the ocean by

(i) Tapping ocean currents

(ii) Using the ocean as a heat engine

(iii) Tidal energy

(iv) Wave energy.

Rivers, oceans, large lakes and bays are in the form of huge reservoirs considered as renewable energy sources which are useful to generate electrical energy. In the World, the energy available through ocean is around 130×10^6 *MW*. Due to various reasons, only less amount of energy can be economically recovered. 70% of the earth's surface is occupied by salt water. There are five principal oceans as follows:

(i) Indian ocean

(ii) Atlantic ocean

(iii) Antarctic ocean

(iv) Pacific ocean

(v) Arctic ocean.

OTEC is an energy technology that converts solar radiation falling on the ocean surface into electric power. The use of stored thermal energy by solar radiation from oceans was first proposed by a French physicist *d'Arsonval* in 1881. OTEC systems use the ocean's natural thermal gradient. The temperature difference between warm surface water on the upper layer of ocean and cold deep water below 600 *m* is about 20°*C*. An OTEC system can produce a significant amount of power using this thermal gradient. The oceans are vast renewable resources with the potential to help in producing billions of watts of electric power. The cold seawater used in OTEC process is also rich in nutrients and it can be used to culture both marine organisms and plant life near the shore or on land.

The first OTEC plant was built in 1930 in Cuba by George Claude and the plant generated 22 *kW* of electricity. Claude plant is the second plant in 1935 was made off the coast of Brazil and was mounted onto a large transporter tanker.

OTEC cogeneration plants deliver electrical energy and fresh water. The unit size of turbine generators is in the range of 10 *MW* to 50 *MW*. The plant ratings are of 50 *MW* and 100 *MW*. OTEC technologies require high capital cost and are difficult to produce. The reason is that the temperature difference even in the tropical region is less and hence, the efficiency is also less. The theoretical efficiency of OTEC is small (~2%).

5.4.1. Principle of OTEC

Ocean thermal energy exists in the form of temperature difference between warm surface water and cold deep water. The absorption of solar radiation by the sea and ocean causes a moderate temperature difference between upper and lower levels of water. Particularly, the oceans in the tropical region collect and store a large amount of solar energy. This stored heat energy can be converted into work with the help of thermodynamic cycle. It is called *ocean thermal energy conversion*.

OTEC is a very clean form of energy. It has virtually no dangerous pollution risk. OTEC is a method of producing electrical energy from difference in water temperature. The upper surface of the ocean water gets heated up naturally due to solar radiation similar to a solar collector and it is considered as infinite heat storage reservoir. The warmest water is found around the equator with surface water reaching a maximum temperature of 24°*C* to 27°*C* whilst the deep water can reach the temperature close to 0°*C*. The OTEC system uses this change in

temperature of the sea water to run a heat engine which converts the heat energy into mechanical work. For OTEC to work, there is a need of a minimum temperature difference between warm water and cold water of 20°C over a 1000 *m* depth. Systems at 20°C are very efficient but they become more efficient with greater temperature difference.

The OTEC plant should have the following to increase its efficiency.

(i) Large intake of warm water

(ii) Large number of units required to generate large amount of power.

The above-mentioned factors will lead to the requirement of large pipe line, pumps, heat exchanger, large plant size, high cost of installation, high cost for power generation etc.

5.4.2. Setting of OTEC Plants

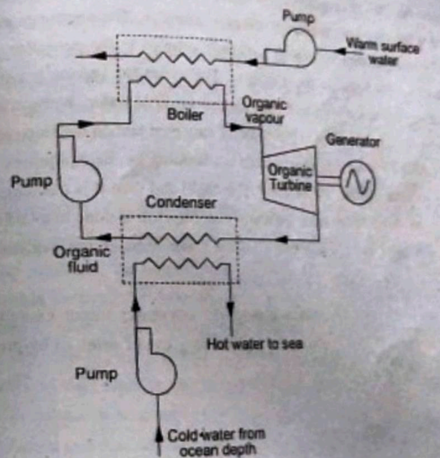


Figure 5.21 OTEC plant

Warm water is collected on the surface of the tropical ocean and pumped by a warm water pump. The water is pumped through the boiler where some of water is used to heat the working fluid. The working fluid may be propane or some similar fluids. If a cooler is used, the working fluid having low boiling point such as ammonia is selected. The propane vapour expands through a turbine which is coupled to a generator to generate electric power. Cold water from the bottom is pumped through condensers where the vapour comes to the liquid state. The fluid is pumped back into the boiler.

Some small fraction of power from the turbine is used to pump water through the system and to power other internal operations but most of them are available as net power. There are two different kinds of OTEC power plants such as land-based plant and floating plant.

5.4.3. Land-based Power Plant

The land-based pilot plant has a building. This building will contain heat exchangers, turbines, generators and controls. It will be connected to the ocean via several pipes.

First, power input is supplied to pumps to start the process. Fluid pump pressurizes and pushes the working fluid to evaporator. Heat addition form hot water is used to evaporate the working fluid within the heat exchanger called *evaporator*. The vapour is expanded in the turbine thereby rotating the shaft which is directly coupled to the generator. Therefore, the electrical energy is produced in the generator. The expanded vapour is condensed in the condenser. The condensation is carried out by supplying cold water. Warm water is collected through a screened enclosure close to the shore. A long pipe laid on the slope collects the cold water. Power and fresh water are generated in the building by the equipment. Used water is first circulated into the marine culture pond (fish farm) and then it is discharged by the third pipe into the ocean, downstream from the warm water inlet. It is done to avoid the re-entering of outflow to the plant since the reuse of warm water reduces the available temperature difference.

A land-based plant costs three times as much per unit power output. One advantage of the land-based power plant is that it makes the process easy use of some of by-products without any expensive transports.

5.4.4. Floating Power Plant

The working principle of floating power plant is similar to the land-based plant but it differs in construction as plant is floating.

5.4.5. Thermodynamic Cycles in OTEC

There are two types of OTEC thermodynamic cycles as follows:

1. Open cycle (Claude cycle, Steam cycle)

2. Closed cycle (Anderson cycle, Vapour cycle)

Both Open and Closed OTEC systems use the temperature difference between warm surface water and deep cold water to create a pressure difference that can be used to generate electricity.

5.4.6. Open Cycle OTEC System

In an open OTEC system, the cold water is used to reduce the pressure in the part of the system so that the warm surface water actually get boiled into a vapour at 80°F. The warm sea water is converted into steam in an evaporator. The steam drives steam-turbine generator to deliver electrical energy. A specially designed steam turbine drives the electrical generator.

The water vapour travels from high-pressure warm side of the system through a turbine to drive a generator and into the low-pressure cold side of the system. Then, the vapour condenses into desalinated water. Steam is condensed in a contact condenser and condensate is discharged into sea by an open cycle OTEC. The big advantage of open system OTEC is that the desalinated water effluent has multiple uses especially drinking water and it can increase the economic efficiency by over 30%.

Working:

In an open cycle OTEC, warm water from ocean surface (at about 26°C) is admitted into the evaporator. The evaporator is maintained at vacuum pressure by means of a vacuum pump. At low vacuum pressures, the boiling point of water reduces and more steam is generated. Steam generated in the evaporator enters into a special steam turbine and the remaining water from evaporator is discharged into the sea. Steam-turbine converts thermal energy into mechanical energy. Steam leaving the evaporator is comparatively at low pressure and high specific volumes as compared to conventional power plants. The steam admitted in steam turbine drives the steam turbine rotor and it is exhausted to the condenser. Exhaust steam from turbine is condensed and discharged in the ocean at 7°C. Cold water from deep sea is admitted into the condenser. The temperature of cold water is about 15°C.

The efficiency can be increased slightly with modified open cycle OTEC system. They are as follows:

(i) Controlled *flash-steam evaporator* is used instead of a conventional type of evaporator

(ii) Contact condenser is replaced by a surface condenser.

(iii) The open cycle OTEC can be used as a cogeneration cycle to produce both electrical power and fresh water.

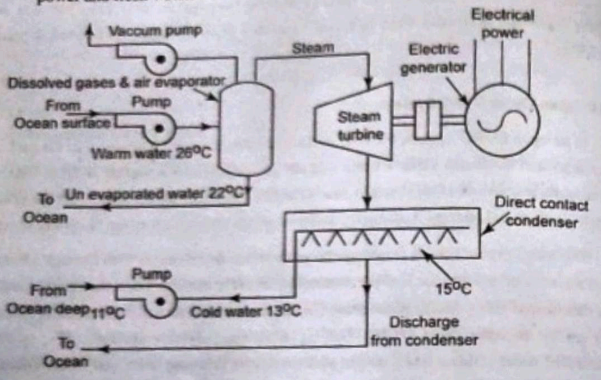


Figure 5.22 Open cycle OTEC power plant

Limitations of open cycle OTEC system:

1. Turbine is physically large.
2. The cost of plant is high.
3. It can allow a very large flow of ocean water in terms of mass and volume.
4. The plant is subjected to ocean storms, high waves, etc.

5.4.7. Closed Cycle OTEC System

In a closed cycle OTEC system rather than boiling water to make steam, one of several refrigerants which have a low boiling point is used. *Ammonia* or *Butane* or *Freon* is used as a refrigerant. The refrigerant boils and it creates a vapour when exposed to the warmth of surface water. The vapour of the working fluid drives a vapour turbine generator to generate electrical energy. Then, the refrigerant condenses and losses the pressure when exposed to cold temperature from deep water.

In a closed cycle OTEC plant, the working fluid is circulated in the cycle comprising of heat exchanger, vapour turbine, surface condenser and liquid vapour pressuriser.

Working:

The working fluid (ammonia, NH_3) is circulated through the closed cycle comprising of the following components.

1. Evaporator
2. Vapour turbine (Turbogenerator)
3. Vapour condenser and
4. Liquid pressurizer.

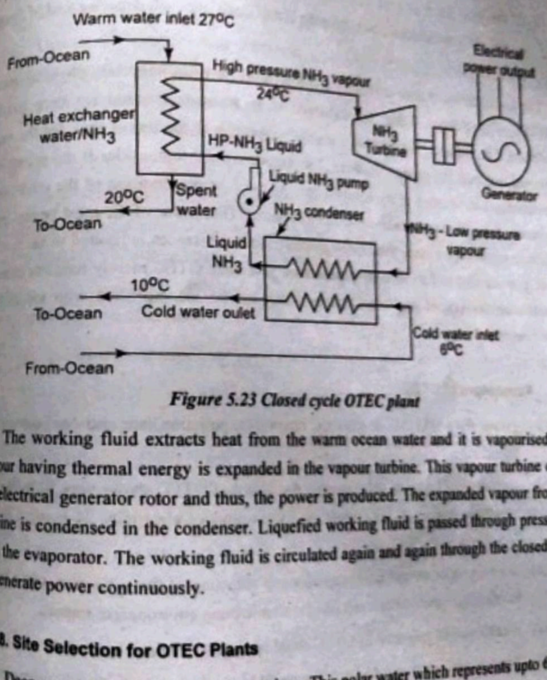


Figure 5.23 Closed cycle OTEC plant

The working fluid extracts heat from the warm ocean water and it is vapourised. The vapour having thermal energy is expanded in the vapour turbine. This vapour turbine drives the electrical generator rotor and thus, the power is produced. The expanded vapour from the turbine is condensed in the condenser. Liquefied working fluid is passed through pressuriser into the evaporator. The working fluid is circulated again and again through the closed cycle to generate power continuously.

5.4.8. Site Selection for OTEC Plants

Deep sea water flows from Polar regions. This polar water which represents upto 60% of all seawater originates mainly from the Arctic for the Atlantic and North Pacific Oceans and from the Antarctic (Weddell Sea) for all other major oceans. A desirable OTEC thermal resource of 20°C requires typical values in the order of 25°C. Globally, regions between latitudes 20°N and 20°S are adequate.

The availability of OTEC thermal resources throughout the World depends on the following factors.

(i) Equatorial water defined as lying between 10°N and 10°S are adequate except for the West Coasts of South America and Southern Africa.

(ii) Tropical water defined as extending from the equatorial region boundary to 20°N and 20°S are adequate except for the West Coasts of South America and of Southern Africa.

The accessibility of deep cold sea water represents the most important physical criterion for OTEC site selection. Once, the existence of an adequate thermal resource has been established. The distance is important from the perspective of the transit time for the vessels that would transport the product to shore. The important point to consider is the preservation of environment in the area of the selected site. As much as preservation of the environment anywhere is bound to have positive effects elsewhere. OTEC is one of the most benign power production technologies since the handling of hazardous substances is limited to the working fluid (e.g. ammonia) and no toxic by-products are generated. OTEC merely requires pumping and returning the various sea water masses which can be accomplished with virtually no adverse impact.

5.4.9. Advantages of OTEC

(i) Power from OTEC is continuous, renewable, pollution free and environmentally friendly.

(ii) Unlike other forms of solar energy, the output of OTEC shows very little daily or seasonal variation. OTEC power plants can produce electricity 24 *hours* a day or 365 *days* a year.

(iii) Drawing of warm and cold sea water and returning of the sea water, close to the thermocline, could be accomplished with minimum environment impact.

(iv) Electric power generated by OTEC could be used to produce hydrogen.

(v) Tropical and sub-tropical island sites could be made free from pollution caused by conventional fuels for electricity generation.

(vi) OTEC system might help in enrichment of fishing grounds due to the nutrients from the unproductive deep waters to the warmer surface waters.

(vii) A floating OTEC plant can generate power even at mid sea and can be used to provide power for off shore mining and processing of manganese nodules.

(viii) Either open or closed system OTEC could be used in either onshore or offshore systems.

5.4.10. Disadvantages of OTEC

(i) Capital investment is very high.

(ii) Seasonal variations and natural calamities affect OTEC performance.

(iii) Due to small temperature difference in between the surface water and deep water, the conversion efficiency is very low about 3-4%.

(iv) Low efficiency of these plants coupled with high capital cost and maintenance cost makes them uneconomical for small plants.

(v) Construction of OTEC plants and laying of pipes in coastal water may cause a localised damage to reefs and near-shore marine ecosystems.

(vi) It needs very large sized turbines due to the use of low pressure of steam having high specific volume in case of open cycle.

5.4.11. Applications of OTEC

OTEC plants are not used only to generate electricity. They are used in the following.

