Non-Conventional Energy Resources

G.S. SAWHNEY

Professor and Head
Department of Mechanical Engineering
Accurate Institute of Management and Technology
Greater Noida

Formerly Professor and Head
Department of Mechanical Engineering
GNIT, Greater Noida and LKIE, Ghaziabad

PHI Learning Private Limited

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NON-CONVENTIONAL ENERGY RESOURCES
G.S. Sawhney

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PREFACE

Fossil fuels are fast depleting, which has led to all-round global efforts to harness alternative energy resources. These resources are called non-conventional energy resources. Every country has plan to develop these resources commercially. There is a need to have more awareness about these resources and technologies to harness them and generate energy. Therefore, the subject matter has been included in the syllabi for engineering and science courses. The book is primarily intended to cover the syllabi prescribed by all major technical universities.

Non-conventional energy resources is, therefore, an important subject which has been given rightful weightage in all branches of the undergraduate engineering curriculum. Based on my teaching experience, I have tried to explain the principles and concepts of renewable energy resources in simple and clear terms. The endeavour is to present the subject matter in the most comprehensive and usable form. The book presents an exhaustive coverage, definitions, formulae and examples which are well supported by plenty of diagrams and problems to make the undergoing principles more comprehensive. The book is precise and easy to understand. Effort has been made to present the concepts in question-answer format so that students assimilate the knowledge and have clear understanding of the subject matter.

I wish to place on record my sincere thanks to my wife, Jasbeer Kaur, for her patience shown throughout the preparation of the book. I am also thankful to my children Jasdev, Tejmohan, Puja and Nandini for their encouragement to spend my spare time in writing work. I have also got the valuable assistance from my faculty members, specially Mr. Subham Sharma, for the early completion of the book. I would appreciate constructive suggestions and objective criticisms from students and teachers alike with a view to further enhancing the usefulness of the book. Readers may mail their suggestions at my email address.

G.S. Sawhney
channi_sawhney@hotmail.com

CHAPTER 1

Energy Resources and Their Utilisation

1.1 INTRODUCTION

The production of electricity and its per capita consumption is regarded as the indication of the standard of living of people in a nation. Energy is a key input in the economic growth. The growth of a nation largely depends on the availability of energy. The energy consumption in the world has been increasing at an alarming rate for the past few decades. The conventional energy resources such as coal, wood, diesel, petrol, natural gas, etc. are depleting. It has been estimated that the conventional fuels may last for 5–6 decades only. To meet the major part of energy demand in future, every nation is making efforts to find non-conventional energy sources such as solar, wind, tidal and geothermal. Energy is defined as the capacity of a substance or a body to do work. Similarly, energy resources are the main sources of energy from which the energy can be extracted and utilised for mankind.

1.2 ENERGY RESOURCES

- **What do you understand by energy resources?**

Energy resources are the main sources of energy from which the energy can be extracted and utilised for mankind. Energy is a key input in economic growth. The growth of a nation largely depends on the availability of energy resources.

1.2.1 Classification of Energy Resources

- **How can energy resources be classified?**

or

- **Discuss the primary and secondary energy resources. Also, describe the future of non-conventional energy resources in India.**

or

- **What are the conventional and non-conventional energy sources? Describe the fossil fuels as the conventional energy resources.**

The energy resources can be classified on the basis of usability of energy resources, traditional usage of energy resources, long-term availability of energy resources, commercial application of resources and origin of resources.

Primary and secondary energy resources

(i) **Primary resources.** Resources available in the nature in the raw form are called primary resources. Fossil fuels (coal, oil and gas), uranium and hydropower are primary energy resources. These energy resources cannot be used in raw form. Primary energy resources have to be located, extracted, processed and converted into a suitable form before use.

(ii) **Secondary resources.** Secondary energy resources are obtained form primary energy resources by processing. Processing helps in transformation of primary resources into the secondary or usable energy form so that it can be utilized by consumers. Electricity, steam, hot water, petrol, diesel, LNG and CNG are secondary energy resources.

Conventional and non-conventional energy resources

(i) **Conventional.** Conventional energy resources are energy resources which have been traditionally used from many years. These resources are also widely used at present and likely to be depleted.

(ii) **Non-conventional.** These are alternate energy resources to the conventional energy resources which are being considered to be used on large scale. The conventional energy resource are likely to be depleted in about 50–60 years and non-conventional energy resources should be fully developed by then to meet the energy requirement.

The comparison of conventional and non-conventional energy resources is given in Table 1.1.

TABLE 1.1 Comparison of conventional and non-conventional energy resources

Conventional resources	*Non-conventional resources*
Traditional	Non-traditional
These have been in use for many years	These are not in routine use at present
These resources can be easily converted into mechanical energy	These resources require some costly method to be converted into mechanical energy
These are likely to be depleted, that is, these have limited availability	These are non-depletable or may be available in vast quantities
Coal, petrol, diesel, nuclear fuels CNG and LPG are conventional energy resources	Solar, wind, tidal geothermal and biogas are non-conventional energy resources

Renewable and non-renewable energy resources

(i) **Renewable.** Resources which can be renewed by nature again and again so that their supply is not adversely affected by the rate of their consumption are called renewable resources.

(ii) **Non-renewable.** Resources which are available in certain finite quantity and cannot be replenished are called non-renewable.

The comparison between renewable and non-renewable resources is given in Table 1.2.

TABLE 1.2 Renewable and non-renewable resources

Renewable resources	*Non-renewable resources*
These are inexhaustable resources	These are exhaustable resources
These are non-traditional in use	These are traditional in use
New methods are being developed to use these resources	Widely used used as energy resources
Efforts are taken to make vast use of these resources	Efforts are taken to conserve these resources
Hydel, solar, wind, tidal and geothermal resources are renewable energy resources	Fossil fuels, nuclear fuels and natural gases are non-renewable resources

Commercial and non-commercial energy resources

(i) **Commercial energy resources.** The secondary usable energy resources such as electricity, CNG, LPG, petrol and diesel are essential for commercial activities. The economy of a nation highly depends on its ability to process and transform the natural raw energy sources into usable commercial energy sources.

(ii) **Non-commercial energy.** The energy which can be derived directly from nature so as to be used without passing through any commercial outlet is known as the non-commercial energy. Wood, animal dung cake and crop residues are non-commercial energy sources.

Energy resources of different origins

The energy resources based on their origin can be nuclear, fossil fuel, hydro, solar, biomass, wind, tidal, geothermal, ocean thermal and ocean tidal resources.

1.3 TYPES OF ENERGY RESOURCES

The energy resources can be thermal, hydel, nuclear, solar, wind, tidal, geothermal and ocean resources.

1.3.1 Thermal Energy

- **What is thermal energy? How are fossil fuels classified?**

Thermal energy is the energy which is stored as the heat energy in the fossil fuels. Fossil fuels are the fuels obtainable from the earth that have been accumulated over thousands and thousands of years by the decaying of plants. These fuels produce heat energy when they are burnt. Heat energy is mainly used for transportation and electric power generation in thermal power plants. The fossil fuels can be classified as shown in the Figure 1.1.

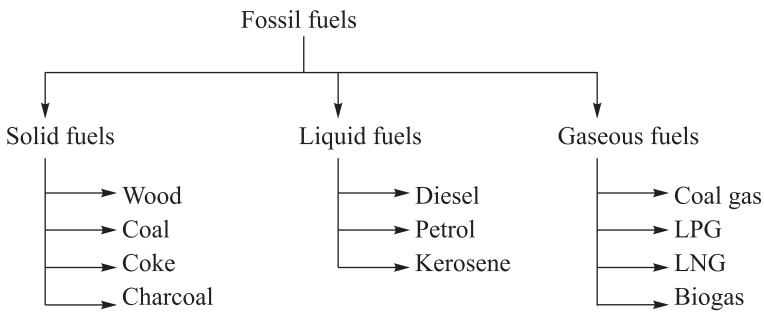


Figure 1.1 Types of fossil fuels.

1.3.2 Hydel Energy

- **What is hydel energy? Describe briefly a hydroelectrical power plant.**

Hydel energy is the potential energy of water created due to the storage of water at a higher level. A dam is built across the river to store water at a higher level. When this stored water in dam at the higher level flows under pressure to the lower level, it can run the turbine to generate electrical power. A hydroelectric power plant is shown in Figure 1.2. It consists of (i) reservoir, (ii) penstock to carry water from reservoir to turbine, (iii) turbine to convert water energy into mechanical work, (iv) generator to convert mechanical work into electrical energy and (v) power transmission system.

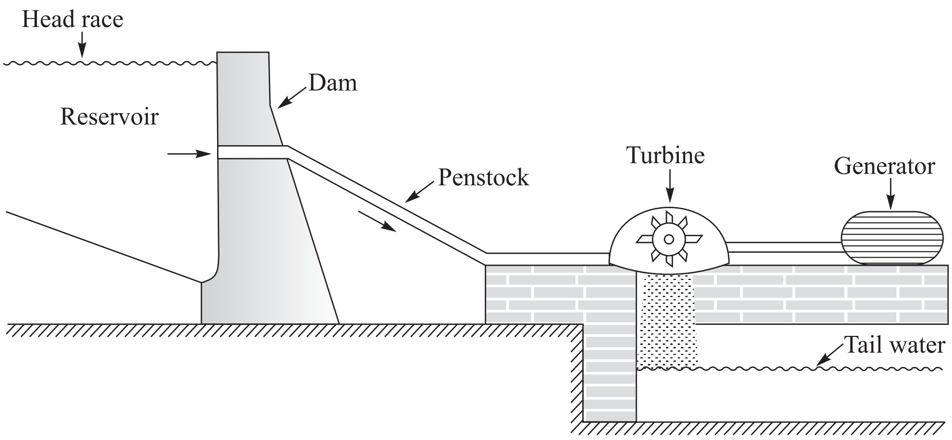


Figure 1.2 A hydroelectrical power station.

1.3.3 Nuclear Energy

- **What is nuclear energy? Explain the process of nuclear fission.**

The nuclear energy is released when atoms of certain unstable material split in the process of fission. A small mass of nuclear fuel such as uranium can release an enormous amount of heat energy when it undergoes fission process. One kilogram of uranium-235 can give heat energy on fission process which is equal to the heat which can be obtained by burning 4000 tons of high-grade petroleum. The uranium can be made to undergo fission process inside a nuclear reactor. The nuclear fission is a chain reaction as shown in Figure 1.3.

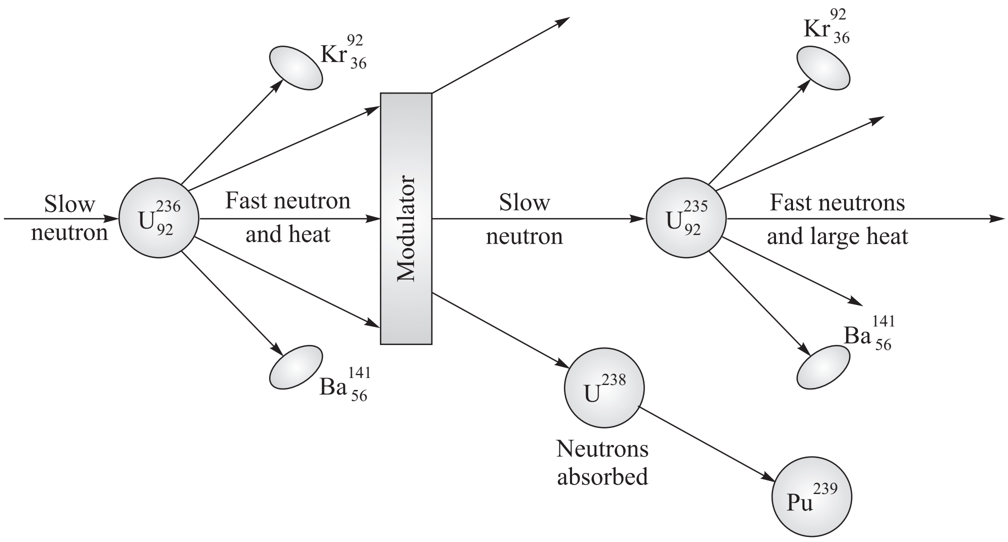


Figure 1.3 Fission process in the nuclear fuel.