1. Open cycle OTEC plant is used to produce desalinated water which is mainly used for irrigation and human consumption.
2. A closed cycle OTEC plant is used as a chemical treatment plant.
3. The deep sea water can be used in refrigeration and air conditioning systems mainly in offshore Industries. In majority of the air conditioning plant, open cycle OTEC is used. The release of used working fluid will be in the sea itself.
4. The power generated by OTEC plants can be used in hydrogen production through water electrolysis process.

5.5. TIDAL ENERGY

5.5.1. Tidal Power

Tidal energy is a form of hydro energy recurring with every tide. The periodic rise and fall of sea water level which are carried by the action of sun and moon on water of the earth is called "*Tide*". The rise and fall of tidal water is maximum near seashore and river mouths. *Tidal power*, also called *tidal energy*, is a form of hydropower that converts the energy of tides into useful forms of power, mainly electricity. It is the only form of energy whose source is the moon.

The basic principle of operation of the tidal cycle is the difference in water surface elevations at high tide and low tide. This differential head is utilized for operating a hydraulic turbine which is coupled to a generator so that the tidal energy can be converted into electrical energy. The difference in potential energy during high-tide and low-tide is converted into tidal energy.

Tidal energy, in particular, is one of the best available renewable energy sources. In contrast to other clean sources such as wind, solar, geothermal etc., tidal energy can be predicted for centuries ahead from the point of view of time and magnitude. Tidal energy can furnish a significant portion of all such energies which are renewable in nature. There is much interest in the use of tidal energy especially in the development of large-scale tidal power schemes. However, the energy source such as wind and solar energy is distributed over larger area which presents a difficult problem for collecting it.

The power is obtained through the flow of water when filling and emptying partially closed sea basins. As the tide runs into the 'low' basin, it drives turbines and as the tide retreats, again turbines are turned to produce large amount of electricity. Unfortunately, the production of tidal energy involves huge initial cost and there may be a possibility of damage to the local ecology. Such a project could also cause a severe damage to wildlife in the area including birds, shore-life and fish and plants that thrive in the delicate ecosystem.

5.5.2. Tidal Energy Potential

The potential in ocean tides resource is estimated as 550 *billion kWh/year* (120 *GW* power). It is in the developing stage. The major limitation for the development of tidal power station is huge capital investment per *kW* of power generation. There are at present only few operational tidal power plants. The first and biggest 240 *MW* tidal power plant was built in 1996 in France at the mouth of La Rance river on Brittany coast. A 20 *MW* tidal plant is located at Nova Scotia, Canada and a 400 *kW* capacity plant is located at Kislaya Guba, Russia on the Barents Sea. Many sites have been identified in USA, Argentina, Europe, India and China for development of tidal power.

...al plants:

...dia has a long coastline with the estuaries and gulfs where tides are strong enough to ...turbines for electrical power generation. The Gulf of Cambay and the Gulf of Kutch in ...at on the west coast have the maximum tidal range of 11*m* and 8*m* with average tidal ...ge of 6.77*m* and 5.23*m* respectively. The Ganges Delta in the Sundarbans is approximately ...with an average tidal range of 2.97*m*. A detailed project report for a 3 *MW* tidal power plant ...Sunderbans area of West Bengal has been prepared through West Bengal Renewable Energy ...elopment Agency.

India is estimated to have a potential of about 54 *gigawatts* (*GW*) of ocean energy ...uding about 12.4 *GW* of tidal power. However, even after four decades of starting efforts ...harness tidal power. India is estimated to have a potential of around 54 *gigawatts* (*GW*) of ...an energy such as tidal power (12.45 *GW*) and wave power (41.3 *GW*) but it is yet to be of ...ctical use as the Indian government's Ministry of New and Renewable Energy (MNRE) ...ys the estimated potential of tidal and wave power is "purely theoretical and does not ...essarily constitute a practically exploitable potential".

5.5.3. Principle of Tide Generation

Mainly, tides are produced by gravitational attraction of the moon and sun on the water of ...id earth. Nearly, 70% of the tide produces force due to moon and remaining 30% by the sun. So, the moon is the main factor to form tides in the sea. During the tide formation, the surface ...ater is pulled away from earth towards moon and sun due to the gravitational force but at the ...me time, the solid earth is pulled away from the water at the opposite side due to centrifugal ...rce of rotation of earth. Therefore, high tides form in these two areas and low tides are formed ...t intermediate points. Due to the rotation of earth, the position of the solid area changes relative ...o moon thereby forming tides. Thus, a periodic succession of high and low tides is formed. Two high tides and two low tides occur in a lunar day of 24 *hours* and 25 *minutes*.

The lunar day is the apparent day of moon revolution about the earth. The time delay ...tween successive tides is 6 *hours*. High tide occurs at a point directly under the moon. Therefore, high tides are produced during full moon and no moon day of the month. These ...des are called *semi-diurnal tides*. So, the rise and fall of sea water is in sinusoidal wave forms ...own in Figure 5.24.

...nge of tide:

Range is the difference between high and low water levels denoted by *R*.

R = Water elevation at high tide – Water elevation at low tide

The range of tides varies from 4.5 m to 12.4 m. The tide range R is higher for high tides and it is low for lower tides. At the same time, the tide range R is less for high tides and high for low tides called *neap tides*. These tides are formed during first quarter and third quarter Moon days.

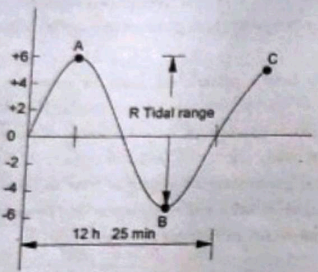


Figure 5.24 Formation of a tide

Spring tides:

If the tide's range is maximum, it is called *spring tide*. These spring tides are called *high tides*. Around no moon and full moon days, the sun, moon and earth form a line. The tidal force due to the sun reinforces the moon. Hence, high tides are produced.

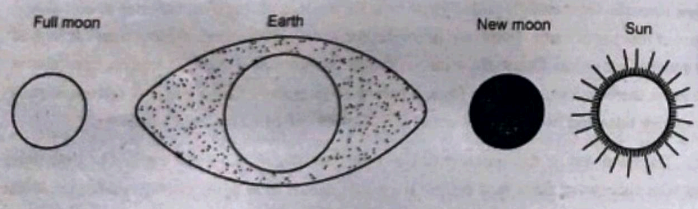


Figure 5.25 Formation of spring tides

Neap tides:

When the Moon is at first quarter or third quarter, the sun and moon are separated by 90° when viewed from the earth and the solar gravitational force partially cancels the moon. At these points in the lunar cycle, the tide's range is minimum called *neap tide*.

Tidal variation in a lunar month:

The tidal variations resulting in spring and neap tides in a lunar month is shown in Figure 5.27.

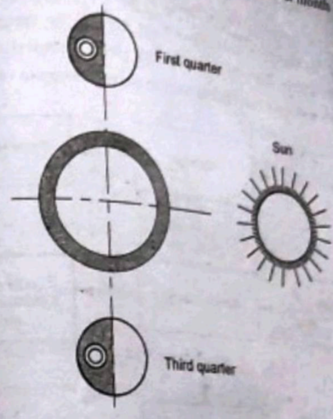


Figure 5.26 Formation of neap tides

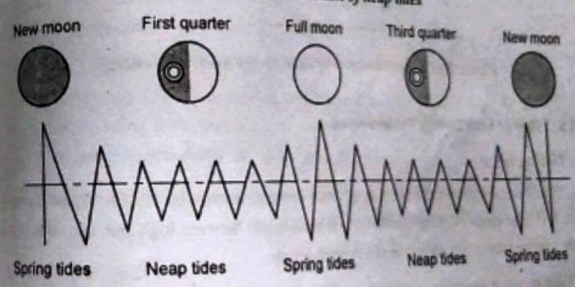


Figure 5.27 Tidal variations in a lunar month

5.5.4. Transformation of Tidal Energy into Electrical Energy

The generation of electricity using tidal power is basically the transformation of tidal power found in tidal motion of water in seas and oceans into electrical energy. It is done using a very basic idea involving the use of a barrage or small dam built at the entrance of a bay where tides are known to reach very high levels of variation. This barrage will trap tidal water behind it creating a difference in water level which will in turn create the potential energy. This potential energy will then be used in creating kinetic energy as doors in the barrage are opened and the water is rushed from the high level to the lower level. This kinetic energy will be converted into rotational kinetic energy that will rotate turbines giving electrical energy. Figure 5.28 shows the process of transformation of tidal energy to electric energy in very simple terms.

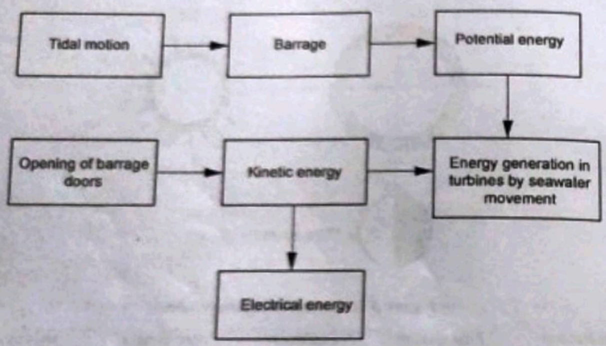


Figure 5.28 Transformation of tidal energy to electric energy

5.5.5. Types of Tidal Energy Technologies

(i) Tidal barrages:

Tidal barrages involve the creation of huge concrete dams with sluices. Tidal barrages make use of the potential energy in the difference in height between high and low tides. Most of the existing tidal power plants use this type of design.

(ii) Tidal stream generators:

Tidal stream generators make use of the kinetic energy of moving water to power turbines. Energy generation is very similar to the principles in wind power generation. Here, water flows across blades which turn a turbine much similar to how wind turns blades for wind power turbines.

(iii) Dynamic tidal power:

This technology is not currently commercial viable but UK, Korea and China have invested heavily in its research. It involves a partial dam which raises the tidal height and several hydropower generators. The difference in height between the head of the dam and low [illegible] coast force water through the generator which is much similar to a traditional hydropower [illegible].

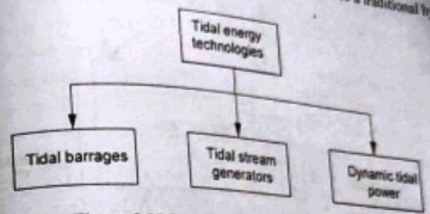


Figure 5.29 Layout of tidal energy technologies

5.5.6. Components of Tidal Barrage Power Plants

The main component of any tidal barrage power plant is the dam or barrage that is built across the mouth of a tidal estuary or inlet. This barrage is fitted with special sluice gates that are opened and closed during the different stages of the tide. It is also fitted with hydraulic turbines that are coupled with electric generators. Figure 5.30 shows the arrangement of various components of in typical tidal barrage power plants.

The tidal energy is produced by trapping water at high tide into the barrage and it is used to drive turbine when it comes back from barrage during low tide. Therefore, the available energy in tides is proportional to the square of amplitude.

The main components of these types of tidal power plant are given below:

(i) Barrage or Dyke or Dam

(ii) Sluice ways

(iii) Embankments

(iv) Power house.

(i) Barrage or dyke or dam:

It makes use of the potential energy possessed by difference in height (or *head*) between high tide and low tide. Barrages are essentially dams across the full width of a tidal estuary and they suffer from high civil infrastructure costs, a worldwide shortage of viable sites and environmental issues. The basic elements of a barrage are caissons, embankments, sluices, turbines and ship locks. Sluices, turbines and ship locks are housed with large concrete blocks. Embankments seal a basin where it is not sealed by caissons. The sluice gates applicable to tidal power are flap gate, vertical rising gate, radial gate and rising sector.

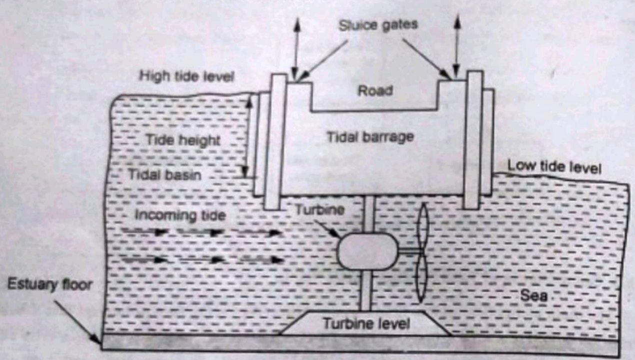


Figure 5.30 Cross section of a typical tidal barrage

(ii) Sluice ways:

Gate controlled devices are called *sluice ways*. They allow water to enter into the basin during high tide and from the basin during low tide. Vertical lift gates and flap gates are mainly used in existing plants.

(iii) Embankments:

They are caissons made out of concrete to prevent water from flowing at certain parts of the barrage and to help in maintenance work and electrical wiring to be connected or used to move equipment or cars over it.

(iv) Power house:

It consists of turbines, electric generators and other auxiliary equipment. Usually, large sizes of turbines are used due to low head availability. Especially, bulb type, rim type and shaft turbines are used. The water with high potential energy is made to run through the turbines to run generators for power production.

5.7. Modes of Operation of Tidal Barrage Power Plants

The various modes of operation of tidal barrage power plants are as follows:

(i) Ebb generation:

It is the simplest and most common form of barrage power generation. In this type, the al basin is filled through sluices during high tide. Then, the sluice gates are closed. The bine gates are kept closed until the sea level filled to create a sufficient head across the rage. The stored water is then made to flow through turbines to sea when its gate is open to nerate power until the head is low. When the generation stops, the gates protecting the bines are closed again and the sluices are opened, turbines are disconnected and the basin is ain filled. The cycle repeats itself. Ebb generation also known as *outflow generation* takes s name because the energy generation occurs as the tide changes the tidal direction.

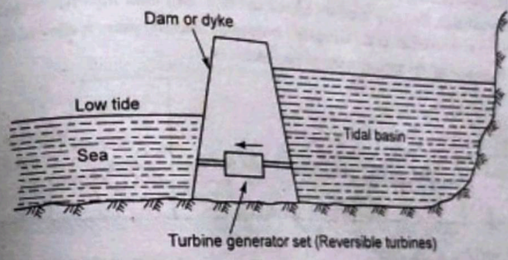


Figure 5.31 Ebb generation

(ii) Flood generation:

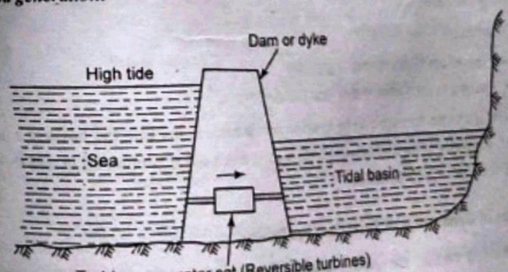
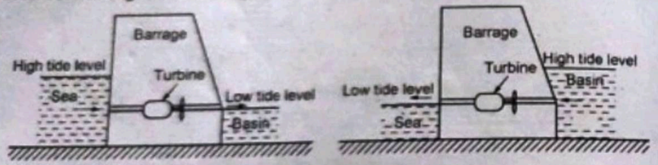


Figure 5.32 Flood generation

In this type, the tidal basin is filled when the sea water is made to flow through the turbine during high tide. This process is just reverse of ebb generation. It is generally much less efficient than ebb generation because the volume contained in the upper half of the basin is greater than the volume of lower half of the basin. Therefore, the available level difference is important for the turbine to produce power between basin side and sea side of the barrage. The available level difference is reduced more quickly than ebb generation. Rivers flowing into the basin may further reduce the energy potential instead of enhancing it as in ebb generation.

(iii) Two-way generation:

In this type, the water is made to flow through turbines for power generation both *during high tides from sea to basin* and *during low tides from basin to sea*. Sluice gates and turbines are closed until near the end of the flood tide when water is allowed to flow through turbines into the basin creating electricity. At the point where the hydrostatic head is insufficient for power generation, the sluice gates are opened and kept open until high tide when they are closed. When the tide outside the barrage has dropped sufficiently, water is allowed to flow out of the basin through the turbines again creating electricity.



(a) During filling *(b) During emptying*

Figure 5.33 Two-way generation

(iv) Pumping and turbining:

The reservoir is filled using:

- ➢ rise of sea water during high tides
- ➢ pumps to pump sea water into the reservoir.

The turbines in the barrage can be used to pump extra water into the basin at a period of low demand, generally at night when demand is low, extra water is pumped in and then power is generated at times of high demand.

5.5.8. Modes of Generation of Tidal Barrage Power

As mentioned earlier, the power generation from tides involves flow between an artificially developed basin and the sea. In order to have a more or less continuous generation,

...sic scheme can be elaborated by having two or more basins. Accordingly, the tidal power ...tion schemes are classified based on the number of basins as follows:

1. Single basin arrangement and
2. Double basin arrangement

...1. Single Basin Arrangement

The single basin schemes have only one basin interacting with sea. The sea and basin are ...ted by a dam or dyke and the flow between them is through sluice gates located ...iently along the dyke as shown in Figure 5.34. The rise and fall of tidal water levels ...ide the potential head. Power generation is intermittent and it is mostly during off-peak ...period on daily load curves. The generation of power can be achieved in a single basin ...gement by either of the following system.

a) Single ebb-cycle system

b) Single tide-cycle system and

c) Double tide-cycle system

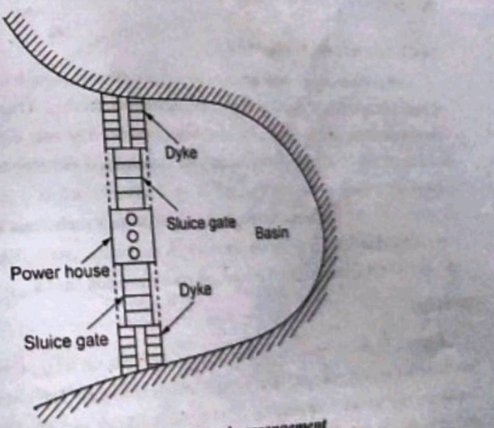


Figure 5.34 Single basin arrangement

Single ebb-cycle system is the one same as '*ebb generation*' as discussed in the earlier ...pic. Similarly, the single tide-cycle system is similar to the '*flood generation*' as discussed in the earlier topic. Double tide-cycle system is the two-way generation system. Figure 5.34

shows a cross section of the general arrangement of single basin tidal power plant (two-way generation). Such plants generally use reversible water turbines to generate on low tide as well as high tide. The turbine-generator units are mounted within the ducts inside the dam or dyke.

When there is incoming tide and sea level and tidal-basin are equal, the turbine conduit is closed. When the sea level reaches sufficient to run turbine, the turbine valves are opened and the sea water is flowing into the basin through the turbine runner and thus, it generates power. The turbine continues to generate power until the tide passes through its high point and it begins to drop. Then, the water head diminishes quickly till it is not enough to supply no-load losses. To gain maximum water level into the basin, a by-pass valve quickly opens and the water comes into the basin. When sea and basin water level are again equal, the valves are closed as well as the turbine conduit. The basin level stays constant while the tide continues to go out. The turbine valves are again opened after getting sufficient water head. The water now flows from basin to the sea thereby generating power.

The actual power generated by tides will be less than the theoretical power due to friction losses, conversion efficiencies of turbine and conversion efficiency of electrical generators. Generally, 25 to 30% power will be lost by losses.

5.5.8.2. Double Basin Arrangement

A single basin plant cannot generate power continuously though it might do so by using a pumped storage plant if the load supply fluctuates considerably. There are two basins but it operates similar to an ebb generation single-basin system. The only difference is a proportion of the electricity is used to pump water into the second basin allowing storage. A double basin scheme can provide power continuously or on demand which is a great advantage. In the simplest double-basin scheme, there must be a dam between each basin and sea and also a dam between basins containing the power house. With two basins, one is filled at high tide and the other one is emptied at low tide. Turbines are placed between basins.

Working:

Figure 5.35 shows a general arrangement of double basin tidal power plant. In this type, two basins are located apart and their water is never exchanged. The turbine is set up between two basins. One basin is intermittently filled by the flood tide and other basin is intermittently drained by the ebb tide. Water flowing from high basin to low basin is through turbines. This flow is controlled. Continuous power is obtained from the plant without waiting for tidal sequence.

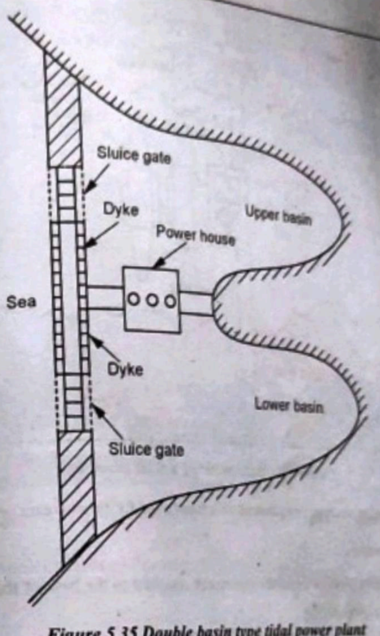


Figure 5.35 Double basin type tidal power plant

5.5.9. Tidal Stream Generators (Non-Barrage Tidal Power Systems)

They make use of kinetic energy of moving water to power turbines in a similar way to windmills which use the moving air. This method is much popular because of low cost and less ecological impact compared to barrages. Tidal stream generators operate during flood and ebb tides. The schematic of a tidal generator is shown in Figure 5.36.

It consists of duct, turbine, hub or rotor, hydraulic pump, hydraulic motor, gear box and generator. Three parts such as a rotor, gearbox and a generator are mounted onto a support structure.

The power taken by turbine is given by

$$P = (\rho C_p A V^3)/2$$

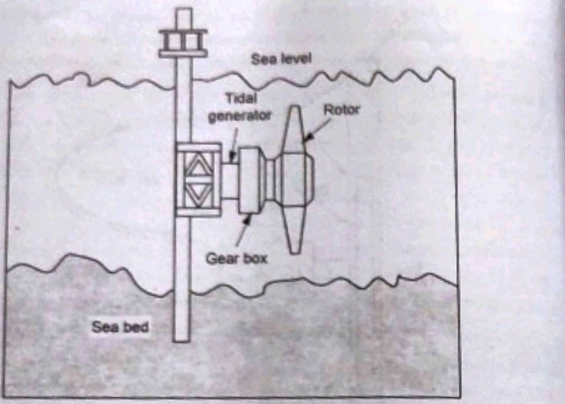


Figure 5.36 Schematic of a tidal generator

There are three main types of support structures used for tidal stream generators:

(a) Gravity structures:

They are massive steel or concrete structures attached to the base of the units to achieve the stability by their own inertia.

(b) Piled structures:

They are pinned to the seabed by one or more steel or concrete piles. The piles are fixed to the seabed by hammering if the ground conditions are sufficiently soft or by pre-drilling, positioning and grouting if the rock is harder.

(c) Floating structures:

They provide a potentially more convincing solution for deep water locations. Tidal stream generators draw more energy from current similar to wind turbines. The density of water is higher which is 800 times than air. It means, a single generator can provide significant power at low tidal flow velocities. The power varies with the density of medium and the cube of velocity. It looks simple in appearance. The speed of water is nearly one-tenth of speed of wind which generates the same power for the same size of turbine system. Since, tidal stream

...rators are an immature technology but a large variety of designs is being experimented. ...re 5.37 illustrates all three types of support structures.

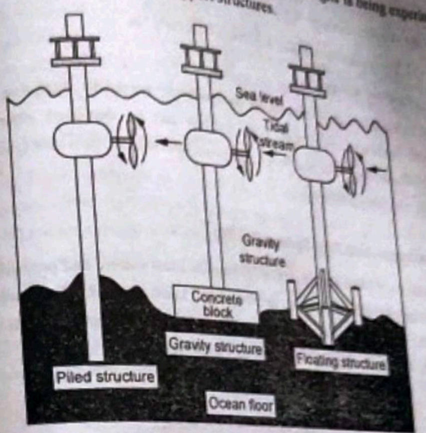


Figure 5.37 Types of tidal stream generator support structures

5.5.10. Solved Anna University Problem on Tidal Energy

AU Problem 5.1

Calculate the average power available for one tidal period if the surface area is 1,50,000 m² and the range of tide is 10.25m. [Anna Univ. (Mech.) May'09]

Solution:

$$\text{Power available, } P = \frac{wQH}{1000} = \frac{\rho g A H}{1000}$$

$$= \frac{1000 \times 9.81 \times 150000 \times 10.25}{1000} = 15.083 MW \text{ Ans.}$$

5.5.11. Types of Tidal Stream Generators

Since tidal stream generators are an immature technology, no standard technology has yet emerged as the clear winner. However, a large variety of designs are being experimented with some very close to large scale deployment.

They are major three types of tidal stream generators as follows:

(a) Axial turbines

(b) Vertical and horizontal axis cross flow turbines

(c) Helical turbine.

Axial turbines are close in concept to traditional windmills operating under the sea. Vertical and horizontal axis cross flow turbines can be deployed either vertically or horizontally. Generally, horizontal flow turbines are selected. Vertical axis cross-flow turbines are used with high ebb generation.

5.5.11.1. Horizontal-Axis Tidal Turbine (HATT)

Horizontal-Axis Tidal Turbines (HATTs) are the most mature and promising technology in several companies. Horizontal-axis turbine is also known as *axial-flow turbine*. A HATT basically works on the same principle as a horizontal-axis wind turbine. This type has rotor axis parallel to the tidal currents and employ propeller type rotor.

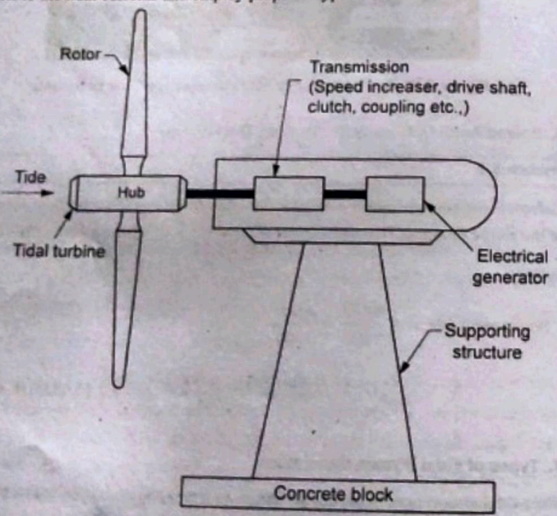


Figure 5.38 Horizontal axis tidal turbine

...harnesses lift force to rotate the rotor. Mainly, Pelton turbine is used as HATTs. HATT ...blades convert the tidal current kinetic energy into the shaft mechanical energy and a ...rator converts this mechanical energy into electricity. Irrespective of configuration used, ...rotor blade is the important component to extract energy from tides. It mainly elaborates ...performance, loads and dynamics of the whole turbine system. Therefore, an efficient blade ...sign is critical to the success of the HATT.

...11.2. Vertical-Axis Tidal Turbine (VATT)

Vertical-Axis Tidal Turbine (VATT) has rotor axis normal to the tidal currents. Darrieus ...bines are most known in vertical type which is shown in Figure 5.39. It has streamlined ...des turning around an axis perpendicular to the flow. The turbine consists of number of ...ved airfoil blades mounted on a vertical rotating shaft or framework. Its blade shape is ...ical structure. The curvature of the blade allows the blade to be stressed only in tension at ...gh rotating speeds. This type uses lift force to rotate the rotor. It has many advantages over ...ATT. In particular, this turbine is suitable for stand-alone power systems on isolated islands ...d in mountainous regions where the power supply using utility grids is very difficult.

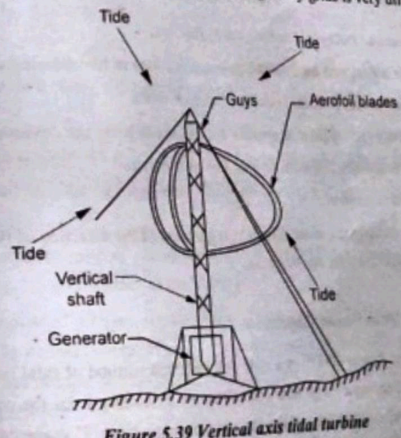


Figure 5.39 Vertical axis tidal turbine

5.5.11.3. Helical Turbine

Tidal energy can be captured efficiently and inexpensively using the helical turbine. Figure 5.40 describes the construction of helical turbine which is self-explanatory.