1.3.4 Solar Energy

- **What is solar energy? Describe with the help of a neat sketch the working of a solar plant.**

or

- **What do you understand by photovoltaic conversion? What are the advantages and disadvantages of solar energy?**

The sun is a continuous fusion reactor in which hydrogen combines to form helium and liberates large amounts of heat in the process. The sun rays contain a large amount of energy in the form of electromagnetic radiation due to the continuous nuclear fusion reaction taking place in the sun. The energy is released at the rate of 3.7×10^{20} MW. This heat energy contained in the sun rays can be utilised to generate electrical power. The sun rays are focused on solar collector to heat butane water to generate butane gas in the butane boiler. The butane gas under high pressure from the boiler is taken to butane turbine to perform mechanical work. A generator is coupled to the turbine to generate electrical power as shown in Figure 1.4. The potential of power generation by solar energy can be in the order of 1.75×10^{11} MW. The mechanical devices which help to collect the solar radiations so as to convert them into heat energy are called solar collectors.

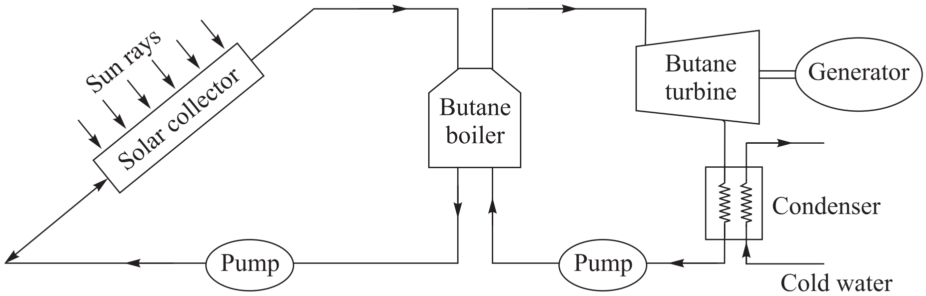


Figure 1.4 The power generation by the solar cell.

Photovaltaic conversion is a direct electricity generation method in which sunlight is converted into electricity using solar cells. The most common solar cells are manufactured from a highly refined silicon material. A single solar cell can produce electric power of 1 W at voltage of 0.5 V. Several solar cells can be connected in series or parallel to produce power of required voltage and current. Solar cells are an intermittent energy source and generally used with batteries to store generated electricity, thereby providing a more economical power generation system.

Advantages of solar energy are as follows:

(i) Solar energy is available freely in nature.
(ii) It is a renewable energy resource.
(iii) It does not pollute the environment.
(iv) It can be directly converted into electricity by employing photovoltaic cells.

Disadvantages of solar energy are as follows:

(i) It is available only during daytimes and clear days.
(ii) Solar energy obtainable also depends on seasonal variations.
(iii) It requires a large area to entrap appreciable solar energy for the generation of an economical amount of electricity.

1.3.5 Wind Energy

- **What is wind energy? How are windmills classified? What are the advantages and disadvantages of wind energy? Why are blades made of fibre-reinforced plastic (FRP)?**

Wind is induced in atmosphere by uneven heating of earth's surface by the sun. The wind energy is associated with the movement of large masses of air from cold to hot regions. The motion results from uneven heating of atmosphere by sun, thereby creating, temperature, density and pressure differences. The wind energy can be used to run windmill, which in turn will drive a generator to produce electric power or run water pumps. The energy available in the wind is about 1.5×10^7 MW.

Windmill is a device which converts the kinetic energy of the moving mass of air or wind into mechanical work. The windmills can be classified depending on the orientation of axis of rotation as horizontal axis windmill as shown in Figure 1.5a and vertical axis windmills as shown in Figure 1.5b. The windmills can also be classified based on the number of blades as single bladed windmill, double bladed windmill, three bladed windmill and multibladed windmill as shown in Figure 1.6.

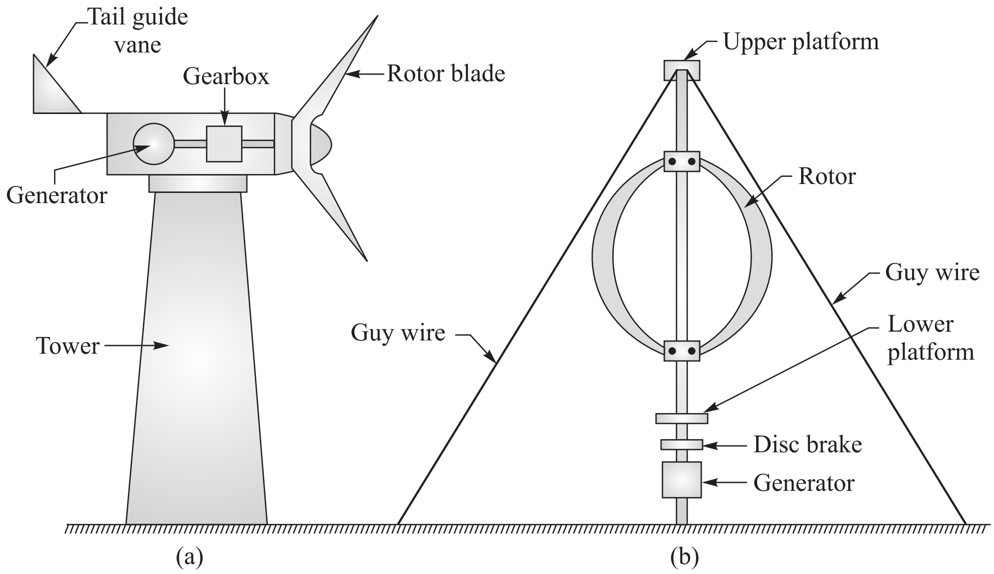


Figure 1.5 Horizontal and vertical axis windmills. (a) Horizontal axis windmill and (b) vertical axis windmill.

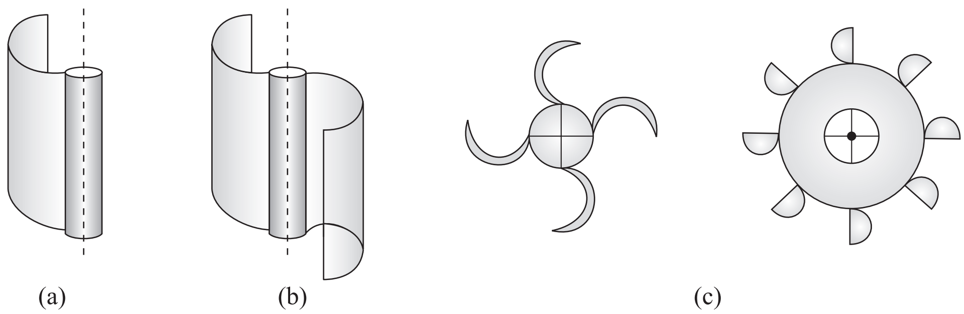


Figure 1.6 Windmills with different number of blades. (a) Single bladed rotor, (b) double bladed rotor and (c) multibladed rotor.

The blades of the windmills are generally made of composite materials such as fibre-reinforced plastic because this material is less costly, easy to use for manufacturing and possesses high strength to weight ratio.

Advantages of wind energy are as follows:

(i) It is freely and abundantly available in nature.
(ii) It is a renewable energy source.
(iii) It does not cause pollution to environment.
(iv) Windmills require minimal maintenance and operating cost.

Disadvantages of wind energy are as follows:

(i) It cannot produce steady and consistent power.
(ii) It can generate only low power.

1.3.6 Tidal Energy

- **What is tidal energy? Explain with a neat sketch the working of a tidal power plant.**

Ocean waves and tides contain a large amount of both potential and kinetic energy which can be utilised for power generation. A tide is the periodical rise and fall of sea water caused principally by the interaction of the gravitational fields of the sun and the moon. The highest level of tidal water is called flood or high tide and the lowest level is called low or ebb tide. The level difference between the high and the low tide is called tidal range. The up and down movement of the tide is used for filling and emptying the tidal basin of the plant. The typical tidal plant is shown in Figure 1.7. The tidal basin is filled up during high tide and it is emptied out during low tide. The flowing in and flowing out water between sea and tidal basin is used to run a turbine and generate electricity.

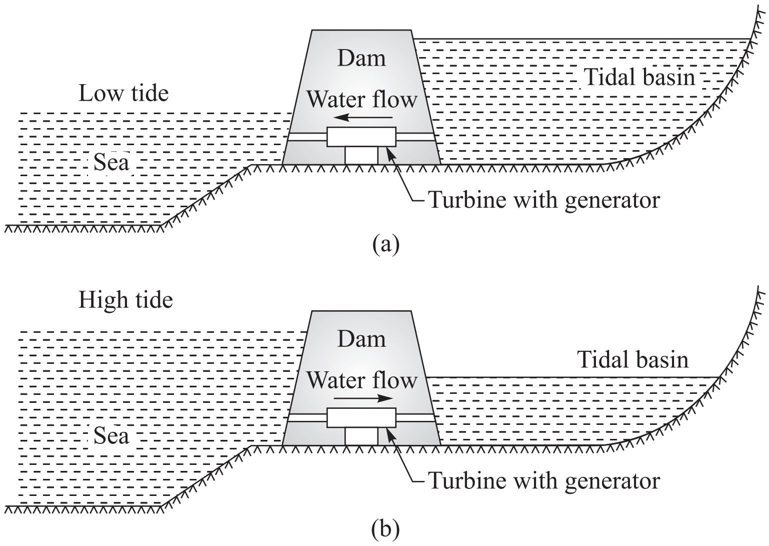


Figure 1.7 High and low tide and working of a tidal plant.
(a) Low tide and water flows out from tidal basin, thereby running turbine.
(b) High tide and water flows in from sea to tidal basin, thereby running turbine.

Advantages of tidal energy are as follows:

(i) It is free from pollution.
(ii) It is superior to hydel energy as it does not depend on rains.
(iii) The tidal basin can also be used for fish farming.
(iv) It is best suited to meet peak power demands.

Disadvantages of tidal energy are as follows:

(i) Tidal power plant is costly compared to thermal and hydel power plants.
(ii) Limited locations are available for the construction of tidal power stations.
(iii) Power generation is not continuous and depends on the capacity of tidal basin.

1.3.7 Geothermal Energy

- **What is geothermal energy? Explain the working principle of a geothermal power plant with the help of a neat sketch.**

The word geothermal is a Greek word meaning the heat of the earth. The temperature at earth's core is on the order of 4000°C. The internal heat energy available at a considerable depth below the surface of the earth is called geothermal energy. It is the heat source in the form of molten rock within the earth which is called magma and it has the temperature of about 3000°C.

A geothermal power plant is shown in Figure 1.8. The water is made to flow down through a porous layer to magma heat source where the water is converted into steam by the heat available at magma. The steam comes out through the vents of the earth surface. This steam is used to vapourise certain low boiling refrigerant. This high pressure refrigerant steam is used to run the turbine. The turbine runs a generator to produce electric power.

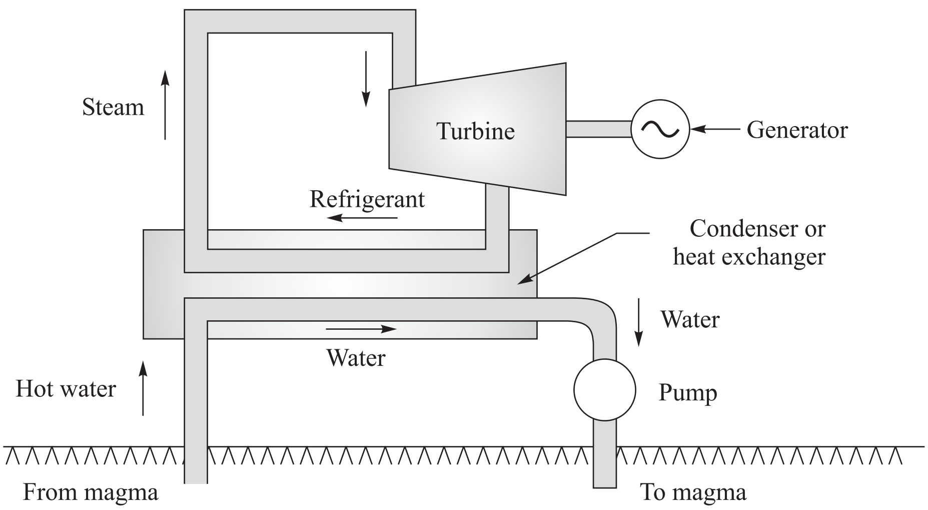


Figure 1.8 Geothermal power plant.