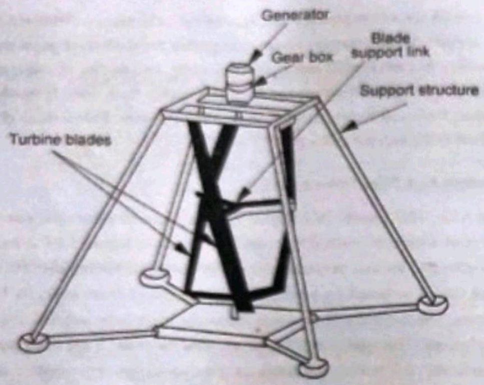


Figure 5.40 Helical turbine

The features of the helical turbine are as follows:

(i) It is designed for hydroelectric applications in free-flowing water.

(ii) It operates in ocean, tidal and river currents.

(iii) It does not require expensive dams that can harm the environment.

(iv) It is self-starting with flow as low as 0.6 *m/s*.

(v) It runs smoothly.

(vi) It rotates in the same direction regardless of the direction of flow thereby making it ideal for tidal applications.

5.5.12. Dynamic Tidal Power Generation

Dynamic Tidal Power (DTP) is a new and untested method of tidal power generation. It would involve in creating a large dam-like structure extending from the coast straight to the ocean with a perpendicular barrier at the far end forming a large 'T' shape called *tidal lagoons*.

They are similar to barrages but they are constructed as self-contained structures not fully across an estuary. They are claimed to incur much low cost and impact overall. Furthermore, they can be configured to generate continuously which is not the case with barrages.

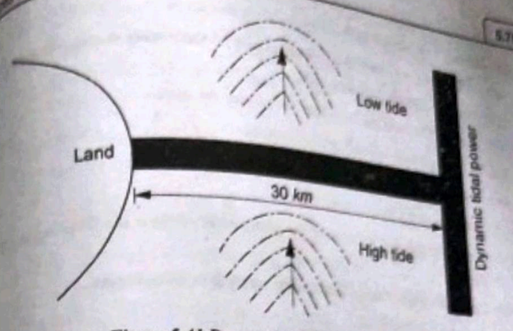


Figure 5.41 Dynamic tidal power generation

DTP dam is a long dam of 30 *km* to 60 *km* which is built perpendicular to the coast straight out into the ocean without enclosing an area. By this, tidal phase ...es are introduced across the dam. There is an interaction between potential and kinetic ... in tidal flows. A single dam can accommodate over 8 *GW* (8000 *MW*) of installed ...ty.

Impact of Tidal Energy on the Environment

(i) Changing the tidal flows by damming a bay or estuary could result the negative impact on aquatic and shoreline ecosystems as well as navigation and recreation.

(ii) Construction of a barrage across a tidal river affects the conditions on both sides of the structure.

(iii) Water movement patterns are affected due to sediment movement which alters the landward and seaward sides of the barrage.

(iv) The movement of marine animals is also affected which leads to a drastic effect on both marine and avian life. For example, fish migration will be significant. It might go inside the turbine and cause the sea water obstruction in and from turbine during power generation.

Site Selection for Tidal Power Plants

The area considered for tidal power plants should have a large tidal range and geographic ... to permit an enclosure of large areas with reasonable short dams. Sluice gates should ... the water to flow in or from the enclosed basin.

The site requirements are as follows:

(i) Short length of dam is to create a basin of reasonable storage. It is possible at a narrow inlet to an estuary of bay.

(ii) It should be near the local location or near the ocean.

(iii) It should be protected from high waves.

(iv) It should not hamper shipping traffic.

(v) The tidal range of ocean is large.

(vi) The geographical features of the plant must enclose the large areas with short dams.

(vii) The sluice gate of dam should allow water to or from basins.

5.5.15. Advantages of Tidal Power Plants

1. Tidal power is a renewable and sustainable energy resource.
2. It is free from pollution as it does not use any fuel.
3. Large area of valuable land is not required.
4. It does not produce any unhealthy waste such as gases and ash.
5. It has unique capacity to meet the peak power demand effectively when it works in combination with thermal or hydroelectric system.
6. It is much superior to hydropower plants as it is totally independent of rain which always fluctuates year to year.
7. It is free from problems of uprooting the people and disturbing the ecology balance.
8. Tidal currents are both predictable and reliable feature which gives them an advantage over both wind and solar systems. Power output can be accurately calculated in advance by allowing for easy integration with existing electricity grids.
9. Tidally driven coastal currents provide an energy density four times greater than air, meaning that a 15 *m* diameter turbine will generate as much energy as a 60 *m* diameter windmill.
10. It reduces country's dependence upon fossil fuels.

5.5.16. Disadvantages or Limitations of Tidal Power Plants

1. Due to variation in tidal range, the output is not uniform.
2. There is a fear of tidal plant components and machinery being corroded due to corrosive sea water.

3. It is difficult to carry out construction in sea.
4. As compared to other sources of energy, the tidal power plant is costly.
5. The power transmission cost is high because the tidal power plants are located away from load centers.
6. The efficiency is affected due to variation in tidal energy.
7. Sedimentation and siltation of basins are serious problems.

5.6. WAVE ENERGY

Wave energy is energy of interchanging potential and kinetic energy in the wave. Among other types of renewable energy, oceans contain energy in the form of waves and tidal currents. Ocean wave energy is an important renewable energy. At the same time, it is regular, periodic and consistent. Ocean wave energy can be either converted into mechanical energy or electrical energy through wave energy conversion plants. Ocean wave energy is needed to be developed in coastal areas. Usually, power extracted from ocean energy is in the range of 10 *kW/m* to 70 *kW/m* with respect to amplitude and wave length.

Ocean waves are created by the interaction of winds with the surface of sea water. Sea water contains both kinetic energy and potential energy. The energy available in the Ocean depends on the wind speed, duration of the wind and distance from which interacts with sea surface water.

Differential warming of the earth causes pressure difference in the atmosphere which generates winds. As winds move across the surface of open bodies of water, they transfer some of their energy to water and create waves.

The amount of energy transferred and the size of wave depend on wind speed, length of time for which the wind blows and distance over which the wind blows or fetch. So, the coastal region which has exposure to the prevailing wind direction and face long expanses of Open Ocean has the greatest wave energy levels.

To extract the stored energy in waves, wave energy conversion devices are used in which two or more bodies move relative to each other while at least one body interacts with waves.

5.6.1. Wave Energy Potential

There are no major development programme carried out till now due to limited availability and uncertainty of power generation capability. The world's first commercial wave energy plant having 0.5 *MW* is located in Isle of Islay and Scotland. Some small prototype devices have been tested. The resource is more concentrated in deep sea where it is difficult to harness and deliver. The estimated potential is 2000 GW. It has been estimated that the total available US wave energy resource is 23 GW which is more than twice as much as Japan and nearly five times as much as Great Britain. It has been estimated that improving technology and economies of scale will allow wave generators to produce electricity at a cost comparable to wind-driven turbines which produce energy at about Rs. 3.5 per kWh.

5.6.2. Estimation of Wave Energy

The total energy obtained from waves is the sum of potential energy and kinetic energy.

1. Potential energy:

The potential energy available in waves is due to the head of sea water above the mean sea level.

Potential energy, $P.E = \frac{1}{4}\rho a^2 \lambda g W$

where

ρ = Density of the sea water (kg/m^3)

a = Amplitude of wave (m)

λ = Wave length (m)

W = Width of the wave (m)

g = Acceleration due to gravity (m/s^2)

2. Kinetic energy:

The energy associated with the movement sea water is called *kinetic energy*. For harmonic motion of waves, average kinetic energy is equal to the potential energy. Therefore,

Kinetic energy, $K.E = \frac{1}{4}\rho a^2 \lambda g W$

Total energy, $E = P.E + K.E$

$$= \frac{1}{4}\rho a^2 \lambda g W + \frac{1}{4}\rho a^2 \lambda g W = \frac{1}{2}\rho a^2 \lambda g W$$

Power, $P = \frac{\text{Energy}}{\text{Time}}$

Wave energy is proportional to wave length times wave height squared ($L \times H^2$) per wave length per unit of crest length. A four-foot (1.2m), ten-second wave striking a coast expends more than 35,000HP per mile of coast.

5.6.3. Concepts of Wave Energy Conversion

The change of water level by tide or wave can move or raise a float in producing linear motion from sinusoidal motion. Water current runs a turbine to produce rotational mechanical energy to drive a pump or generator. Slow rotation speed of approximately one revolution per second to one revolution per minute is less to harm marine life. A turbine reduces energy downstream and could protect shoreline.

5.6.4. Wave Power Devices or Wave Energy Conversion Devices

The technologies developed to generate energy from waves and currents called *hydrokinetic energy conversion devices* are generally categorized as either *Wave Energy Converters* (WECs). WECs utilize the motion of two or more bodies relative to each other. One of these bodies called the displacer is acted on by waves. The second body and the reactor moves in response to the displacer. The available energy in waves can be converted into either mechanical or electrical energy by the various devices. There are three fundamental but very different wave energy devices used in converting wave power into electric power and they are given below,

(a) Wave profile devices:

These are wave energy devices which turn the oscillating height of the ocean's surface into mechanical energy.

(b) Oscillating water columns:

These are wave energy devices which convert the energy of the waves into air pressure.

(c) Wave capture devices:

These are wave energy devices which convert the energy of the waves into potential energy.

(d) Rotating wave devices:

Rotating wave devices capture the kinetic energy of a flow of water such as a tidal stream, ocean current or river as it passes across a rotor.

5.6.4.1. Wave Profile Devices

Actually, waves move horizontally but water moves vertically. Mechanical power is obtained by floats making use of the motion of water up and down. Wave profile devices are a device which floats on or near to the sea surface and it moves in response to the shape of the incident wave.

Most types of wave profile devices float on the surface absorbing the wave energy in all directions by following the movements of waves at or near the sea surface which is similar to a float. If the physical size of the wave profile device is very small compared to the periodic length of the wave, this type of wave energy device is called a *"point absorber"*. If the size of the device is larger or longer than the typical periodic wavelength, it is called a *"linear absorber"* but more commonly they are collectively known as *"wave attenuators"*.

The main difference between the two wave energy devices is how the oscillating system converts the wave energy between the absorber and a reaction point. This energy absorption can be achieved either by a floating body. It oscillates a solid member or oscillating water within a buoys structure itself.

(i) Point absorber:

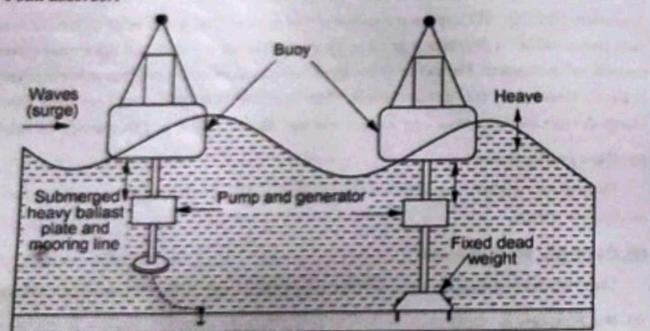


Figure 5.42 Point absorber

The pitching and heaving of the waves causes a relative motion between an absorber and reaction point. The *point absorbers* use a heavy ballast plate suspended below the floating buoy. The buoy is prevented from floating away by a mooring line attached to a sea-floor anchor. This mooring line allows the point absorber to operate offshore in deeper waters. As the buoy bobs up-and-down in the waves, a oscillatory mutual force reaction is generated between freely moving absorber and heavy plate causing a hydraulic pump in between to rotate a generator producing electricity. The middle wave energy device operates in a similar manner

to the previous floating buoy device. The difference this time is that the freely heaving buoy reacts against a fixed reaction point such as a fixed dead-weight on the ocean floor. As this type of point absorber is bottom mounted, it is operated in shallower near shore locations.

(ii) Linear absorber (Wave attenuator):

The *linear absorber (wave attenuator)* floats on the surface of the water. It is also known as *heave-surge devices*. It is tied to the ocean floor so that it can swing perpendicularly towards the incoming waves. As the waves pass along the length of this snake such as wave energy device, they cause the long cylindrical body to sag downwards into the troughs of the waves and arch upwards when the waves crest is passing. Connecting joints along the body of the device flex in the waves exerting a great deal of force which is used to power a hydraulic ram at each joint. The hydraulic ram drives oil through a hydraulic motor which drives a generator to produce electricity.

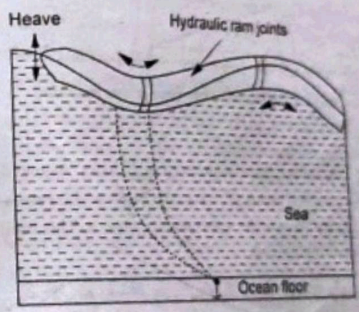


Figure 5.43 Linear absorber

(iii) Dolphin-type wave-power machine:

The wave generator has four components such as dolphin, float, connecting rod and two electrical generators. The float is connected with dolphin by a connecting rod shown in Figure 5.44. The float has two motions. One motion is for rolling motion and revolving movements which means float can roll about its fulcrum with the connecting rod. The other motion is for vertical oscillatory motion about the connecting rod fulcrum. These movements of float during wave movements are magnified and converted into rotary motion by gears. The two electrical generators are driven by rotary motion of gears.

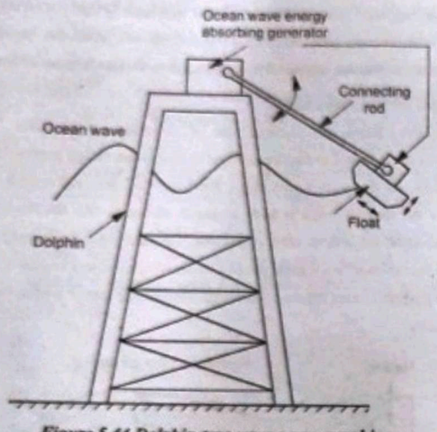


Figure 5.44 Dolphin-type wave-power machine

(iv) Nodding duck:

It is also called *Salter's duck*. It is a large cam-shaped "ducks" mounted on a long-floating frame. Ducks oscillate and nod moves relative to the frame which drives hydraulic pumps. Salter "ducks" rock up and down as the wave passes beneath it. This oscillating mechanical energy is converted to electrical energy.