Advantages of geothermal energy as follows:

(i) Energy is continuously available. It is more reliable.
(ii) It has a good potential to meet the power requirement.
(iii) Capital cost is low in comparison to nuclear and thermal power plants.

Disadvantages of geothermal energy are as follows:

(i) Components of the plants are liable to be corroded.
(ii) Gaseous effluent creates nuisance at the site for the workers.
(iii) Gaseous effluent also creates thermal pollution to the environment.
(iv) Groundwater is likely to be polluted from gaseous effluents.

1.3.8 Ocean Energy

- **What are the various types of energy which ocean can provide? Explain Ocean Temperature Energy Conversion (OTEC) and working of an OTEC power plant with the help of a sketch.**

The various types of energy resources which ocean can provide are as follows:

(i) The tides of the ocean can be used to generate electricity.
(ii) The wind produces large waves in the ocean having high kinetic energy which can be converted into electric power.
(iii) The temperature gradient from the surface of ocean to the great depth inside the ocean can be used to provide thermal energy to generate electricity.

The water at the ocean surface is around 25°C, while it is about 5°C at a depth of 100–200 m. Hence, these is a temperature gradient of about 20°C between these two levels and this can be used for generation of electricity by Ocean Thermal Energy Conversion (OTEC). A low boiling point liquid such as ammonia, propane or freon can be vapourised into high pressure vapour using the heat of warm water available at the ocean surface into a boiler as shown in Figure 1.9. The liquid vapour is then used to run a turbine coupled with a

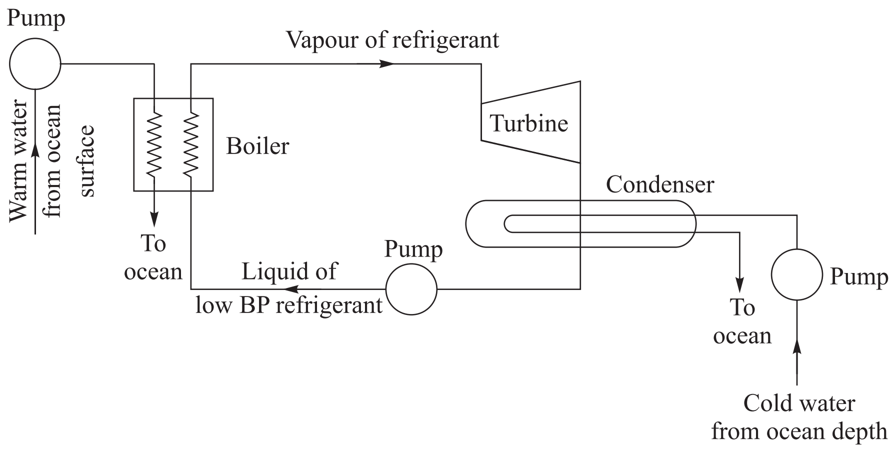


Figure 1.9 OTEC power plant.

generator to produce electricity. After expansion in the turbine, the liquid vapour is condensed into liquid in the condenser using cold water from the deep ocean at a temperature of about 5°C. The condensed liquid is pumped back to the boiler so as to be heated by warm water from the ocean surface. This cycle is repeated.

Advantages of OTEC are as follows:

(i) Power generation is continuous throughout the year.
(ii) Energy is available from nature at no cost.

Disadvantages of OTEC are as follows:

(i) It has a small temperature gradient which gives a small thermodynamic efficiency.
(ii) Capital cost is high due to necessity of heat exchanger, boiler and condenser.

1.4 ENERGY PARAMETERS

The consumption of energy as well as the growth of energy requirement has to be monitored by every nation. To conserve energy resources, it is necessary for every nation to adopt measures to maximise economic development with minimum energy consumption. The energy parameters are measured using the yardstick of gross domestic product (GDP). The GDP is the value of all finished goods and services produced in a given period.

1.4.1 Energy Intensity

- **What do you understand by energy intensity? What are the factors affecting the energy intensity?**

The energy intensity is defined as the ratio of energy consumption and GDP.

$$\text{Energy intensity} = \frac{\text{Energy consumption}}{\text{GDP}}.$$

The energy ratio is a measure of the efficiency in utilising energy in developing national economy. High value of energy intensity indicates that higher amounts of energy resources are used in converting these resources to national GDP or economy. Lower energy intensity indicates that a lower price or cost is made in converting energy resources into national GDP. Factors affecting energy intensity are as follows:

(i) Energy efficiency of the appliances and buildings by proper design and provision of insulation
(ii) Fuel economy of vehicles
(iii) Frequency of travel and larger geographical distances, resulting in greater travelling and energy consumption
(iv) Economical means and pattern of transportation
(v) Availability of mass transit system and its capacity and utilisation
(vi) Efforts to conserve energy
(vii) Weather with mild temperature not requiring heating or cooling

Developed countries such as the USA and Japan have reduced energy intensity compared to underdeveloped countries. India has power intensity which is 8.5 times higher than that of Japan and 2 times higher than that of the USA.

1.4.2 Energy Elasticity

- **What is energy elasticity?**

It is defined as the growth in energy requirement per GDP.

$$\text{Energy elasticity} = \frac{\text{Growth in energy requirement}}{\text{GDP}}$$

The energy should contribute in increasing the GDP. The lower is the value of energy elasticity the more is the growth of GDP. The value of energy elasticity for the developed countries ranges from 0.8 to 1.0. The value of energy elasticity for India is about 1.2. Hence, in our country, there is scope for improvement in the efficiency of energy consumption as well as energy saving in industry.

1.5 INDIAN AND GLOBAL ENERGY RESOURCES

The average percentage consumption of various primary energy resources in the world is shown is Figure 1.10. There is currently heavy dependence on fossil fuels. Nearly 87% of the world's energy supply primarily comes from fossil fuels. India's use of fossil fuels constitutes more than 90% of its total energy consumption.

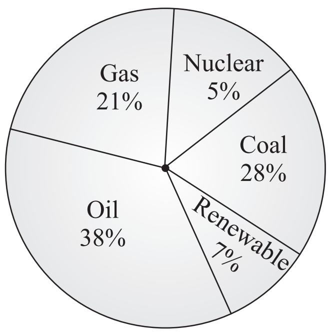


Figure 1.10 Percentage consumption of primary energy resources in the world.

1.5.1 Significance of Non-Conventional Energy Resources

- **Why importance is being given to non-conventional energy resources?**

There is a growing concern worldwide on the use of fossil fuels for the following reasons:

(i) There is ever-increasing use of fossil fuels.
(ii) Depletion of fossil fuels is taking place at a rapid pace.

(iii) There may be oil crisis as happened in 1973. Organisation of Petrol Exporting Countries (OPEC) put an embargo on oil production in 1973 and these countries started an oil pricing control strategy, resulting in severe energy crisis and steep rise in oil prices worldwide.

Owing to above reasons, more importance is being given to the development of alternative sources of energy such as non-conventional, renewable and environmental-friendly. The importance of non-conventional energy resources is also increasingly felt due to the following reasons:

(i) The demand of energy is rapidly increasing due to fast industrialisation and population growth. The conventional energy resources are insufficient to meet such growing demand.
(ii) The conventional energy resources are non-renewable and these are depleting fast.
(iii) The conventional energy resources (fossil fuels) on usage cause pollution, thereby degrading the environment.
(iv) The projects to harness large hydro resources affect wildlife, cause deforestation and affect nearby villagers due to submerging of a vast area.
(v) Fossil fuels are also used as raw materials in the chemical industry. There is need to conserve fossil fuels for future generation.

It is important to explore and develop non-conventional energy resources to reduce excessive dependence on conventional resources. The present trend is to develop non-conventional resources to serve as supplement rather than alternative for conventional sources for some more time to come.

1.5.2 Energy Policy in India

- **What is the energy policy formulated by the Government of India?**

The Government of India has formulated an energy policy to ensure adequate energy supply at minimum cost, self-sufficiency in energy supplies and protection of environment from an adverse impact of utilising energy resources in any unjust manner. The policy has the following features:

(i) Accelerated exploitation of domestic conventional energy resources such as fossil fuels, hydro and nuclear energy
(ii) Intensification of exploration to achieve, indigenous production of oils and gases
(iii) Management of demand of oil and other forms of energy
(iv) Energy conservation and its management
(v) Optimum utilisation of existing capacity in the country
(vi) Development and exploitation of renewable source of energy to meet energy requirement of rural communities
(vii) Intensification of resources and development activities in new and renewable energy resources
(viii) Organisation of training for personal engaged at various levels in the energy sector.

1.5.3 World Energy Status

- **Describe briefly the world energy status.**

The present availability of energy resources in world is discussed next.

Conventional resources

(i) **Fossil fuels.** The fossil fuels have been a major source of energy. These include coal, oil and gas. These fuels are formed by slow decomposition of organic matters under pressure, heat and bacterial action at a considerable within the depth earth. Fossil fuels are expected to last for few decades.

(ii) **Hydro resources.** These are renewable and non-polluting. These require huge capital investment. So far 20% potential has been harnessed. The global installed generating capacity is about 627,000 MW, thereby generating 23% of total electricity produced in the world.

(iii) **Nuclear resources.** Uranium reserves are scarce in the world and they are expected to last for 5 decades. There are about 440 nuclear power plants in the world, generating about 1/6th of the world's electricity. Fast breeder reactors (FBRs) utilise fast neutrons and these generate more fissile materials than they consume.

Non-conventional sources

(i) **Solar energy.** Solar energy can be a major source of power which can be used in thermal and photovoltaic conversion systems. The earth continuously intercepts solar energy of 178 billion MW, which is 10,000 times more than the world's requirement. However, solar PV power cells are an expensive source of power.

(ii) **Wind energy.** The power estimated to be harnessed from wind energy turbines is about 1.6×10^5 MW. It is the most economical energy resource. The worldwide installed wind energy generation capacity is 47,317 MW.

(iii) **Biomass energy.** Biomass energy resources consist of (i) wood, leave and forest industry waste, (ii) algae and other vegetation from ocean and lake, (iii) municipal and industrial waste and (iv) rural waste. Biomass materials can be transformed by biological processes to produce biofuels such as methane, producer gas, ethanol and charcoal. Biomass can supply energy which is estimated to be about 2×10^{21} J in a year.

(iv) **Geothermal energy.** The present installed electrical power generating capacity from geothermal resources is about 7704 MW in the world while the direct thermal use installed capacity is about 16,649 MW.

(v) **Ocean tidal energy.** There is a potential of about 550 billion kW/year energy, which is possible from ocean tidal energy resources. Currently, very few tidal power plants are installed worldwide.

(vi) **Ocean wave energy.** The estimated potential of this resource is 20×10^5 MW. However, no major development work has been carried out to utilise this resource.

(vii) **Ocean thermal energy conversion.** It has more potential than that of tidal or wave energy resources. No commercial installation has been done so far to utilise this resource.

1.5.4 Indian Energy Scenario

- **Describe the future of non-conventional energy sources in India.**

or

- **What is meant by renewable energy sources? Explain in brief these energy sources with special reference to India.**

or

- **Discuss the possibility of exploiting the non-conventional energy in India.**

or

- **What is the present installed power generation capacity in India? Discuss the contribution of different types of power plants.**

or

- **Discuss the merits and demerits of various renewable technologies developed in India.**

or

- **Discuss in details about reserves and production of petroleum and natural gas in India with problem area.**

or

- **Describe the various non-conventional energy resources relevant to India.**

or

- **Write your views on the energy planning issues aiming to bridge the gap between the energy demand and the supply situation in India.**

or

- **How renewable energy is spreading wings in India?**

or

- **Describe the energy position in India.**

or

- **Give brief review of various sources of renewable energy.**

Energy position in India

In India, enormous demand for electricity has arisen due to the economic growth during the past two decades. In India, the total power generation capacity in 1947 was only 1360 MW. According to the five-year plans, the total power generation capacity should be 425,000 MW by 2007 but actual installed capacity is much lower. However with the liberalisation of Indian economy, the power sector has been made open to the private sector, and it is now expected that the growth rate of power generation capacity will be faster than what is estimated in the five-year plan. Generation capacity by different types of power plants in India as planned is shown in Table 1.3. However, at present the total installed generation capacity is about 182,689 MW. The breakdown of the same as per sector and type of fuels is shown in Tables 1.4 and 1.5.

TABLE 1.3 Indian generation capacity (in MW) as planned

Power plant	*Year* (1991)	8th *Plan* (1997)	9th *Plan* (2007)	10th *Plan* (2007)	*Total*
Thermal	45,000	28,000	32,000	58,000	16,300
Hydro	18,443	8,680	26,000	23,000	76,123
Nuclear	1,500	1,320	2,880	–	5,700
Others	–	38,000	61,000	81,000	180,000
Total	64,943	76,000	121,880	162,000	424,823

TABLE 1.4 Total installed capacity as per sector in India

Sector	MW	%
State sector	83,563.65	47.74
Central sector	56,572.63	30.96
Private sector	42,553.34	23.29
Total	182,689	

TABLE 1.5 Total installed capacity as per the fuel type in India

Fuel	MW	%
Total thermal	119,040.90	65.16
Coal	100,098.38	54.29
Gas	17,742.85	9.71
Oil	1,199.75	0.65
Hydro	38,706.40	21.18
Nuclear	4,780	2.16
RES (Renewable energy sources)	20,162.24	11.03
Total	1,82,689	

Nuclear energy. About 2.6% of power generating capacity is nuclear based in India. It corresponds to about 4780 MW of the installed capacity. Tarapore was the first atomic power station with foreign technology and Kalpakkam atomic power plant in Madras in 1983 was first indigenously commissioned plant. The nuclear fuel such as uranium is found in Bihar, Rajasthan and Chennai. Uranium reserve in India is estimated to be about 33,000 tons. Thorium is another nuclear fuel and it is present in the monazite beach sand in Kerala Bhabha Atomic Research Centre (BARC) at Trombay is the major centre for research in atomic energy in India. The major atomic power plants are as follows:

(i) Tarapore Plant in Maharashtra
(ii) Madras Atomic Power Station, Kalpakkam, Tamil Nadu
(iii) Rana Pratap Sagar Rajasthan
(iv) Narora, Uttar Pradesh

Solar energy. Solar electrification in remote villages has begun. Salijipally in Andhra Pradesh became the country's first village to be electrified using SPV (Solar photovoltaic) system. The first two 100 KW partial grid interactive SPV power projects at Kalyanpur in Aligarh district and Saraisadi in More district have been commissioned. Work on solar power is being carried out by (i) IIT, Mumbai, (ii) BHEL, Hyderabad, (iii) NPL, New Delhi, and (iv) NAL, Bangalore.

Fossil fuels. The amount of coal deposition in India is estimated to be about 85,000 million, tons. The major portion, that is 60% of the coal, exists in the eastern part of the country, which includes Jharkhand and West Bengal. The low-grade coal called lignite is found in Tamil Nadu and Rajasthan.

The major thermal power plants in India are shown in Table 1.6.

TABLE 1.6 Thermal power plants

S.No.	*State* (MW)	*Power plant*	*Capacity*
1.	Tamil Nadu	Neyveli	900
		Encore	450
2.	Andhra Pradesh	Kothagudam	240
		Barauni	445
3.	Bihar	Bakaro	325
		Badarpur	400
4.	Delhi	Harduaganj	640
5.	Uttar Pradesh	Obra	550
		Nagpur	670
6.	Maharashtra	Chandrapur	480
7.	West Bengal	Durgapur	290
		Faridabad	385
8.	Haryana	Panipat	220

Wind energy. The total wind energy potential is estimated at 20,000 MW. Currently, total capacity of 732 MW has been installed. Following are sites where windmills are installed:

(i) Kayathar wind farm, Thirunelveli (Tamil Nadu)
(ii) NAL, Bangalore
(iii) BHEL, Hyderabad
(iv) Sholapur, Maharashtra
(v) Jodhpur, Rajasthan

Hydel energy. India has a huge hydropower potential, which is estimated at 150,000 MW, but only about 38,700 MW has been installed so far. A few major hydroelectric power plants are shown in Table 1.7.

TABLE 1.7

S.No.	*Hydel project*	*River and state*	*Capacity* (MW)
1.	Bhakra and Nangal Dam	Sutlej, Punjab	1150
2.	Methur project	Cavery, Tamil Nadu	360
3.	Periyor project	Periyor, Tamil Nadu	150
4.	Kodayar porject	Kodayar, Tamil Nadu	100
5.	Koyan Hydro Electric project	Koyan, Maharashtra	960
6.	Sharavathi project	Sharavathi, Karnataka	890
7.	Sri Sailam Hydel project	Godavari, Andhra Pradesh	710
8.	Idukki Hydel project	Idukki, Kerala	800

Tidal energy. The tidal power potential in India is estimated to be about 9000 MW. The potential sites identified are as follow:

(i) Gulf of Cambay in Gujarat
(ii) Gulf of Kutch in Gujarat
(iii) Sundarban area in West Bengal

Geothermal energy. There are nearly 250 potential sites in India. The most potential sites are located at Puga valley in Ladakh and Manikaran in Himachal Pradesh.

Ocean thermal energy. There is 50,000 MW power potential from ocean thermal energy source. Potential sites are located near the islands of Lakshadweep and Andaman and Nicobar.

Non-conventional energy

The Indian government is encouraging New and Renewable Source of energy (NRSE) to meet (i) the growing demand of energy without dependence on the conventional energy sources which are fast depleting, (ii) needs of the rural areas and (iii) requirements of clean fuels which do not contribute to pollution. The department of "Non-Conventional Energy Sources (DNES)" was set up in 1982, which has been now upgraded as Ministry of Non-Conventional Energy Sources (MNES). The ministry would look after the development of new non-conventional sources of energy. Its main activities involve the following:

(i) To start programme for development of solar energy, wind energy, ocean energy, hydrogen energy, biomass energy, chemical sources of energy, energy from waste, biogas, waste recycling, magnetiohydrodynamics (MHD), thermoelectric and geothermal energy
(ii) To elicit the cooperation of local communities by meeting their needs for small power, such as energy for cooking, supply of water for minor irrigation, drinking and domestic purposes and street lighting
(iii) To create a number of industrial bases in the country for the development of technology to harness various renewable energy sources, such as solar thermal, solar photovoltaic, wind, small hydro, biomass and ocean. An aggregate capacity of about 900 MW has been installed based on these technologies

(iv) To develop alternative fuels to diesel and motor spirit in order to reduce the consumption of these commercial fuels as their reserves are limited and their consumption involves outflow of precious foreign exchange. The various alternatives are compressed natural gas (CNG), hydrogen, gasohol and hydrocarbon.

Status and potential of renewable power

Renewable sources can provide both grid connected power and off-grid power for lighting, pumping, thermal and heat generation and transportation. According to the assessment by MNES, the country has potential of 135,853 MW, while 14,914 MW has been installed as shown in Table 1.8.

TABLE 1.8 Renewable power status and potential

S.No.	*Source*	*Potential* (MW)	*Installed* (MW)
1.	Wind energy	48,561	10,464
2.	Small hydropower	14,292	2,461
3.	Biogas	5,000	1,555
4.	Bio-power	61,000	773
5.	Waste energy	7,000	59
6.	Solar photovoltaic (SPU)	20	2
	Total	135,853	14,914

New solar power generation technologies such as concentrating solar thermal power (CSP) and "concentrating photovoltaic (CPV)" are being developed. These new technologies are capable of large-scale power generation from the sun energy. It is estimated that these technologies when applied in desert area can produce 100,000 MW from the area of 80×60 km^2. A state such as Rajasthan has about 200,000 km^2 of desert land. Hence, the potential of renewable power is tremendous in India. India has to put more efforts in developing renewable energy technologies accompanied with drastic measures for energy conservation such as better designs of buildings, appliances and transport modes.

Alternative fuels

MNES is taking appropriate measures to develop alternative fuels to reduce the consumption of conventional fuels such as diesel and motor spirit. The various alternative fuels which are being developed to replace commercial resources are as follows:

(i) **Compressed natural gas (CNG).** The CNG is compressed 160 to 200 times the atmospheric pressure so as to store in proper size cylinders that can be mounted on vehicles. In petrol engines, CNG is expanded to subatmospheric pressure by a convertor before it is fed into the carburettor, while in diesel engines, it is injected in small doses into the cylinder. Nowadays, buses and trucks are primarily running on CNG and CNG is also extensively used in auto-rickshaws and taxis. Gas Authority of India Limited (GAIL) has set a target to convert about 65,000 petrol running cars to run on CNG. A car with two CNG cylinders can run for 100 km while buses or trucks with six cylinders can run for 300 km.

(ii) **Hydrogen.** Hydrogen is an ideal fuel as it is non-polluting. However, hydrogen is a light gas and only a small amount of hydrogen can be carried in a cylinder as it cannot be liquidified at normal temperature. Hence, a vehicle can run for small distance with the stored hydrogen in a cylinder. Unless hydrogen can be carried in sufficient quantity in a cylinder, it is impossible to use hydrogen as suitable fuel for the vehicles.

(iii) **Gasohol.** The mixture of petrol and alcohol is called gasohol. The gasohol can be used in place of petrol in the petrol-driven cars. India follows Brazil and has made the use of gasohol (petrol + 5% ethanol) compulsory in its nine states. This step will help to curb India's huge import of crude oil. Gasohol is cheaper fuel than normal petrol. Brazil is using 22% alcohol in its blended fuel. Gasohol will give a boost to sugarcane production. Sugarcane is fermented to make ethanol. Petrol–ethanol blending is only a small step forward as diesel use accounts for almost four-fifths of Indian vehicles.

(iv) **Hydrocarbon.** Directorate General of Hydrocarbon (DGH) was established in 1997 under Ministry of Petroleum and Natural Gas to promote sound management of oil and natural gas resources in order to maintain balance in environment, safety, technical and economic aspects of the petroleum activity. The directorate is also entrusted with the task of future expansion and development of non-conventional hydrocarbon energy such as coal bed methane and also futuristic hydrocarbon energy resources such as gas hydrates and oil shales. Hydrocarbons can be produced from crude oil, plants, biomass, gas hydrate and oil shale. Algae *Botryococcus braunii* has hydrocarbon content as high as 75%. Hydrate is a mixture of water and natural gas and it occurs in the porous spaces of sedimentary rocks. Oil shale is an organic-rich, fine-grained sedimentary rock from which hydrocarbons called shale oil can be produced. Shale oil can be a good substitute for the crude oil but its production cost is high at this stage.

Renewable energy spreading wings in India

India has a vast potential for renewable sources and a number of technologies have been developed to harness these sources. Ministry of non-conventional energy sources is responsible for the development of these resources for commercial exploitation. A number of industrial bases have been set up in the country to develop technologies for their commercial exploitation. Various renewable energy resources are as follows:

(i) **Solar energy.** Sun is a source of enormous energy. Only 0.10% of 75,000 trillon kWh of solar energy reaches the earth, which is enough to fulfil the complete energy requirement of the world. In India, the two 100 kW solar photovoltaic projects at Kalyanpur in Aligarh and Saraisadi in Mau district have been commissioned. A 35 MW solar thermal power project at Maithania village in Jodhpur (Rajasthan) has been proposed.

(ii) **Biomass energy.** Biomass is available in plenty in India. A 10 MW rice straw-based thermal plant has been commissioned by BHEL at Jakhari in Punjab. A 100 kW gasifier system has been established at Port Blair.

(iii) **Ocean energy.** India has a vast potential for ocean thermal energy, which is about 50,000 MW. The potential sites are at Lakshadweep and Andaman and Nicobar Islands. First plant has been proposed at the coast of Tamil Nadu, which has the capacity of 100 MW.