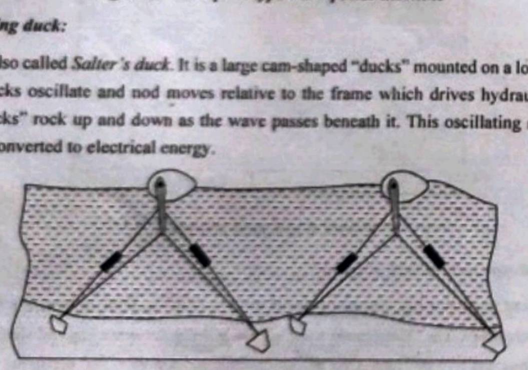


Figure 5.45 Nodding duck

5.6.4.2. Oscillating Water Column

An *Oscillating Water Column* (OWC) has a partially submerged structure which opens to the ocean below the water surface. This structure is called *wave collector*.

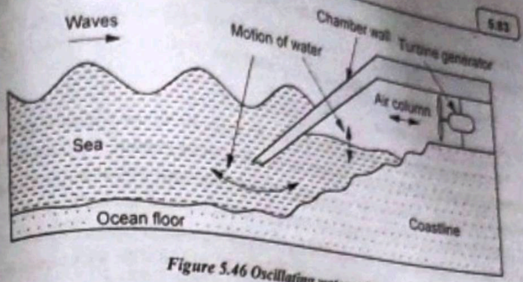


Figure 5.46 Oscillating water column

This design creates a water column in the central chamber of the collector with a volume of air trapped above it. As a wave enters the collector, the surface of the water column rises and compresses the volume of air above it. The compressed air is forced into an aperture at the top of the chamber thereby moving past a turbine. As the wave retreats, the air is drawn back through the turbine due to the reduced pressure in the chamber.

The type of wind turbine generator used in an oscillating water column design is the key element to its conversion efficiency. The air inside the chamber is constantly reversing direction with every up-and-down movement of the sea water producing a sucking and blowing effect through the turbine. Therefore, a special type of turbine called *Wells turbine* is used.

The Wells turbine has the remarkable property of rotating in the same direction regardless of the direction of air flow in the column. The kinetic energy is extracted from the reversing air flow by the Wells turbine and is used to drive an electrical induction generator. The speed of the air flow through the wells turbine can be enhanced by making the cross-sectional area of the wave turbines duct much less than that of the sea column.

5.6.4.3. Wave Power Capture Device

A *Wave Capture Device* also known as a *Overtopping Wave Power Device* is a shoreline to near shore wave energy device that captures the movements of the tides and waves and converts it into potential energy. Wave energy is converted into potential energy by lifting the water up onto a higher level. The overtopping wave energy converter works in much the same way as hydroelectric dam works. Sea water is captured and stored at a height above sea level creating a low head situation which is then drained out through a reaction turbine, usually a Kaplan Turbine.

Some of the wave capture devices are explained here.

(i) Wave overtopping device:

The wave overtopping device uses a ramp design on the device to elevate part of the incoming waves above their natural height. As the waves hit the structure, they flow up a ramp and over the top (hence the name "overtopping") into a raised water impoundment reservoir on the device in order to fill it. The reservoir creates a head of water i.e. a water level higher than that of the surrounding ocean surface which generates the pressure necessary to turn a hydro turbine (low-head Kaplan turbine) as the water flows out the bottom of the wave capture device, back into the sea.

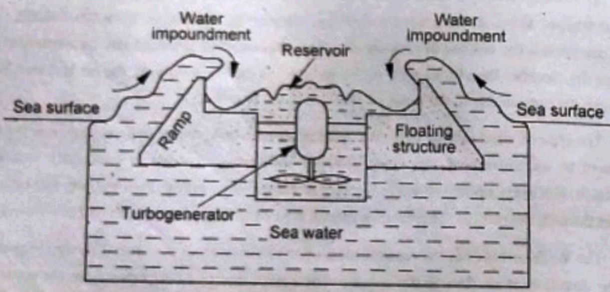


Figure 5.47 Wave overtopping device

(ii) High-level reservoir wave machine:

The special feature of this method is the use of magnification piston or composite piston to produce energy by using waves. This wave machine works based on the principle of reciprocating pumps. Two inlet valves are provided one at the top of the cylinder and the other one at the bottom of the cylinder in order to obtain double action. So, sea water can enter on both sides of the cylinder but not at the same time. The valve provided at the top will open and allow water inside the cylinder during trough period (lowest peak) of waves and the bottom valve will open during crest period of waves thereby compressing the water at the front side. When water is entered the cylinder though top inlet check valve, the water in the rear side will be compressed. The outlet of the cylinder is connected with natural or artificial reservoir which

above wave generator. The wave generator is located near shore line. Then the water in the reservoir is allowed to flow through a turbine which is coupled to a generator. The water leaving the turbine comes back to sea level.

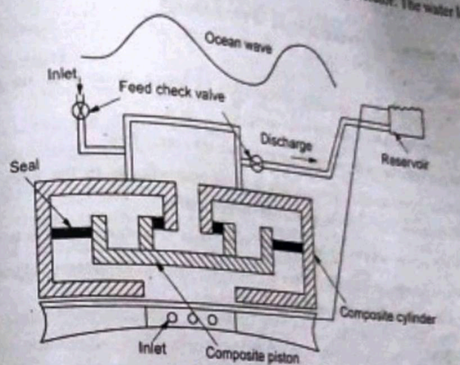


Figure 5.48 High-level reservoir wave machine

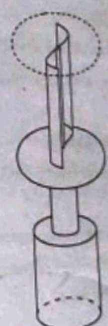


Figure 5.49 Savonius rotor

5.6.4.4. Rotating Wave Devices

Savonius rotor is the mostly used rotating wave device. Savonius rotor (generally used as a windmill) is used here to extract energy from waves of ocean. The rotor is permanently fixed with its horizontal and perpendicular to the direction of wave propagation. Water is allowed to pass through the rotor both forward and back at various time and depth.

5.6.5. Advantages and Disadvantages of Wave Energy

Advantages:

1. The wave energy naturally concentrated by accumulation at all times, space and transported than wind and solar energies.
2. Wave conditions are predictable and hence the energy too.
3. Wave from transportation across a plane perpendicular to the wave propagation direction at a good site is from 10 to100 times large.
4. Wave power devices are not required to use large land masses such as wind or solar.
5. Wave energy conversion devices are pollution free due to releasing of sea water back to sea itself after extracting energy from waves.

Disadvantages:

1. The main disadvantages are difficult maintenance, construction cost, life time and reliability due to wave energy available on the ocean. Also, it needs a greater distance to shore for transporting energy.
2. Wave energy conversion devices must withstand severe peak stresses during storms.
3. Irregularity of wave pattern in amplitude, phase and direction makes it difficult to extract power efficiently.
4. Harnessing the power of it is difficult.
5. Due to the need of large waves for energy production, they are scarcity of accessible sites.
6. Wave energy conversion devices are complicated when it is in use.
7. Economic factors such as capital investment, maintenance cost, repair and replacement costs are unknown and seem to be large.

5.7. HYDROPOWER

Hydropower or *water power* is one of the most established renewable sources for electricity generation from stored water at a given height. Kinetic energy in falling water from a height is converted into mechanical energy by a turbine and then electrical energy by a

generator to meet the energy needs for a variety of tasks. Thus, the power is known as *hydroelectric power*.

The purposes of developing hydro projects are mentioned below:

(i) To meet the power need during peak and off-peak requirements.

(ii) To run of the river.

(iii) To obtain a clean process of power generation.

(iv) To avoid suffering from the limitation of inflation on account of fuel consumption in the long run.

The idea of utilising hydraulic energy to develop mechanical energy has prevailed for more than 2000 years. In water turbine, blades are attached to the shaft and when flowing water passes against the blades of a turbine, the shaft rotates. The coupling of a generator with a turbine shaft finally produces electrical energy.

The amount of electrical energy generated from a water source depends on two aspects, namely (i) the water to fall from a height and (ii) the quantity of water flowing. Height or head of water fall may be natural due to the topographical situation or may be created artificially by means of dams. Once developed, it remains fairly constant. Water flow on the other hand is a direct result of the intensity, distribution and duration of rainfall. Hence, one of the essential components of the hydraulic power generation is the availability of a continuous source of water with a large amount of hydraulic energy.

The present installed capacity as on September 30, 2013 was around 39,788.40 *MW* which means 17.39% of total electricity generation in India. The public sector has a predominant share of 97% in this sector. National Hydroelectric Power Corporation (NHPC), Northeast Electric Power Company (NEEPCO), Satluj Jal Vidyut Nigam (SJVNL), THDC and NTPC-Hydro are few public sector companies developing hydro projects in India.

In north India, Bhakra Beas Management Board (BBMB) has an installed capacity of 2.9 GW and it generates 12,000-14,000 million units per year. BBMB is a major source of peaking power and black start to the northern grid in India.

End of March 2015 India is planning to install capacity of 267.637 *GW*. India became the world's third largest producer of electricity in the year 2013 by surpassing Japan and Russia. India generates 27.25% of total installed capacity power from renewable power plants and 72.75% from non-renewable power plants. 84,000 *MW* hydroelectric power at 60% load factor and 6,780*MW* in terms of installed capacity from small, mini and Micro Hydel schemes have been evaluated. Also, 56 sites for pumped storage schemes with the total installed capacity of

94,000MW have been identified. Hydroelectric energy is mainly used in the form of renewable energy. India stands in 5th place for hydro-electric potential in the world on global scenario.

5.7.1. Advantages of Hydropower

(i) The electricity can be produced at constant rate from hydro power.

(ii) If the electricity does not require, the sluice gates can be shut and stopped electricity generation.

(iii) Dams are designed to last many decades and so they can contribute to the generation of electricity for many years.

(iv) The lake forms behind the dam using water sports and leisure/pleasure activities.

(v) The lake's water can be used for irrigation purposes.

(vi) The energy from stored water in the lake can be stored and it can be released to produce electricity.

(vii) Electricity produced by dam systems does not produce greenhouse gases. They do not pollute the atmosphere.

5.7.2. Disadvantages of Hydropower

(i) Constructing the standard dams is highly expensive.

(ii) It has the restriction to operate the dam for many decades to become profitable due to high cost involved in building dams.

(iii) The flooding area needs to be large to meet the destruction caused by natural calamity.

(iv) People living in villages and towns near dams should be moved during flood period. So, the power generation will be affected.

(v) The building of large dams can cause serious geological damage.

(vi) Although modern planning and design of dams is good, it may lead to deaths and flooding.

(vii) Dams built blocking the progress of a river may lead to water scarcity in river for the normal use.

(viii) Building a large dam alters the natural water table level.

5.7.3. Minihydel Power Plants

Depending on the capacity of the unit, the hydropower plant may be divided into two types such as higher capacity and lower capacity. In early days, higher capacity plants were

developed for producing more power for less cost. But after 1973, small sized hydel plants were given more importance because of increase in oil cost. These plants are also offers many advantages such as environmental friendly operation, operationally flexible, suitable as peak plant as well as standalone plant in isolated remote areas.

Hydropower projects of ratings less than 10 MW are regarded as *small hydropower systems*. These systems can be designed and built by local staff and smaller organisations using smaller components / equipments made locally. It has standard designs for plant components and often not connected to grid and usually meant for local use.

The installed capacity of small hydro in the globe is around 50,000 MW against the estimated potential of 1,80,000MW. India has several rivulets, streams and rivers. It has the world's largest irrigation canal networks with thousands of dams. In India, the estimated potential of small hydro is around 15,000 MW.

The small hydro power stations can help for building the availability of decentralized power. Low head installations can be built everywhere in the mountain region, plains or even at the sea level. With the help of hydro power, pumped irrigation and rural water supply can be accomplished. Rural electrification at house hold level can be done. Saw mills and grinding mills can be run with small hydro-electricity. Reciprocating compressors or screw type compressors can be operated for cold storage or heat pump system.

Advantages of Small Hydro:

Small hydro power is a reliable, mature and proven technology. It is non-polluting and does not involve setting up of large dams or problems of deforestation, submergence and rehabilitation. India has an estimated potential of 10,000 MW.

5.7.4. Classification of Minihydel Power Plants

According to the Central Electricity Authority and Bureau of Indian Standards, the hydro power systems are classified depending on the capacity and available head. The classifications are as follows:

I. Depending on the capacity:

Depending upon the capacity of power generation these plants are classified as follows:

(i) Micro hydel plant ⇒ Producing less than 100 kW power

(ii) Mini hydel plant ⇒ Producing 100 kW to 1 MW power

(iii) Small hydel plant ⇒ Producing 1 MW to 10 MW power.

Mini hydro plants are used in isolated remote areas where the grid does not exist. Typically, it provides power to just one rural industry or one rural community. Mini and small hydro plants sometimes make small contribution to national grid supplies.

2. Depending on the head:

On the basis of heads available, the small hydro power systems are classified into the following types.

(i) Ultra low head plant ⇒ Below 3 *m*

(ii) Low head plant ⇒ Less than 30 *m*

(iii) Medium head ⇒ Between 30 to 75 *m*

(iv) High head ⇒ Above 75*m*.

3. Depending on the usage:

On the basis of usage of power, the small hydro power systems are classified into

(i) Independent scheme

(ii) Subordinate scheme.

In an independent scheme, a stream flow is captured, regulated and developed for power generation only. The low head schemes are not observed to be economical for independent generation. High head or medium head schemes are considered.

In subordinate schemes, the primary objective is irrigation or drinking water and secondary objective is power generation. These schemes are appropriate for those regions where there is extensive network of irrigation canals and water can be stored in the form of reservoir.

4. Depending on the construction:

The small / mini / micro plants are further classified as follows:

(i) Storage plants and

(ii) Run-of-the-river plants.

A storage plant makes use of a dam to stop river flow for building up a reservoir of water behind the dam. The water is then released through turbines when power is needed. The advantage of this type is that rainfall can accumulate during the wet season of the year and then release power during some or all of the drier periods of the year. A run-of-the-river plant does not stop the river flow but instead diverts a part of the flow into a channel and pipe and then through a turbine.

4.1. Essential Components of Minihydel power plants

A typical arrangement of a mini-hydel power station is shown in Figure 5.50. The basic components are as follows:

1. Diversion and intake
2. Desilting chamber or tank
3. Water conductor system
4. Forebay/balancing reservoir
5. Surge tank
6. Penstock
7. Power house comprising of turbine, generator, protection and control system, dewatering system, drainage system, auxiliary power system, grounding, emergency and standby power system, lighting and ventilation.
8. Tail race channel.

1. Diversion system:

In a hydro-electric power generation system, dam, barrages, solid boulder structure and trench type weir are used to divert the required flow from the river bed or streams to the intake structure. But for small hydro-electric power generating system, solid boulder structure and trench type weir are considered. Boulder type is preferred when boulders are available in the river and the rock is encountered in the river bed within one meter depth whereas trench type is used where the rock is not available in the river bed.

The diversion weir should divert all lean season flows and the structure should be safe during monsoon flood. Diversion structures in hill streams often face chocking of intake. Boulder weir is comparatively cheaper than other diversion system.

2. Desilting chamber or tank:

It is required to exclude the coarse particles to achieve power without abrasion effects on the turbine and other parts. It is needed where the water contains large quantities of course silt which causes erosion damage to the turbine runner, *etc.* As the head increases, the abrasion effect will also increase. The recommended horizontal flow velocity is kept within 0.4 to 0.6 m/s to minimize the erosion damages to the turbine runner.

3. Water conductor system:

Water conductor system should be designed to have minimum loss of head and loss of water due to seepage. The canal may be lined with tiles. The type of water conductor system depends on the site conditions and materials availability. Commonly trapezoidal section is used for the channel section of the water conductor system.

4. Forebay / Balancing reservoir:

When forebay is used as a balancing reservoir about 4 to 6 *hours*, the storage facility is to be provided but when the forebay is used as a transit point and storage of about 2 *minutes* may be adequate. It is generally constructed with reinforced concrete of stone masonry. Forebay helps to provide a minimum head over the penstock.

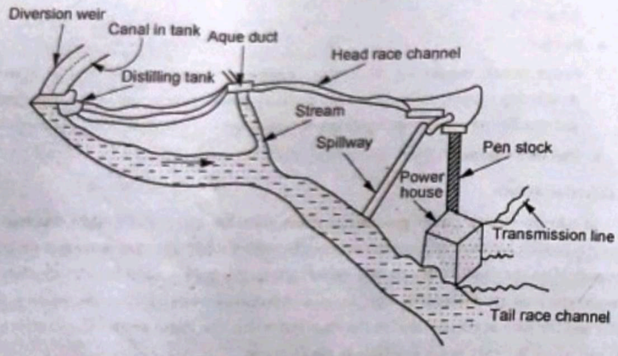


Figure 5.50 Typical arrangement of minihydel power plant

5. Surge tank:

Surge tank will be necessary for the water conductor conduit length of more than 5 times the head on the machine.

6. Penstock:

Penstock is used to feed the water to the machine through it. In its hydraulic design consideration, diameter of the penstock is determined by considering its economic aspect also. During structural design of penstock, its thickness is assessed. The materials for penstock pipes may be mild steel and PVC depending on the design pressure. A bell mouth entry is preferred to ensure in the reduction of head losses and a smooth entry of water from forebay tank into the penstock.

Spillway:

The presence of a spillway is important as it does not allow the water level to rise and the area during the load rejection of the plant. Its crest is kept at the permissible water level. The channel or pipe can be used for the spillway.

Power house:

In power house, turbine, generator, control panels, auxiliary equipments, *etc.*, are kept. Therefore, its building should accommodate them and it is usually constructed by RCC or stone masonry. The height of the power house is generally kept about 3 to 5 *m*.

Tail race:

Tail race is a water channel or cut and cover conduit. The water passes from the turbine outlet *i.e.*, draft tube to the river through tail race. In the tail race, generally, the allowed maximum water velocity is considered to be 1 *m/s*. The shape of the channel is usually trapezoidal or rectangular. It is constructed by stone masonry or brick masonry depending on the availability of the material locally with minimum cost.

5.7.4.2. Turbines for Minihydel Power Plants

In small and mini hydro power systems, the following types of turbines are usually used.

(a) Bulb turbine:

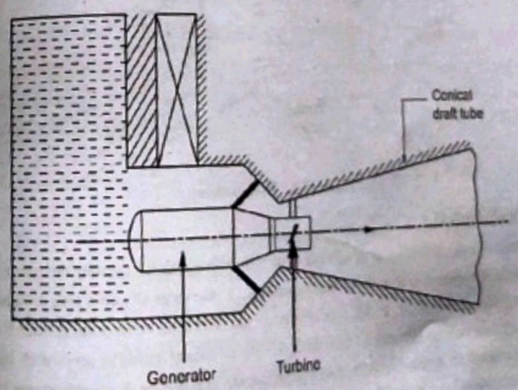


Figure 5.51 Bulb turbine

In this type, the electric generator coupled to the Kaplan turbine is enclosed and works inside a straight passage having the shape of a bulb. The water tight bulb is submerged directly into a stream of water and bends at inlet to casting, draft tube, *etc.* which are responsible for the loss of head dispensed. The unit then needs less installation space with a consequent reduction in excavation and other civil engineering works. These turbines are referred to as tubular or bulb turbines. The tubular turbine is a modified axial flow turbine. The economical harnessing of fairly low heads on major rivers is possible with high-output bulb turbines.

(b) Tube turbine:

Tube turbine with inclined axis is shown in Figure 5.52. The turbine is housed in a slightly curved tube-shaped flow-path. The turbine shaft is inclined and extends up to the generator room through guide bearing. The generator is mounted away from the water passage tube either in up-stream location or in downstream location. The downstream generator location is preferred for very large, low speed and low head units. This type of turbine is a variant of bulb turbine. In this, only the turbine is housed inside the conduit and the generator is mounted outside in a pit by bringing the turbine shaft out of the turbine casing. It is also known as "*pit type*" turbine. It has the advantage of easy accessibility of the generator. It is the modification of the Kaplan type which has been developed for water-heads below 15 *m*.

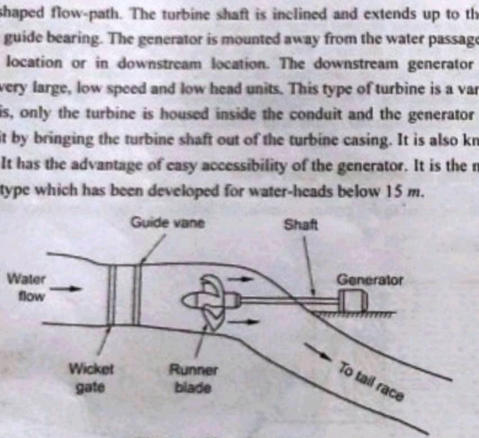


Figure 5.52 Tube turbine

(c) Straflo turbine:

Straflo is the abbreviation of straight flow which is a similar system design as Kaplan turbines and it operates with external rim generators *i.e.*, the rotor sits on a ring attached to the runner blades of the turbine. In this type of turbine, the steel bulb behind the runner is the only bearing of the turbine. Because of their design, a flat efficiency curve at an overall high level can be realized for straflo-turbines. Another advantage in this type is a large range of output and head that can be utilized. The disadvantage of this design is that it is costly sealing between runner and generator. Such a design requires smaller size of the power house.

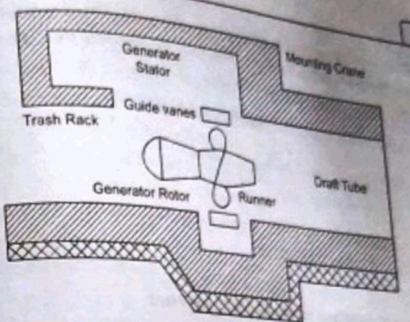


Figure 5.53 Straflo Turbine

5.7.5. Power Obtained from a Minihydel Power Plant

The energy associated with water manifests in three ways: potential energy, pressure energy and kinetic energy. The energy in hydroelectric system starts with potential energy by virtue of its height above some reference level. In this case, the height above the power house produces potential energy. Water under pressure in the penstock is able to do work when released. So, there is energy associated with pressure also. Finally, as water flows, there is the kinetic energy that associated with any mass which is moving.

It is convenient to express each of these three forms of energy on per unit of weight basis in which case energy is referred as *head* in *metres*. Total energy is the sum of the potential, pressure and kinetic energy and is given by

$$\text{Energy head} = Z + \frac{p}{\gamma} + \frac{v^2}{2g}$$

where Z = Elevation above the reference height in *m*

p = Pressure in N/m^2

γ = Specific weight in N/m^3

v = Average velocity in m/s

To determine the power potential of the water flowing in a river or stream, it is necessary to determine both the flow rate of the water and the head through which the water can be made to fall. The *flow rate* is the quantity of water flowing past a point in a given time. Typical flow rate units are *litres per second* or *cubic metres per second*. The *head* is the vertical height in metres from the turbine up to the point where the water enters the intake pipe or penstock. The potential power can be calculated as follows:

Theoretical power (P) = Flow rate (Q) × Head (H) × Gravity (g)

where Q is in *cubic metres* per *second*,

H in *metres*, and

$g = 9.81\ m/s^2$ then,

$P = 9.81 \times Q \times H\ (kW)$

5.7.6. Suitable Conditions for Minihydel Power Plant

The best geographical areas for exploiting small-scale hydro power are those where there are steep rivers flowing all year around. For example, the hill areas of countries with high year-round rainfall, or the great mountain ranges and their foothills are Andes and the Himalayas. Islands with moist marine climates such as Caribbean Islands, Philippines and Indonesia are also suitable. Low-head turbines have been developed for small-scale exploitation of rivers where there is a small head but sufficient flow to provide adequate power.

To assess the suitability of a potential site, the hydrology of the site needs to be known and a site survey carried out to determine actual flow and head data. Hydrological information can be obtained from the meteorology or irrigation department usually run by the national government. This data gives a good overall picture of annual rain patterns and likely fluctuations in precipitation and therefore, flow patterns. The site survey gives more detailed informations of the site conditions to allow power calculation to be done and design work to begin. Flow data should be gathered over a period of at least one full year where possible, so as to ascertain the fluctuation in river flow over the various seasons.

5.7.7. Economics of Minihydel Power Plant

Multiple micro scale hydro generating units can be planned over a catchment area consisting of several potential installation sites to extract the maximum possible energy per unit investment cost.

The most effective method of computing the economic quality of investment in mini hydro plant is to consider the payback period in years against the net revenue from the plant taking place to recover the capital invested. This period is sensitive to inflation rates, interest rates on

borrowed capital and tariffs applied. Over the trading period of time, the revenue and expenditure may be increased to take account of inflation but the actual sums of money may become difficult to relate with the present value based on the investment capital in later years. Therefore, Net present value or discount cash flow methods are often employed.

The capital costs are minimized and revenue from energy produced is maximized. The intake, penstock and discharge pipe work at water treatment works may already occur which will reduce the capital cost of the scheme. To maximize the revenue from energy cells, the plants should be operated at maximum capacity for the longest possible periods of time for the highest tariff for energy produced and sold. So, the following types of costs applied to mini hydro projects are analysed.

(i) Initial cost:

It includes hydrological and environmental assessment, preliminary designs, permits and approvals (for water, land use and construction), land rights, interconnection studies, Power Purchase Agreements (PPA), project management and financing fees. Several sites could be potentially developed. So, the cost analysis and economical risks are assessed to simplified manner and comparisons done.

(ii) Construction cost:

This type of costs is incurred after the project is taken. Such costs include engineering, insurance premiums, civil works and equipment.

(iii) Operation and maintenance cost:

These are regular costs occurring on a yearly basis and include transmission line maintenance, general administration, repairs and contingencies. Operation and maintenance costs mainly include the maintenance of the civil works and the equipment of the microhydropower plant.

(iv) Revenue:

Revenues come from specific purchase contracts signed with the electric utilities. Based on the legislation, electric utilities are usually obliged to buy the electricity generated from renewable energy resources on a priority basis. The different support schemes can affect the development of mini-hydel plants. Sometimes, market-based schemes can reveal themselves too uncertain. Therefore, the selection of this type of plants is unattractive to developers. To estimate the revenues, the promoter of an MHPP has to estimate the production and sales during various periods defined in the tariff legislation. Usually, the tariffs have an hourly and seasonal structure to take into account the shape of the load demand curve and the marginal costs of electricity production during every period.

The costs of geothermal power plant and hydroelectric power plant are for 500 *MW*.

Year	*Geothermal power plant*		*Hydroelectric power plant*	
	Capital cost (Dollar/kW)	*Operating cost (Dollar/kW-year)*	*Capital cost (Dollar/kW)*	*Operating cost (Dollar/kW-year)*
2008	10,400	31	3,600	---
2010	9,900	31	3,500	6
2015	9,720	31	3,500	6
2020	9,625	31	3,500	6
2025	9,438	31	3,500	6
2030	9,250	31	3,500	6
2035	8,970	31	3,500	6
2040	8,786	31	3,500	6
2045	8,600	31	3,500	6
2050	8,420	31	3,500	6

5.7.8. Advantages and Limitations of Minihydel Power Plant

Advantages:

1. It requires the shortest time for developing a unit.
2. Once, it is built the running expenditure almost negligible.
3. It is free from hazards of pollution.
4. It has no environmental problems, no submergence of land and no loss of agricultural land.
5. The construction of small hydro is simple.

Limitations:

1. Non-availability of indigenous equipment for generating plant and import procedures are time-consuming.

2. General lack of awareness of benefits from small development.
3. Remoteness of sites especially in hilly areas and adverse geological conditions in Himalayan region.

5.8. TWO MARK QUESTIONS AND ANSWERS

1. *Write short note on 'Hydrogen as a fuel'.*

Hydrogen in its liquid form has been used as a fuel in space vehicles for years. Hydrogen has high combustion energy per *kg* relative to other fuels which means hydrogen is more efficient on a weight basis than fuels currently used in air or ground transportation. This weight factor makes hydrogen an attractive fuel.