(iv) **Wave energy.** The wave energy potential along the 6000 km long Indian coast is estimated to be about 40,000 MW. A 1 MW wave energy plant is being set up in Andaman and Nicobar Islands.

(v) **Tidal energy.** India has a huge potential for tidal energy and it is estimated to be about 900 MW.

(vi) **Wind energy.** Total wind energy potential in India is estimated to be about 20,000 MW. Coastal areas of Tamil Nadu, Gujarat, Andhra Pradesh and Maharashtra are suitable sites for wind power. A total of 732 MW has been installed.

(vii) **Geothermal energy.** In India, 340 hot springs at different locations have been identified with average temperature ranging 80–100°C. A pilot plant of 5 kW has been commissioned at Manikaran in Kulu district (Himachal Pradesh).

(viii) **Magnetohydrodynamic (MHD).** It converts thermal energy directly into electricity. In this process, turbine and generator are combined into a single unit. A 5 MW research and development porject is under development. Efficiency of renewable energy resources is generally low. However, this does not matter as these resources are freely available in nature. Besides, it is worthwhile to harness these resources as these are non-depleting and non-polluting types. These resources can be harnessed in rural areas where the equipment for harnessing can be provided at subsidized rates. Biogas plant and solar photovoltaic (SPV) units for (i) street lighting, (ii) pumping of water and (iii) house lighting in rural areas are being set up with the government assistance.

Merits and demerits of renewable resources

Solar energy

(a) **Merits**

(i) Non-polluting source of energy
(ii) Available free of cost in nature
(iii) Non-depleting source of energy

(b) **Demerits**

(i) It is intermittent type in nature and it is unavailable at night-time. Hence, energy generated in day hours is required to be stored for using in night hours.
(ii) The cost of solar devices is high and their efficiency of conversion is low.
(iii) It has seasonal variation.
(iv) It requires large area to entrap.

Wind energy

(a) **Merits**

(i) It is available free of cost in nature.
(ii) It is non-polluting.
(iii) It is non-depleting.
(iv) It can run a generator or a water pump.

(b) **Demerits**

(i) It is available in small amount, depending on wind speed. It is also fluctuating type and depends on wind speed.

(ii) It is suitable where wind speed is sufficiently high, such as in the coastal area.
(iii) The size of windmill has to be large.
(iv) The wind direction keeps on changing. Windmill should be capable of utilising wind irrespective of its direction.
(v) Maintenance cost of windmills is high.

Biomass energy

(a) **Merits**

(i) It helps to utilise wood and agriculture wastes which are available almost free of cost.
(ii) It can be converted into liquid fuels which have commercial use like conventional fuels.
(iii) Biogas can be used in industrial applications.
(iv) It is non-depleting, cheap and uninterrupting type.

(b) **Demerits**

(i) Power generations units are bulky.
(ii) Unsuitable for cold regions as the conversion of waste into biomass needs warm climate or heating.

Tidal energy. See Section 1.3.6 for merits and demerits of Tidal energy.

Geothermal energy. See Section 1.3.7 for merits and demerits of geothermal energy.

Ocean energy. See Section 1.3.8 for merits and demerits of Ocean energy.

Growth of energy sector and its planning in India

Power is essential for the growth of national economy. Power is directly linked to the national GDP. India is the 6th largest energy consumer in the world. India has 6% growth rate in power generation, while its demand is increasing at the rate of 9%. Hence, the gap in supply and demand is ever-increasing in India. There is a shortfall of power amounting to about 20%. The installed capacity has increased from 1360 MW in 1947 to 182,689 MW in 2010. The capacity utilisation is estimated to be less than 60%. The energy planning with demand installed capacity and shortage are given in Table 1.9. The country needs additional power generation of 100,000 MW in the next few years. National goal is to achieve power

TABLE 1.9 Energy planning in the past five-year plans

Five-year plan	*Demand* (MW)	*Installed capacity* (MW)	*Shortage* (MW)
6th (1980–1985)	52,000	47,000	5,000
7th (1985–1990)	75,000	65,000	10,000
8th (1990–1992 and 1992–1997)	100,000	85,000	20,000
9th (1997–2002)	132,000	110,000	22,000
10th (2002–2007)	146,000 (158,000 by 2012)	182,689 as on Nov 2010	60%

generation of 200,000 MW by 2012, which includes 10,000 MW from non-conventional energy sources.

There is about 6 lakh villages in the country and about 1 lakh villages are without electrification. Electrification of rural areas is very important to ensure uniform development of the country. There are about 25,000 villages that are located in remote and difficult areas which cannot be electrified by the conventional electric grid method. These villages have to be electrified using non-conventional energy sources such as mini-hydro, solar energy or biomass energy generation. It is proposed to electrify all villages by 2012.

Petroleum and natural gas reserve and production

Forty per cent energy requirement of the world is met by oil petroleum. However, the rising prices of oil has brought a considerable strain to the world's economy. With present consumption rate, a resource amount of 250,000 million tons of oil is needed per year. It would suffice for about 100 years or so unless more oil is discovered. There is apprehension and question is being asked whether and alternative to conventional oils would be developed by that time. The world has started searching for an alternative to change the world's economy dominated by oils being produced by refining petroleum.

India is not rich in petroleum reserves. The potential oil-bearing areas are located in Assam, Manipur, Tripura, West Bengal, Punjab, Himachal Pradesh, Ganga Valley, Kutch, Eastern and Western coastal areas, Andaman and Nicobar islands, Lakshadweep and adjoining sea such as Bombay High. Almost 1200 MW power is generated using conventional oils in India.

Natural gas is not fully utilised at present in India. A huge quantity of gas is burnt off in the oil production and refining stages because proper facilities for its storage and commercial utilisation are not available. Another reason is the high transportation cost of the gas. Large reserves of gas are located in difficult and inaccessible areas. Almost 17,742.85 MW power is generated using gas in India.

Coal: reserve and production

Coal is the major source of energy and it accounts for about 54.92% of power generation. There is about 100,098 MW installed power capacity using coal as the fuel. Coal is available at Raniganj (West Bengal), Jharia, Bokaro, Karanpura (Jharkhand), Chhattisgarh, Singarni (Andhra Pradesh), Talcher (Orissa) and Chanda (Maharashtra). India has coal reserves of 52.24 billion tons. This may deplete in the period of few decades or so unless more deposits are located. Coal serves as the primary source of energy for 25% of population of India who are below the poverty line. Coal is also widely used in industrial production in sectors such as textiles chemicals, food processing, steel, cement and machinery. Challenges to coal mining are as follow:

(i) Majority of coal deposits are in the eastern and central parts of India while thermal plants are widely dispersed and coal transportation for long distances is costly.
(ii) Crude methods are used in production which increase the cost of production.
(iii) A large amount of impurities are present in coal and it cannot be used as such due to risk of polluting the environment.

(iv) Mines are being operated in small scale, thereby causing high cost of production.
(v) There is high requirement of coal for industrial and domestic consumption.

Drivers and inhibitors in energy sector

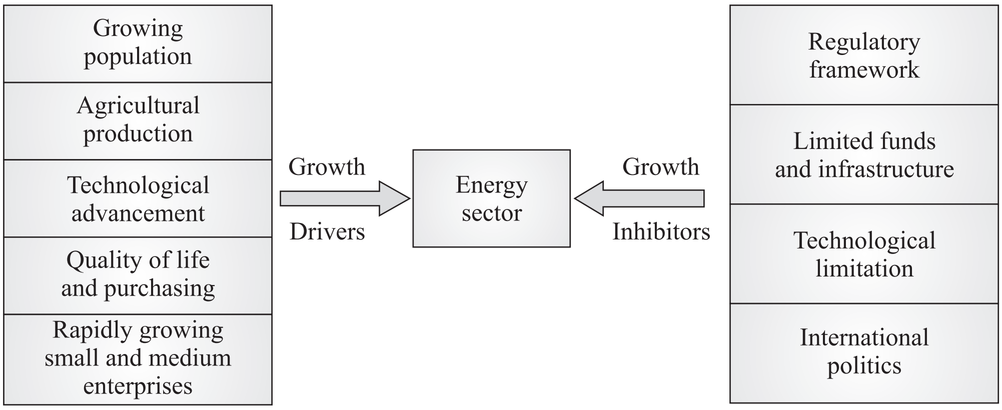


Figure 1.11 Growth drivers and inhibitors in the energy sector.

The growth drivers and inhibitors in energy sectors are shown in Figure 1.11. The energy growth rate depends on growth in population, agricultural and industrial production, GDP and economic growth. However, certain stringent government policies, technological limitation, shortage of funds and infrastructure act as inhibitors to the growth of energy sectors. The key Indian players in energy sectors are IOC, HPCL, BPCL, ONGC and RIL. The three major consumers for energy are household segment, industrial sector and the transport segment. The expected sectoral rates of consumption by 2019 is estimated and it is shown in Figure 1.12. India produces oil of about 785,000 bbl/day as against oil reserves of 5.7 billion bbl. India stands at 24th position in the world in annual oil production and it is the 10th largest importer of oil in the world. Natural gas is rated as the second fastest growing primary energy source in the world. India has meagre 10% of world's gas reserve. The consumption of gas is likely to increase at the rate of 4.8% per year as against production growth rate of 3.5% per year. The current consumption level of refined products (gasoline, diesel, LPG, kerosene, etc.) is 2,623,000 bbl/day, while the production level is 1 billion ton. Hence, India expects to export 900,000 bbl/day of refined products, thereby becoming the second largest refined product exporter in the world.

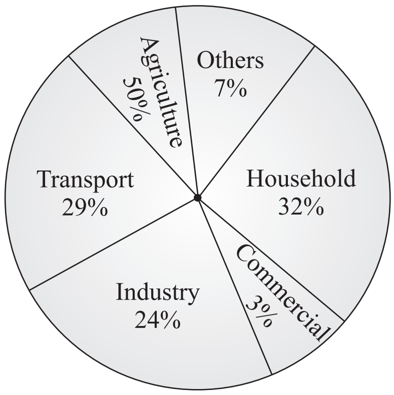


Figure 1.12 Expected sectoral rates of energy consumption (2019).

1.6 ENVIRONMENT ASPECTS OF ENERGY

1.6.1 Pollution

- **What are the pollutants produced during energy conversion? What do you understand by indoor and outdoor pollution? What are the remedial actions?**

During every energy conversion process, some energy is released into the atmosphere in the form of heat. Some pollutants in the form of gases are also produced during conversion and these gases are also emitted into the surroundings. Both heat and gases can cause degradation of the environment. The emitted gases are as follows:

(i) **Carbon dioxide (CO_2).** Excess emission of CO_2 in the atmosphere causes global warming.
(ii) **Carbon monoxide (CO).** It severely impairs the oxygen-dependent tissues in the human body.
(iii) **Sulphur oxide (SO_x).** It causes respiratory diseases, acid rains and corrosion of metals and building stones.
(iv) **Nitrogen oxide (NO_x).** It can cause respiratory and cardiovascular diseases, deprive body tissues of oxygen and form acid in lungs.

The pollution can be of following types:

(i) **Indoor pollution.** Indoor pollution occurs by the use of conventional chullahs in rural areas. Nearly 5 lakh children and women die every year from diseases caused by indoor air pollution. Indoor pollution can be avoided by the use of improved household stove.
(ii) **Outdoor pollution.** This is mainly caused by the use of fossil fuels (coal and oil) in industry and transports.

The remedial actions are as follows:

(i) Lesser use of fossil fuels and use of more gasified coal.
(ii) Alternative fuels such as hydrogen which are non-polluting should be used.
(iii) Vehicles running on electricity or battery to be used instead of IC engines.

1.6.2 Greenhouse Effects

- **What do you understand by greenhouse effect?**

A greenhouse made of transparent glass sheets behaves differently to incoming shortwave radition and outgoing longwave radiation. It allows the entry of sunlight but prevents the exit of heat (reflected infrared radiation). The greenhouse can maintain a controlled and warm environment inside for growth of plants. The earth has an envelope of carbon dioxide (CO_2) which behaves similar to greenhouse. The envelope allows heat from sun to enter but prevent heat to escape from earth by stopping reflected infrared radiation. This phenomenon of greenhouse effect by CO_2 envelope helps the earth to maintain the surface temperature to 15°C (hospitable to life), otherwise the earth would become a frozen planet. Normal concentration of CO_2 is about 0.03% and any increase in the concentration of CO_2 will upset the temperature balance, resulting in further warming of the globe. The carbon dioxide emission is more from developed countries, accounting for 82% of total greenhouse gas emission of the world.

1.7 ENERGY CHAIN

- **What do you understand by energy chain?**

The primary energy sources in the raw form cannot be used directly. It is impossible to drive a vehicle or electric motor using coal, petroleum or uranium. The energy available in primary energy sources is called raw energy. The primary energy sources have to be transformed into useful forms of energy resources which are then called secondary energy resources fuels.

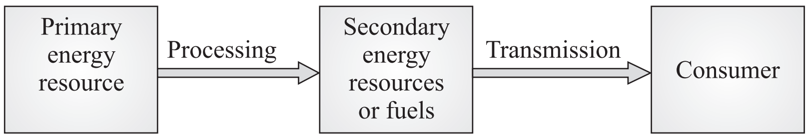


Figure 1.13 Energy chain or route.

The sequence of energy transmission from primary to secondary energy is called energy chain or energy route as shown in Figure 1.13. Mechanical energy, electrical energy and thermal energy can be obtained from primary and secondary energy resources.

CHAPTER 2

SOLAR RADIATION

2.1 INTRODUCTION

The sun is the largest member of our solar system. It is a sphere of extremely hot gaseous matter with a diameter of 1.39×10^9 m and it maintains a distance of 1.495×10^{11} m from the earth as shown in Figure 2.1. Sun's high temperature is maintained by enormous nuclear energy being released by the continuous fusion reaction. The fusion reaction involves four hydrogen atoms combining to form one helium atom ($4 \times {}_1H^1 \rightarrow {}_2He^4 + 26.7$ MeV). The sun as other hot bodies radiates heat energy uniformly in all directions. The radiated heat energy moves out as electromagnetic waves. The radiated heat energy increases the temperature of a body on its interception and absorption. This radiated heat energy from the sun is called solar energy and it provides the energy needed to sustain life in our solar system.

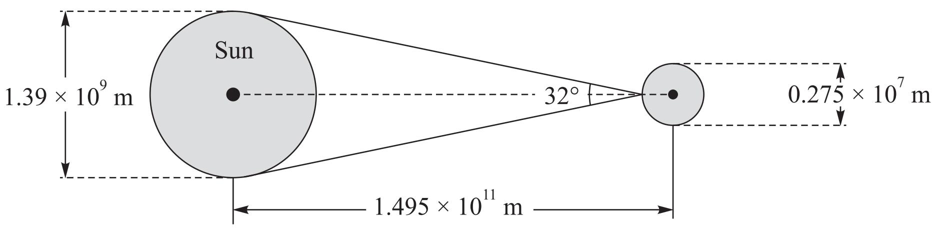


Figure 2.1 Sun and earth in the solar system.

2.2 RADIATION SPECTRUM FROM SUN AND EARTH

- **Explain the radiation spectrum emitting from the sun and the earth. What do you understand by irradiance and irradiation?**

Sun can be considered for all practical purposes as a black body having high surface temperature of 6000 K. The radiation spectrum consists of emission at various wavelengths but more at shorter wavelengths as shown in Figure 2.2(a). The maximum emissive power of the radiation takes place at wavelength of 0.48 μm. Similarly the earth can also be considered a black body at temperature of 288ºC. The radiation spectrum from the earth consists of emission generally of longer wavelengths as shown in Figure 2.2(b). The maximum emission is taking place at wavelength of about 10 μm.

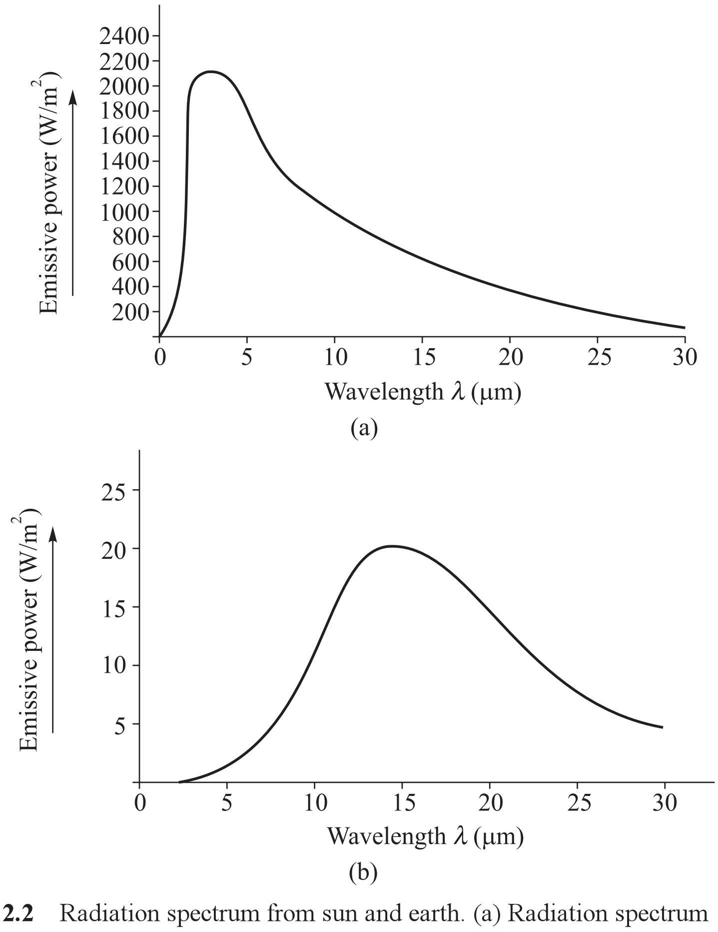


Figure 2.2 Radiation spectrum from sun and earth. (a) Radiation spectrum from the sun. (b) Radiation spectrum from the earth.

Irradiance

It is the rate at which radiant energy is incidenting on a unit surface area. It is the measure of power density of sunlight falling per unit area and time. It is measured in watt per square metre. Heat energy is measured in joules and while watt or joules per second is unit of power.

Irradiation

It is solar energy per unit surface area which is striking a body over a specified time. Hence it is integration of solar illumination or irradiance over a specified time (usually an hour or kilowatt a day). It is measured in kilowatt-hour or kilowatt day per square metre. For example, if irradiance is 20 kW/m^2 for 5 h, irradiation is $20 \times 5 = 100$ kWh/m^2.

2.3 EXTRATERRESTRIAL RADIATION AND SOLAR CONSTANT

- **Explain (i) extraterrestrial radiation, (ii) solar constant, and (iii) terrestrial radiation.**

or

- **Define solar constant. What are the reasons for variation in solar radiation reaching the earth and that received outside the earth atmosphere?**
- **Differentiate between beam and diffuse radiation.**

or

- **Explain (i) beam radiation, (ii) diffuse radiation, (iii) total radiation, and (iv) airmass.**

The earth revolves around the sun in an elliptical orbit as shown in Figure 2.3. The earth is closest to the sun on 21 March and 23 September. The earth is farthest from the sun on 21 June and 22 December. The mean distance of the earth from the sun is 1.495×10^{11} m.

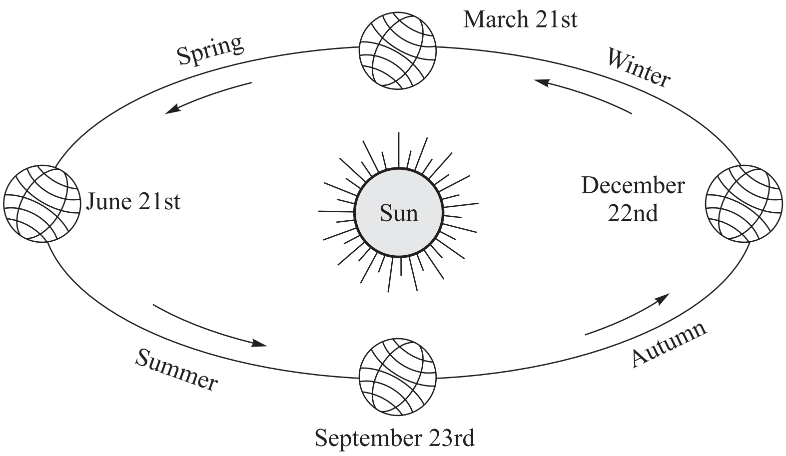


Figure 2.3 Elliptical orbit of earth's revolution.

The intensity of solar radiation outside the earth's atmosphere reduces with distance and it is dependent on the distance between the earth and the sun. In fact, the intensity of solar radiation reaching outside the earth's atmospheric varies with the square of the distance between the centres of the earth and the sun. This is the reason why earth receives 7% more radiation on 21 March and 23 September as compared to 21 June and 22 December. The intensity of solar radiation keeps on attenuating as earth propagates away from the surface of the sun, but the content of wavelengths in the radiation spectrum does not change.

The earth axis is tilted about 23.45° with respect to earth's orbit around the sun as shown in Figure 2.4. Owing to this tilting of earth's axis, the northern hemisphere of the earth points towards the sun in the month of June and it points away from the sun in the month of December. However, earth's axis remains perpendicular to the imaginary line drawn from the earth to the sun during the months of September and March. The sun–earth's distance varies during earth's rotation around the sun, thereby varying the solar energy reaching its surface during revolution, which brings about seasonal changes. The northern hemisphere has summer when the earth is tilting forwards the sun and winter when the earth is tilting away from the sun. In the months of September and March, both the hemispheres are at the same distance from the sun and receive equal sunshine. During the summer, the sun is higher in the sky, while the sun is lower in the sky during winter for the northern hemisphere.

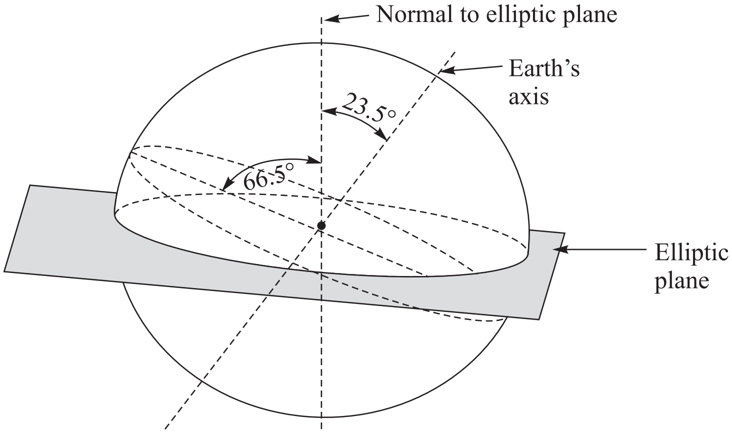


Figure 2.4 Inclination of earth's axis.

Extraterrestrial radiation

Solar radiation incident on the outer atmosphere of the earth is called extraterrestrial radiation. The extraterrestrial radiation varies based on the change in sun–earth's distance arising from earth's elliptical orbit of rotation. The extraterrestrial radiation is not affected by changes in atmospheric condition.

Solar constant

It is defined as the energy received from the sun per unit time on a unit surface area perpendicular to the direction of propagation of solar radiation at the top of earth's atmosphere when earth is at its mean distance from the sun. The value of solar constant is taken as 1367 W/m^2.

The extraterrestrial radiation can be determined by using solar constant as follows:

$$I_{ext} = I_{sc} \times \left(\frac{R_{av}}{R}\right)^2 \text{ W/m}$$

where I_{ext} is the extraterrestrial radiation,
I_{sc} is the solar constant (1367 W/m^2),
R_{av} is the mean distance between the sun and the earth, and
R is the actual sun–earth distance.

It can also be given as

$$I_{ext} = \left[1 + 0.033 \cos\left(\frac{360\, n}{365}\right)\right] \text{W/m}^2$$

where n is the number of days from 1st January.