2. *Write down the advantages of using hydrogen as fuel.*

1. Hydrogen combustion produces only water as a by-product. Hydrogen generates energy without releasing greenhouse gasses or pollutant particles.
2. The only pollution-free source of hydrogen is water which is also the most abundantly available. A simple process called *electrolysis* can liberate hydrogen from water.
3. Hydrogen has higher energy density than petroleum-based fuels. It means, it supplies more energy per volume than gasoline, diesel or kerosene.
4. Hydrogen has the potential to run a fuel-cell engine with greater efficiency over an internal combustion engine.

3. *Mention the various disadvantages of using hydrogen as fuel.*

1. Heavy and bulky fuel storage both in vehicle and at the service station. Hydrogen can be stored either as a cryogenic liquid or as a compressed gas. If stored as a liquid, it would have to be kept under pressure at very low temperature. It would require a thermally super-insulated fuel tank. Storing in a gas phase would require a heavy pressure vessel with limited capacity.
2. It is difficult to refuel.
3. Fuel cost would be high at present-day technology and availability.
4. NOx emissions are high because of high flame temperature.

4. *What are the methods of producing hydrogen?*

(i) Steam reforming

(ii) Electrolysis

(iii) Steam electrolysis

(iv) Thermochemical water splitting

(v) Photo-electrochemical system

(vi) Photo-biological system and (vii) Biological system.

5. *Define electrolysis process.*

The hydrogen and oxygen in water can be dissociated with an electric current in a process called *electrolysis*.

6. *State the advantages of using high pressure electrolyser.*

1. Reduction in specific power consumption
2. Delivery of gas to eliminate the cost gas compressors
3. Reduction in the size of electrolysis cells.

7. *What is the principle involved in thermochemical method of producing hydrogen?*

Thermochemical hydrogen production technologies use heat and chemical reactions to convert hydrocarbon feed stocks to hydrogen. Thermochemical processes are mainly oxidation process in which hydrogen is removed by a chemical reaction.

8. *State the various modes of hydrogen storage.*

(i) Compressed gas storage

(ii) Liquid storage

(iii) Line pack storage system

(iv) Underground storage

(v) Storage as metal hydrides

(vi) Carbon adsorption

(vii) Microspheres.

9. *Mention any two challenges in hydrogen storage.*

1. Weight and volume:

The weight and volume of hydrogen storage systems are too high by resulting in inadequate vehicle range compared to conventional petroleum-fueled vehicles.

2. Efficiency:

Energy efficiency is a challenge for all hydrogen storage approaches. The energy required to get hydrogen in and out is an issue for reversible solid-state materials. The

energy associated with compression and liquefaction must be considered for compressed and liquid hydrogen technologies.

10. *List down the various energy conversion technologies.*

(i) Combustion in internal combustion engines

(ii) Direct steam generation by hydrogen or oxygen combustion

(iii) Catalytic combustion

(iv) Electrochemical conversion in fuel cells and

(v) Metal hydride technologies.

11. *Mention the applications of hydrogen energy.*

1. A fuel in H_2-O_2 fuel cell system
2. Manufacturing synthetic Ammonia, synthetic Methanol and synthetic Urea or ammonium nitrate.
3. An aviation fuel by hydrogenation process.
4. Chemical reduction and various heating process.
5. A coolant in large generators and motors.
6. Used in the manufacturing of tungsten filaments for lamps.

12. *What is fuel cell?*

A fuel cell is an electrochemical device in which the chemical energy of a conventional fuel is directly converted into low voltage DC electrical energy.

13. *List down the possible reaction involved in fuel cells.*

Hydrogen/oxygen	1.23 *V*	$2H_2 + O_2 \Rightarrow 2H_2O$
Hydrazine	1.56 *V*	$N_2H_4 + O \Rightarrow 2H_2O + N_2$
Carbon (Coal)	1.02 *V*	$C + O_2 \Rightarrow CO_2$
Methane	1.05 *V*	$CH_4 + 2O_2 \Rightarrow CO_2 + 2H_2O$

14. *Mention the various parts of fuel cell.*

(i) Membrane electrode assembly

(ii) Catalyst

(iii) Chemistry of a Fuel Cell

(iv) Hardware.

15. List down the major sections of a fuel cell.

(i) Fuel processing section

(ii) Fuel cell power pack

(iii) Power conditioning section

(iv) Switchgear and supply section

(v) Control subsystem section

(vi) Heating section.

16. Compare the fuel cell and battery. ***[Anna Univ. Apr'23]***

S. No.	Fuel cell	Battery
1.	Fuel cell generates energy by converting the available fuel.	A battery stores energy and uses when it is required.
2.	As long the fuel is available, it generates electricity.	It can be used anytime and anywhere.
3.	Fuel can have a battery to store energy and use later.	Fuel cell can not be used as a storage device for battery.
4.	Fuel cell is more expensive.	Battery cost is less.

17. Classify fuel cells based on electrolyte.

(a) Hydrogen-oxygen fuel cell

(b) Polymer Electrolyte Membrane (PEM) Fuel Cell

(c) Direct methanol fuel cell

(d) Alkaline fuel cell

(e) Phosphoric acid fuel cell

(f) Molten carbonate fuel cell

(g) Solid oxide fuel cell

(h) Regenerative fuel cell.

18. What are the advantages of fuel cells?

1) Fuel cells have the potential to replace the internal combustion engine in vehicles and provide power for stationary and portable power applications.

2) They can be used in transportation applications such as powering automobiles, buses, cycles, and other vehicles.

3) Many portable devices can be powered by fuel cells such as laptop computers and cell phones.

4) They can also be used for stationary applications such as providing electricity to power homes and businesses.

19. What are the disadvantages of fuel cells?

1) Initial cost is high. Fuel cells are currently very expensive to produce, since most units are hand-made.

2) Service life is low.

3) Operation requires replevisable fuel supply.

4) Some fuel cells use expensive materials.

20. List the various applications of fuel cells.

1. Fuel cells have the potential to replace the internal combustion engine in vehicles. They can be used in transportation applications such as powering automobiles, submarines, spacecraft and other vehicles.

2. Fuel cells using gasified coal as fuel can be used in central power stations. The efficiency of such plant would be higher due to direct energy conversion. Thus coal can be used more efficiently with reduced emissions.

3. Many portable devices can be powered by fuel cells such as laptop computers, mobile phones and other low power applications.

4. To meet the demand of isolated sites such as construction sites, military camps and small village community or hamlet, fuel cells are more suitable than diesel generator.

21. What is geothermal energy? ***[Anna Univ. Apr'23]***

Geothermal energy is the heat from high pressure steam coming from within the earth. It is a renewable source of energy derived from the rain water in the earth heated to over 180°C by subterranean hot rocks.

22. List various geothermal resources.

Basic kinds of geothermal sources are as follows:

1. Hydrothermal

(a) Vapour dominated or dry steam fields

(b) Liquid dominated system

(c) Hot-water fields

2. Geopressured
3. Hot dry rock or Petrothermal
4. Magma resources and 5.Volcanoes.

23. *What are the forms of geothermal energy stored deeply inside the earth?*

(a) Hot water springs

(b) Fumaroles

(c) Volcanic eruptions.

24. *What are the important criteria while selecting the geothermal energy?*

(a) Temperature of geothermal fluid, °C.

(b) Discharge rate, m^3/day

(c) Useful life of production well, years

(d) Mineral contents $gram/m^3$.

25. *Define the geothermal gradient.* ***[Anna Univ. Nov'22]***

Geothermal gradient is the rate of temperature change with respect to increasing depth in Earth's interior.

In normal continental crust, a typical geothermal gradient within the first 3 to 5 *km* (2 or 3 *miles*) of Earth's surface is about 25°*C/km*.

26. *What are the different direct uses of geothermal energy?*

Direct use of geothermal energy is appropriate for sources below 150°*C*. It is used for:

(i) Space heating

(ii) Air conditioning

(iii) Industrial processes

(iv) Drying

(v) Greenhouses

(vi) Aquaculture

(vii) Hot water

(viii) Resorts and pools

(ix) Melting snow.

Briefly explain the working principle of direct use of geothermal energy.

(i) Direct sources function by sending water down a well to be heated by the Earth's warmth.

(ii) Then a heat pump is used to take the heat from the underground water to the substance that heats the house as shown in Figure 5.54.

(iii) Then the cold water is injected back into the Earth.

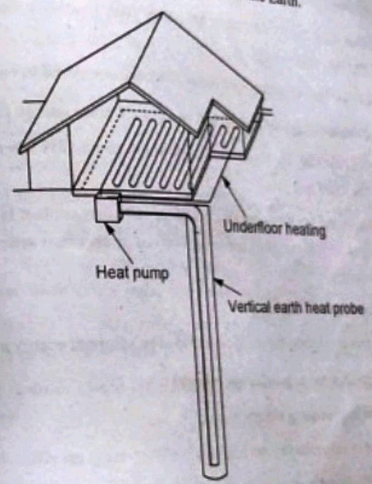


Figure 5.54 Direct use of geothermal energy

28. *Classify geothermal electrical power plants.*

1. According to geothermal energy resource

(a) Geothermal steam

(b) Geothermal brine

(c) Geothermal hot water

(d) Hot rock.

2. According to thermodynamic cycle
   (a) Steam turbine cycle
   (b) Binary cycle
   (c) Total flow concept.

29. *List down the advantages of geothermal energy over other energy forms.*

1. It is versatile in its use and reliable source of energy.
2. It is cheaper as compared to energies obtained from other sources both zero fuels and fossil fuels.
3. It delivers a greater amount of net energy from its system than other alternative or conventional systems.
4. It has the highest annual load factor of 90% as compared to conventional plants.

30. *What are the disadvantages of geothermal energy over other energy forms?*

1. Overall efficiency for power production is low about 15% when compared to 35-40% for fossil fuel plants.
2. The steam and hot water gushing out of the earth may contain H_2S, CO_2, NH_3 and radon gas, *etc.* These gases are to be removed by chemical action before they are discharged.
3. Drilling operation is noisy.
4. Large area is required for the exploitation of geo-thermal energy as much diffused.

31. *What are the applications of geothermal energy?*

1. It is used in generating electric power.
2. It is used in industrial process heat.
3. It is used in space heating for various kinds of buildings.
4. It is used in agricultural and related applications.

32. *What is the principle of OTEC?*

Ocean thermal energy exists in the form of temperature difference between warm surface water and cold deep water. The absorption of solar radiation by the sea and ocean causes a moderate temperature difference between upper and lower levels of water. Particularly, the oceans in the tropical region collect and store a large amount of solar energy. This stored heat energy can be converted into work with the help of thermodynamic cycle. It is called *ocean thermal energy conversion (OTEC).*

What is OTEC technology? Which Thermodynamic Cycle is used in OTEC? *[Anna Univ. Nov'19]*

OTEC is an energy technology that converts solar radiation falling on the ocean surface into electric power. OTEC systems use the ocean's natural thermal gradient. This system can produce a significant amount of power using this thermal gradient. The most commonly used Thermodynamic cycle for OTEC to date is the *Rankine cycle.*

List the peculiarities of ocean thermal energy conversion system. *[Anna Univ. Nov'20]*

(i) Power from OTEC is continuous, renewable, pollution free and environmentally friendly.

(ii) Unlike other forms of solar energy, the output of OTEC shows very little daily or seasonal variation. OTEC power plants can produce electricity 24 *hours* a day or 365 *days* a year.

(iii) Drawing of warm and cold sea water and returning of the sea water, close to the thermocline, could be accomplished with minimum environment impact.

(iv) Electric power generated by OTEC could be used to produce hydrogen.

(v) Tropical and sub-tropical island sites could be made free from pollution caused by conventional fuels for electricity generation.

(vi) OTEC system might help in enrichment of fishing grounds due to the nutrients from the unproductive deep waters to the warmer surface waters.

(vii) A floating OTEC plant can generate power even at mid sea and can be used to provide power for off shore mining and processing of manganese nodules.

(viii) Either open or closed system OTEC could be used in either onshore or offshore systems.

35. *What are the different types of OTEC cycles?*

(a) Open cycle (Claude cycle, Steam cycle)

(b) Closed cycle (Anderson cycle, Vapour cycle).

36. *How can be the efficiency increased slightly with modified open cycle OTEC system?*

(a) Controlled *flash-steam evaporator* is used instead of a conventional type of evaporator

(b) Contact condenser is replaced by a surface condenser.

(c) The open cycle OTEC can be used as a co-generation cycle to produce both electrical power and fresh water.

37. What are the limitations of open cycle OTEC system?

1. Turbine is physically large.
2. The cost of plant is high.
3. It can allow a very large flow of ocean water in terms of mass and volume.
4. The plant is subjected to ocean storms, high waves, etc.

38. List down the components of closed cycle OTEC system.

1. Evaporator
2. Vapour turbine (Turbogenerator)
3. Vapour condenser
4. Liquid pressuriser.

39. What are the working fluids in closed cycle OTEC?

(a) Ammonia (NH_3)

(b) Freon

(c) Butane.

40. Write down the advantages of closed system OTEC over open system OTEC.

[Anna Univ. Nov'21]

In the closed cycle OTEC, the same working fluid is circulated again and again within the turbine but in the open cycle, the working fluid replaced by discharging into sea after expansion in the turbine.

41. List down the factors considered for locating OTEC power plants.

(i) During continuous power generation, the large flow of hot and cold water might change the local and global environment.

(ii) Carbon dioxide present in the deep sea water might be released suddenly while pumping and heated in the evaporator. The releases of carbon dioxide will deaerate the sea water before entering into the evaporator.

(iii) There may be a possibility that biota including eggs, larvae and fish could be entertained and destroyed due to intake and expulsion of large volumes of water. Also, OTEC plant might affect the life of sea animals.

(iv) Release of large quantities of cold water into warmer surface environment will also have biological effects.

42. Mention the advantages of OTEC.

(i) Power from OTEC is continuous, renewable, pollution free and environmentally friendly.

(ii) Unlike other forms of solar energy, output of OTEC shows very little daily or seasonal variation. OTEC power plants can produce electricity 24 *hours* a day or 365 *days* a year.

(iii) Drawing of warm and cold sea water and returning of the sea water, close to the thermocline, could be accomplished with minimum environment impact.

(iv) Electric power generated by OTEC could be used to produce hydrogen.

43. State the disadvantages of OTEC.

(i) Capital investment is very high.

(ii) Seasonal variations and natural calamities affect OTEC performance.