Terrestrial radiation

When radiation passes through earth's atmosphere, it is subjected to the mechanism of atmospheric absorption and scattering depending on atmospheric conditions. Earth's atmosphere contains various constituents, suspended dust and solid and liquid particles, such as air molecules, oxgen, nitrogen, carbon dioxide, carbon monoxide, ozone, water vapour and dust. Therefore, solar radiation or intensity of radiation is depleted during its passage through the atmosphere. The solar radiation that reaches earth's surface after passing through earth's atmosphere is called terrestrial radiation. The propagation of solar radiation through earth's atmosphere is shown in Figure 2.5.

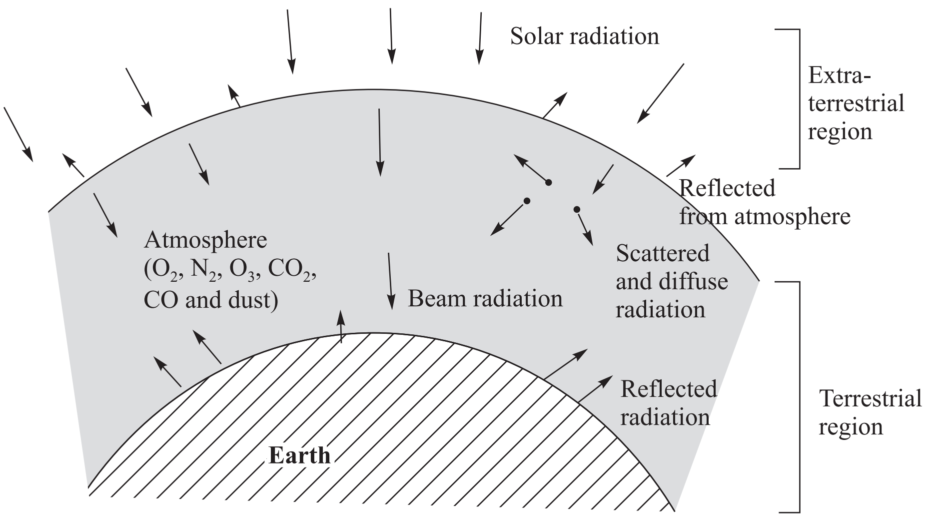


Figure 2.5 Extraterrestrial and terrestrial regions with solar radiation.

From extraterrestrial region, the solar radiation reaches earth's surface in two ways: (i) a part of sun's radiation travels through earth's atmosphere and its reaches directly, which is called direct or beam radiation, and (ii) the remaining major part of the solar radiation is scattered, reflected back into the space or absorbed by earth's atmosphere. A part of this radiation may reach earth's surface. This radiation reaching earth's surface by the mechanism of scattering and reflecting, that is, reradiation, is called diffuse or sky radiation. The diffuse radiation takes place uniformly in all directions and its intensity does not change with the orientation of the surface. However, direct or beam radiation depends on the orientation of the surface. The beam radiation depends on the angle of incident on the surface and its intensity is maximum when the solar radiation is falling normal to the surface. The solar radiation propagating normal to its direction is specified by I_n.

Beam radiation

Solar radiation along the line joining the receiving point and the sun is called beam radiation. This is radiation has any unique direction.

Diffuse radiation

It is the solar radiation which is scattered by the particles in earth's atmosphere and this radiation does not have any unique direction.

Total or global radiation

Total or global radiation at any location on earth's surface is the sum of beam radiation and diffuse radiation.

Air mass (*m*)

The radiation reaching earth's surface depends on (*i*) atmospheric conditions and depletion and (*ii*) solar attitude. Air mass is the ratio of the path length through the atmosphere which the solar beam actually traverses up to earth's surface to the vertical path length through the atmosphere (minimum height of terrestrial atmosphere).

At sea level, the air mass is unity when the sun is vertically is in the sky (inclination angle 90º).

$$\text{Air mass } (m) = \frac{\text{Path length travelled by beam radiation}}{\text{Vertical path length of the atmosphere}}$$

$$= \frac{AC}{AB} \text{ (as shown in Figure 2.6)}$$

$$= \text{cosec } \alpha = \sec \theta_z$$

where α is the inclination angle and
θ_z is the zenith angle.

$$m = 1 \text{ when } \theta_z = 0 \text{ and } m = 2 \text{ when } \theta_z = 60º$$

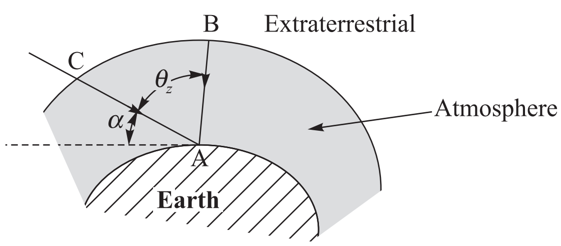


Figure 2.6 Concept of air maas.

2.4 LATITUDE AND LONGITUDE

- **What do you understand by latitude and longitude?**

Any location on the earth can be described by two numbers—latitude and longitude.

Latitude

On a globe of the earth, lines of latitude are circles of different sizes. The largest one is the circle at equator (circle at equator with centre at earth's centre) whose latitude is taken as zero. The circles at the poles have latitude of 90º north and 90º south (or –90º) where these circles shrink to a point. To specify the latitude of some point "*P*" on the earth's surface, draw the radius *OP* to the point *P* from centre *O*. The elevation angle (λ) of the point *P* above the equator is called latitude λ as shown in the Figure 2.7(a). There are 180 circles, of which 90 in each hemisphere specify the latitude of various points on earth's surface as shown in Figure 2.7(b). Each degree of latitude is about 111 km apart. Latitude lines run horizontally and these are parallel.

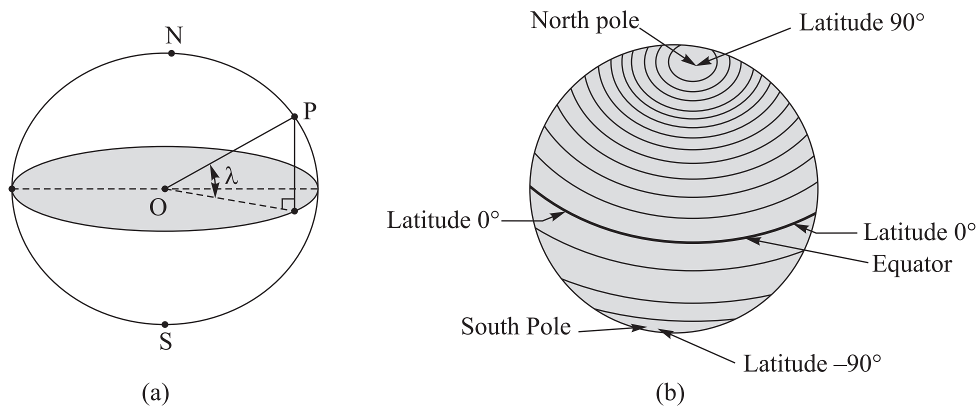


Figure 2.7 Concept of latitude. (a) The latitude angle (λ) and (b) 90 latitude lines in each northern and southern hemisphere.

Longitude

On the globe, vertical lines of constant longitude (meridians) extend from pole to pole similar to the segment boundaries on peeled orange. Every meridian has to cross the equator and equator is a circle. Like any circle, it has 360 degrees or divisions. Hence, longitude of a point is the marked value of that division where its meridian meets the equator circle. The meridian passing through the Royal Astronomical Observatory at Greenwich, UK had been chosen as zero longitude. The meridian passing through this location is called prime meridian. The prime meridian or longitude is considered zero longitude and there are 180 longitude lines or degrees at cast (+180º) and 180 degrees at west (–180º) of Greenwich. The longitude lines meet at poles and these have wide separation at the equator (about 111 km). The longitudinal lines are shown in Figure 2.8. Solar noon is the time when the sun is at the longitude of the place.

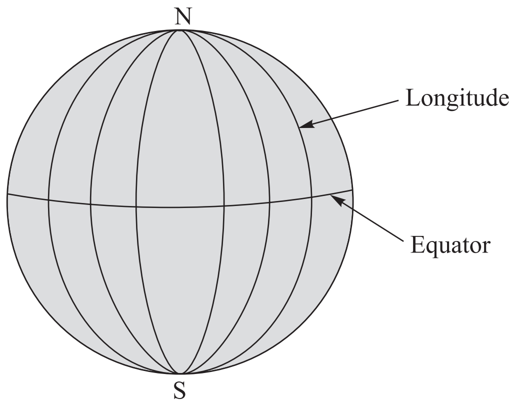


Figure 2.8 Concept of longitudinal lines.

2.5 BASIC SUN–EARTH ANGLES

- **Explain following angles used in solar radiation analysis:**
  (a) latitude of location, (b) hour angle, (c) solar azimuth angle, (d) zenith angle and (e) declination angle.

  or
- **Explain latitude, declination angle and surface azimuth angle.**

Latitude or angle of latitude (λ)

The latitude of a location on earth's surface is the angle made by the radial line joining the specified location to the centre of earth with the projection of this line on the equatorial plane as shown in Figure 2.9. The latitude at equator is zero and and it is 90º at poles.

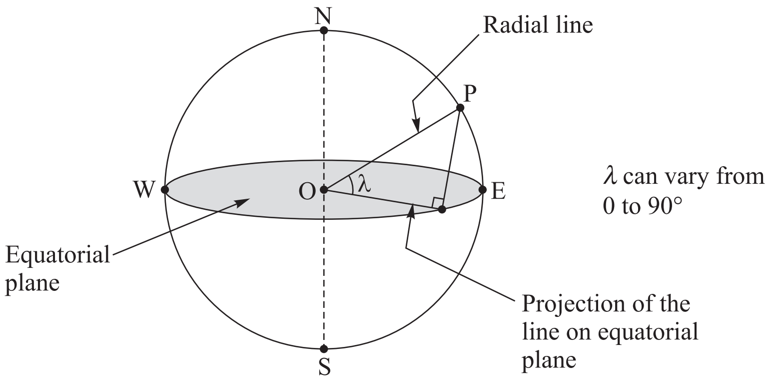


Figure 2.9 The angle of latitude.

Declination angle (δ)

It is the angle made by the line joining the centres of sun and earth with the equatorial plane as shown in Figure 2.10.

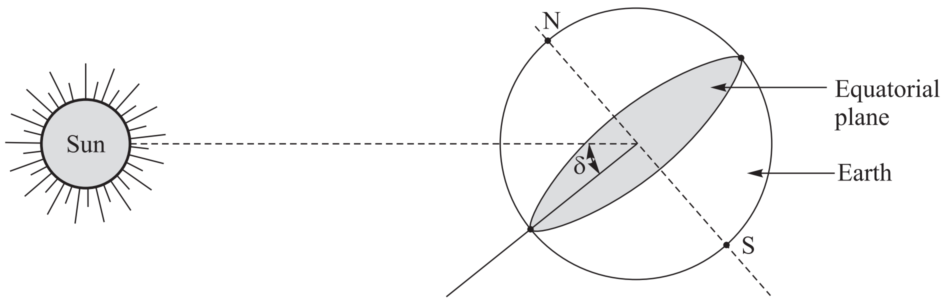


Figure 2.10 Angle of declination.

The angle of declination varies when earth revolves around the sun. It has maximum value of 23.45° when earth achieves a position in its orbit corresponding to 21 June and it has minimum value of –23.45° when earth is in orbital position corresponding to 22 December. The angle of declination is taken positive when it is measured above the equatorial plane in the northern hemisphere. The angle of declination can be given by

$$\delta = 23.45 \times \sin\left[\frac{360}{365}(284 + n)\right]$$

where n is the number of days counted from 1 January.

Hour angle (ω)

The hour angle at any instant is the angle through which the earth has to turn to bring the meridian of the observer directly in line with sun's rays. It is an angular measure of time. It is the angle in degree traced by the sun in 1 h with reference to 12 noon of the location. The convention of measuring it is that the noon-based calculated local apparent time (LAT) is positive in afternoon and negative in forenoon as shown in Figure 2.11. The earth completes one rotation (360°) in 24 h. Hence, 1 h corresponds to 15° of earth's rotation. As at solar noon

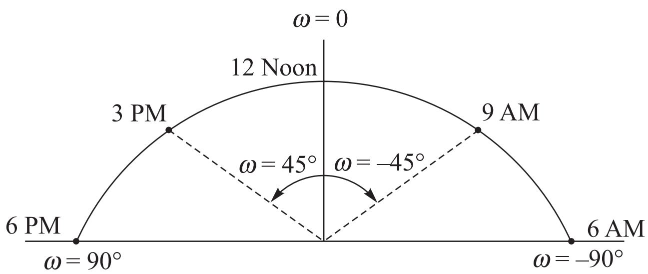


Figure 2.11 Hour angle is an angular measure of time.

the sun rays is in line with local meridian or longitude, the hour angle at that instant is zero. The hour angle can be given as follows:

$$\omega = [\text{Solar time} - 12] \times 15^{o}$$

Inclination or altitude angle (α)

It is the angle between sun's ray and its projection on horizontal surface as shown in Figure 2.12.