(iii) Due to small temperature difference in between the surface water and deep water, the conversion efficiency is very low about 3-4%.

(iv) Low efficiency of these plants coupled with high capital cost and maintenance cost makes them uneconomical for small plants.

44. What are the applications of OTEC?

(i) Open cycle OTEC plant is used to produce desalinated water which is mainly used for irrigation and human consumption.

(ii) A closed cycle OTEC plant is used as a chemical treatment plant.

(iii) The deep sea water can be used in refrigeration and air conditioning systems mainly in offshore Industries. In majority of the air conditioning plant, open cycle OTEC is used. The release of used working fluid will be in the sea itself.

[Anna Univ. Apr'22]

45. How are ocean tides created?

Tides are produced mainly by the gravitational attraction of moon and sun on the water of solid earth and oceans. *Tidal power* or *tidal energy* is a form of hydropower that converts the energy of tides into useful forms of power, mainly electricity.

[Anna Univ. Apr'23]

46. Define the tide range with respect to tidal power plant.

Range is the difference between high and low water levels denoted by R.

R = water elevation at high tide – water elevation at low tide.

47. What are spring tides? How these tides are formed?

If the tide's range is maximum, it is called *spring tide*. These spring tides are called *high tides*. Around no moon and full moon days, the sun, moon and earth form a line. The tidal force due to the sun reinforces the moon. Hence, high tides are produced.

48. What is meant by neap tide?

When the moon is at first quarter or third quarter, the sun and moon are separated by 90° when viewed from the Earth and the solar gravitational force partially cancels the moon. At these points in the lunar cycle, the tide's range is minimum called *neap tide*.

49. Briefly explain how the tidal energy is converted into electrical energy.

The generation of electricity using tidal power is done using a barrage or small dam built at the entrance of a bay where tides are known to reach very high levels of variation. This barrage will trap tidal water behind it creating a difference in water level which will in turn create the potential energy. This potential energy will then be used in creating kinetic energy as doors in the barrage are opened and the water is rushed from the high level to the lower level. This kinetic energy will be converted into rotational kinetic energy that will rotate turbines giving electrical energy.

50. List down the types of tidal energy technologies.

(a) Tidal barrages

(b) Tidal stream generators

(c) Dynamic tidal power.

51. What are the components of tidal power plants?

1. Barrage or dam or dyke
2. Sluice ways
3. Embankments
4. Power house.

52. What are the modes of operation of tidal barrage power plants?

(a) Ebb generation

(b) Flood generation

(c) Two-way generation

(d) Pumping and turbining.

53. How are the barrage type tidal power plants classified?

1. Single basin arrangement
   a) Single ebb-cycle system
   b) Single tide-cycle system
   c) Double cycle system
2. Double basin arrangement.

54. Classify tidal stream generator support structures.

(a) Gravity structures

(b) Piled structures

(c) Floating structures.

55. Mention the major types of tidal stream generators.

(a) Axial turbines

(b) Vertical and horizontal axis cross flow turbines

(c) Helical turbine.

56. List down the main features of the helical turbine.

- It is designed for hydroelectric applications in free-flowing water.
- It operates in ocean, tidal, and river currents.
- It does not require expensive dams that can harm the environment.
- It is self-starting with flow as low as 0.6 *m/s*.
- It runs smoothly.

57. What are the main hurdles in the development of tidal energy? *[Anna Univ. Apr'23]*

- The largest barrier to tidal energy is the high cost associated with building tidal power stations.
- Also, a major concern is the potentially negative environmental effects on marine life.
- Spinning blades can injure living organisms due to water fouling resulting from various system components.
- It is limited installation sites
- Turbines can impact the surrounding ecosystem and
- Power produced does not always match up with peak energy demand.

58. *State any four site requirements for tidal power plant erection.*

(i) Short length of dam is to create a basin of reasonable storage. It is possible at a narrow inlet to an estuary of bay.

(ii) It should be nearer to local location or nearer to the ocean.

(iii) It should be protected from high waves.

(iv) It should not hamper shipping traffic.

59. *What are the advantages and disadvantages of tidal power?* ***[Anna Univ. Nov'21]***

Advantages:

(i) Tidal power is a renewable and sustainable energy resource.

(ii) It is free from pollution as it does not use any fuel.

(iii) Large area of valuable land is not required.

(iv) It does not produce any unhealthy waste such as gases and ash.

(v) It has unique capacity to meet the peak power demand effectively when it works in combination with thermal or hydroelectric system.

Disadvantages:

(i) Due to variation in tidal range, the output is not uniform.

(ii) There is a fear of tidal plant components and machinery being corroded due to corrosive sea water.

(iii) It is difficult to carry out construction in sea.

(iv) As compared to other sources of energy, the tidal power plant is costly.

60. *Define wave energy.*

Wave energy is energy of interchanging potential and kinetic energy in the wave.

61. *Write a note on wave energy.* ***[Anna Univ. Nov'22]***

Wave energy is energy of interchanging potential and kinetic energy in the wave. Among other types of renewable energy, oceans contain energy in the form of waves and tidal currents. Ocean wave energy is an important renewable energy. At the same time, it is regular, periodic and consistent. Ocean wave energy can be either converted into mechanical energy or electrical energy through wave energy conversion plants. Ocean wave energy is needed to be developed in coastal areas. Usually, power extracted from ocean energy is in the range of 10 *kW/m* to 70 *kW/m* with respect to amplitude and wave length.

Ocean waves are created by the interaction of winds with the surface of sea water. Sea water contains both kinetic energy and potential energy. The energy available in the Ocean depends on the wind speed, duration of the wind and distance from which interacts with sea surface water. Differential warming of the earth causes pressure difference in the atmosphere which generates winds. As winds move across the surface of open bodies of water, they transfer some of their energy to water and create waves.

The amount of energy transferred and the size of wave depend on wind speed, length of time for which the wind blows and distance over which the wind blows or fetch. So, the coastal region which has exposure to the prevailing wind direction and face long expanses of Open Ocean has the greatest wave energy levels.

To extract the stored energy in waves, wave energy conversion devices are used in which two or more bodies move relative to each other while at least one body interacts with waves.

62. *What is wave energy? How power available in waves is calculated?* ***[Anna Univ. Nov'21]***

Wave energy is the energy of interchanging potential and kinetic energy in the wave. Among other types of renewable energy, oceans contain energy in the form of waves and tidal currents. Ocean wave energy is an important renewable energy. At the same time, it is regular, periodic and consistent.

The total energy obtained from waves is the sum of potential energy and kinetic energy.

1. *Potential energy:*

The potential energy available in waves is due to the head of sea water above the mean sea level.

Potential energy, $P.E = \frac{1}{4}\rho a^2 \lambda g W$

where

ρ = Density of the sea water (kg/m^3)

a = Amplitude of wave (m)

λ = Wave length (m)

W = Width of the wave (m)

g = Acceleration due to gravity (m/s^2)

2. *Kinetic energy:*

The energy associated with the movement sea water is called *kinetic energy*. For harmonic motion of waves, average kinetic energy is equal to the potential energy. Therefore,

Kinetic energy, $K.E = \frac{1}{4}\rho a^2 \lambda g W$

Total energy, $E = P.E + K.E$

$$= \frac{1}{4}\rho a^2 \lambda g W + \frac{1}{4}\rho a^2 \lambda g W = \frac{1}{2}\rho a^2 \lambda g W$$

Power, $P = \frac{\text{Energy}}{\text{Time}}$

63. *What are wave energy converters?*

The technologies developed to generate energy from waves and currents called *hydrokinetic energy conversion devices* are generally categorized as either *Wave Energy Converters* (WECs).

64. *Mention the various wave energy conversion devices.*

(a) Wave profile devices
  (i) Point absorber
  (ii) Linear absorber (Wave attenuator)
  (iii) Dolphin-type wave-power machine
  (iv) Nodding duck
(b) Oscillating water columns
(c) Wave capture devices
  (i) Wave overtopping device:
  (ii) High-level reservoir wave machine:
(d) Rotating wave devices.

65. *Write the principle of attenuator for wave energy conversion.* ***[Anna Univ. Apr'22]***

The *linear absorber* (*wave attenuator*) floats on the surface of the water. It is tied to the ocean floor so that it can swing perpendicularly towards the incoming waves. As the waves pass along the length of this snake such as wave energy device, they cause the long cylindrical body to sag downwards into the troughs of the waves and arch upwards when the waves crest is passing. Connecting joints along the body of the device flex in the waves exerting a great deal of force which is used to power a hydraulic ram at each joint. The

hydraulic ram drives oil through a hydraulic motor which drives a generator to produce electricity.

66. *Write brief note on point absorber.*

The *point absorbers* use a heavy ballast plate suspended below the floating buoy. The buoy is prevented from floating away by a mooring line attached to a sea-floor anchor. As the buoy bobs up-and-down in the waves, a oscillatory mutual force reaction is generated between freely moving absorber and heavy plate causing a hydraulic pump in between to rotate a generator producing electricity.

67. *What is the difference between point absorber and linear absorber?*

If the physical size of the wave profile device is very small as compared to the periodic length of the wave, this type of wave energy device is called "*point absorber*".

If the size of the device is larger or longer than the typical periodic wavelength, it is called "*linear absorber*".

68. *What is called wave collector?*

An *Oscillating Water Column* (OWC) has a partially submerged structure which opens to the ocean below the water surface. This structure is called *wave collector*.

69. *List out the advantages of wave energy generation.* ***[Anna Univ. Nov'20]***

(a) The wave energy naturally concentrated by accumulation at all times, space and transported than wind and solar energies.
(b) Wave conditions are predictable and hence the energy too.
(c) Wave from transportation across a plane perpendicular to the wave propagation direction at a good site is from 10 to100 times large.
(d) Wave power devices are not required to use large land masses such as wind or solar.
(e) Wave energy conversion devices are pollution free due to releasing of sea water back to sea itself after extracting energy from waves.

70. *What are the disadvantages of wave energy?*

(a) The main disadvantages are difficult maintenance, construction cost, life time and reliability due to wave energy available on the ocean. Also, it needs a greater distance to shore for transporting energy.
(b) Wave energy conversion devices must withstand the severe peak stresses during storms.

(c) Irregularity of wave pattern in amplitude, phase and direction makes it difficult to extract power efficiently.

71. What is hydroelectric power?

The turbine converts the hydraulic energy into mechanical energy. This mechanical energy is converted into electrical energy. So, the conversion of energy from hydraulic form to electric form is called *hydroelectric power*.

72. What are the various factors considered in designing a micro hydel scheme? ***[Anna Univ. Nov'21]***

1. Flow duration curve (FDC) to obtain the choice of turbine type, size and speed based on the net head and maximum water flow rate,
2. Flow rate measurement to measure cross sectional area (A_c) and velocity (V_c):
3. Weir and open channel
4. Trash rack design
5. Penstock design
6. Head measurement
7. Turbine power
8. Turbine speed.

73. For which purposes hydro projects are developed? ***[Anna Univ. Dec'13]***

(a) To meet the power needs during peak and off-peak requirements

(b) To run of the river

(c) To obtain a clean process of power generation

(d) To avoid suffering from the limitation of inflation on account of fuel consumption in the long run.

74. What are the uses of mini hydro power plants?

Mini hydro plants are used in isolated remote areas where the grid does not exist. Typically, it provides power to just one rural industry or one rural community. Mini and small hydro plants sometimes make small contribution to national grid supplies.

75. How are hydro power plants classified?

1. Depending on the capacity:

(i) Micro hydel plant ⇒ Producing less than 100 kW power

(ii) Mini hydel plant ⇒ Producing 100 kW to 1 MW power

(iii) Small hydel plant ⇒ Producing 1 MW to 10 MW power.

2. Depending on the head:

(i) Ultra low head plant ⇒ Below 3 m

(ii) Low head plant ⇒ Less than 30 m

(iii) Medium head ⇒ Between 30 to 75 m

(iv) High head ⇒ Above 75m.

3. Depending on the usage:

(i) Independent scheme

(ii) Subordinate scheme.

4. Depending on the construction:

(i) Storage plants and

(ii) Run-of-the-river plants.

76. List down the components of small hydroelectric power system.

(a) Diversion and intake

(b) Desilting chamber or tank

(c) Water conductor system

(d) Forebay/balancing reservoir

(e) Surge tank

(f) Penstock

(g) Power house comprising of turbine, generator, protection and control system, dewatering system, drainage system, auxiliary power system, grounding, emergency and standby power system, lighting and ventilation.

(h) Tail race channel.

77. What are the advantages and limitations of mini hydro power systems?

Advantages:

1. It requires the shortest time for developing a unit.
2. Once, it is built the running expenditure almost negligible.
3. It is free from hazards of pollution.
4. It has no environmental problems, no submergence of land and no loss of agricultural land.
5. The construction of small hydro is simple.

Limitations:

1. Non-availability of indigenous equipment for generating plant and import procedures are time-consuming.
2. General lack of awareness of benefits from small development.
3. Remoteness of sites especially in hilly areas and adverse geological conditions in Himalayan region.

5.9. SOLVED QUESTIONS

1. What is the basic principle involved in electrolysis process of hydrogen production? Explain the method in detail with a neat sketch.

   Refer chapter **5.1.3.1** on Page **5.4**.

2. Write short notes on hydrogen storage.

   Refer chapter **5.1.4** on Page **5.7**.

3. Discuss various methods of hydrogen storage systems.

   Refer chapter **5.1.4.1-5.1.4.4** on Page **5.8-5.11**.

4. What are the challenges in storing hydrogen?

   Refer chapter **5.1.4.5** on Page **5.11**.

5. Discuss various applications of hydrogen as fuel.

   Refer chapter **5.1.6** on Page **5.15**.

6. Discuss the principle of operation of a fuel cell with a neat sketch. [*Anna Univ. Nov'05*]

   Refer chapter **5.2.1** on Page **5.17**.

7. Explain the construction of various types of fuel cells. [*Anna Univ. Apr'23*]

   Refer chapter **5.2.2** on Page **5.18**.

8. Explain the working of hydrogen-oxygen fuel cell with a neat sketch.

   Refer chapter **5.2.2.1** on Page **5.22**.

9. Describe the working of polymer electrolyte membrane fuel cell with a neat sketch.

   Refer chapter **5.2.3.2** on Page **5.23**.