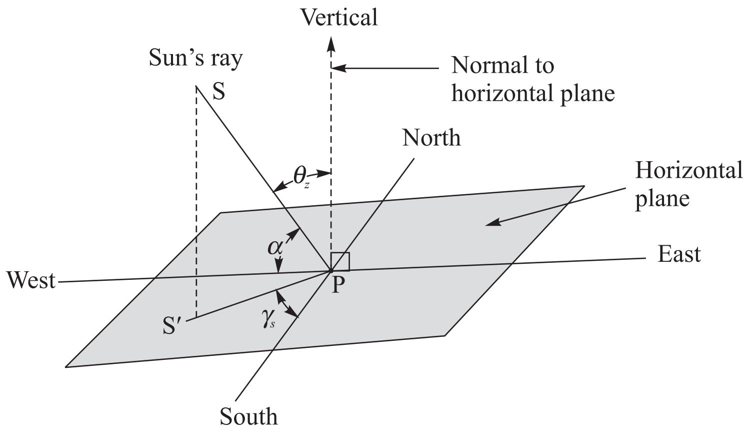


Figure 2.12 Inclination (altitude) angle, solar azimuth angle and zenith angle.

Zenith angle (θ_z)

It is the angle between sun's ray and normal to the horizontal plane as shown in Figure 2.12.

Solar azimuth angle (γ_s)

It is the angle between the projection of sun's ray to the point on the horizontal plane and line due south passing through that point. The value of the azimuth angle is taken positive when it is measure form south towards west.

Angle of incidence (θ)

The angle of incidence for any surface is defined as the angle formed between the direction of the sun ray and the line normal to the surface as shown in the Figure 2.13.

Tilt or slope angle (β)

The tilt angle is the angle between the inclined slope and the horizontal plane as shown in the Figure 2.13.

Surface azimuth angle (γ)

It is the angle in horizontal plane between the line due south and the horizontal projection of normal to the inclined plane surface. It is taken as positive when measured form south towards west.

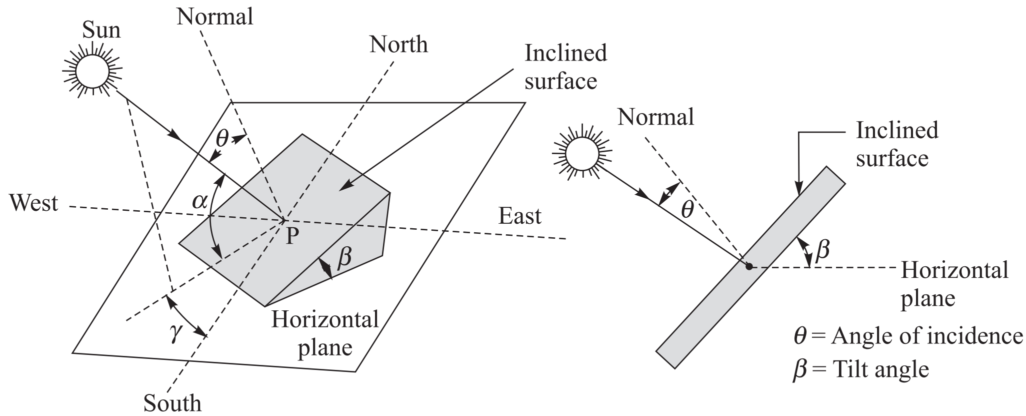


Figure 2.13 Angle of incidence and tilt angle.

2.6 ANGLE BETWEEN INCIDENT BEAM AND NORMAL TO INCLINED SURFACE (θ)

- **What is the expression for the angle of incidence (θ) for an inclined surface? Find the angle of incidence (θ) when (i) tilt angle $\beta = 0$, (ii) tilt angle $\beta = 90^\circ$, (iii) surface azimuth angle $\gamma = 0$ and (iv) $\beta = 90^\circ$ and $\gamma = 0^\circ$.**

The angle of incidence can be given by the following expression.

$$\cos\theta = \sin\lambda\,(\sin\delta\cos\beta + \cos\delta\cos\omega\sin\beta) + \cos\lambda\,(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta) + \cos\delta\sin\gamma\sin\beta\sin\omega$$

Case I. Tilt angle $\beta = 0$

When tilt angle β is zero, the surface is horizontal. In this condition, the angle of incidence becomes equal to the zenith angle of the sun (θ_z). Hence, we have

$$\cos\theta = \cos\theta_z = \cos\delta\cos\lambda\cos\omega + \sin\delta\sin\lambda$$

Case II. Tilt angle $\beta = 90^\circ$

In this position, the surface is normal to the horizontal plane. Hence, we have

$$\cos\theta = \sin\lambda\cos\delta\cos\gamma\cos\omega - \cos\lambda\sin\delta\cos\gamma + \cos\delta\sin\gamma\sin\omega$$

Case III. Surface facing south, that is, $\gamma = 0^\circ$

For the inclined surface facing south the angle of incidence can be given as

$$\cos\theta = \sin\lambda\sin(\lambda - \beta) + \cos\delta\cos\omega\cos(\lambda - \beta)$$

Case IV. $\beta = 90^\circ$ and $\gamma = 0$

In this condition, the vertical surface is facing south. Hence, we have

$$\cos\theta = \sin\lambda\cos\delta\cos\omega - \cos\lambda\sin\delta$$

2.7 LOCAL APPARENT TIME

- **Explain local apparent time. How it is calculated?**

Local apparent time (LAT) differs from place to place depending on the longitude of the place. The sun rises in the east and any location in the east will have earlier sunrise and earlier sunset.

Hence, LAT is the time used for determining hour angle. LAT can be determined from standard time by applying two corrections. The first correction is needed due to the difference between the longitude at the location (where LAT is to be determined) and the longitude of the place whose standard time is used for the calculation. As 15° or 15 longitudes is equal to 1 h, a correction of 4 min per longitude difference is given to the standard time. The second correction is called time correction which is needed as both earth's orbit and rate of rotation are subjected to small fluctuations. Hence, we have

$$\text{LAT} = \text{Standard time} \pm 4\ (\text{standard time longitude} - \text{location longitude}) + (\text{equation of time correction})$$

The negative sign should be used for LAT for the eastern hemisphere and positive sign for LAT for the western hemisphere.

- **Calculate hour angle for the local apparent time given by (i) 6 AM, (ii) 9 AM, (iii) 12 noon, (iv) 3 PM, (v) 6 PM and (vi) 9 PM.**

The hour angle is given by

$$\omega = [\text{Solar time} - 12] \times 15^\circ$$

(i) Solar time = 6 AM

$$\omega = (6 - 12) \times 15^\circ = -90^\circ$$

(ii) Solar time = 9 AM

$$\omega = (9 - 12) \times 15^\circ = -45^\circ$$

(iii) Solar time = 12

$$\omega = (12 - 12) \times 15^\circ = 0$$

(iv) Solar time = 3 PM = 15

$$\omega = (15 - 12) \times 15^\circ = 45^\circ$$

(v) Solar time = 6 PM = 18

$$\omega = (18 - 12) \times 15^\circ = 90^\circ$$

(vi) Solar time = 9 AM = 21

$$\omega = (21 - 12) \times 15^\circ = 135^\circ$$

- **Determine LAT corresponding to 1500 h (IST) Mumbai (19º 07′, 75º 51 E) on 1 July. In India, IST is based on 82.50º E. On 1 July, equation of time correction is equal to – 4.**

As Mumbai is towards west of IST location, negative sign is to be taken.

$$\text{LAT} = \text{time} \pm (\text{standard time longitude} - \text{location longitude}) \times 4 \text{ min} + (\text{equation for time correction})$$

$$= 1500 \text{ h} - 4(82.50 - 72.85) \text{ min} - 4 \text{ min}$$

$$= 1500 \text{ h} - (4 \times 9.65 + 4) \text{ min}$$

$$= 1500 \text{ h} - (38.60 + 4) \text{ min}$$

$$= 1500 \text{ h} - 42.6 \text{ min}$$

$$= 1417.4 \text{ h}$$

2.8 SUNRISE, SUNSET AND SOLAR DAY LENGTH

- **Derive an expression for solar day length.**

or

- **How can you find out hour angle at sunrise and sunset?**

or

- **How can be the duration of day sunshine found out?**

At sunrise, the sun rays propagate parallel to the horizontal surface. Hence, the angle of incidence and zenith angle are equal and have the value of 90º ($\theta = \theta_z = 90º$). The corresponding hour angle can be given as

$$\cos \theta = \cos 90º = 0 = \cos \lambda \cos \delta \cos \omega + \sin \delta \sin \lambda$$

or

$$\cos \omega = -\tan \lambda \tan \delta$$

$$\omega = \cos^{-1}(-\tan \lambda \tan \delta)$$

Similarly, the sun rays are parallel to horizontal plane during sunset and hour angle is

$$-\omega = \cos^{-1}(-\tan \lambda \tan \delta)$$

The angle between sunrise and sunset or solar day length can be given as

$$\text{Solar day length} = 2\omega = 2 \cos^{-1}(-\tan \lambda \tan \delta)$$

Ths sun traverses is 15º in 1 h duration. The sunshine is available between sunrise and sunset or in solar day length. The duration of sunshine hour (t_d) or daylight hours can be given as

$$t_d = \frac{\text{Angle between sunrise and sunset}}{15^\circ} \times 1\,\text{h}$$

$$= \frac{2 \times \omega}{15} \times 1$$

$$= \frac{2}{15} \times \cos^{-1}(-\tan\lambda \tan\delta)$$

The latitude angle increases from the equator to poles, and so daylight hours will increase as we move towards poles as shown in Figure 2.14.

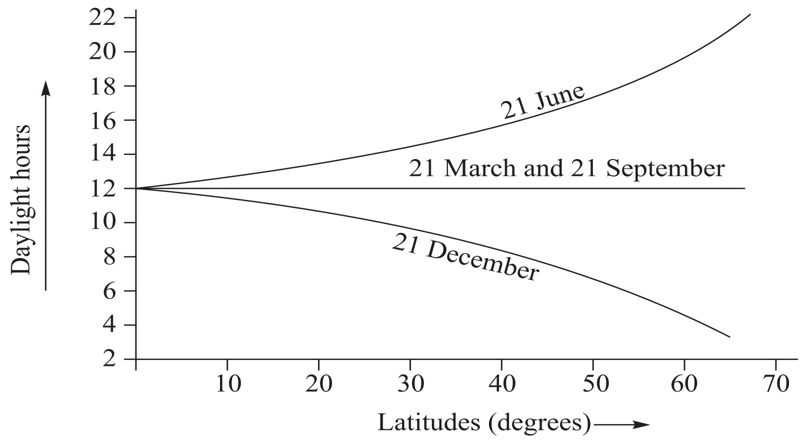


Figure 2.14 Change of daylight hours with latitude.

- **Calculate the number of daylight hours in Srinagar for 1 January and 1 July. Take latitude of Srinagar as 34°05′ N.**

The declination angle δ is given as

$$\delta = 23.45 \times \sin\left[\frac{360}{365} \times (284 + n)\right]$$

where n is number of days of the year counted from 1 January.

Case I. 1 January

$$n = 1$$

$$\therefore \quad \delta = 23.45 \times \sin\left[\frac{360}{365} \times (284 + 1)\right]$$

$$= -23.01^\circ$$

$$\therefore \qquad t_d = \frac{2}{15}\cos^{-1}[-\tan\lambda \times \tan\delta]$$

$$= \frac{2}{15}\cos^{-1}[-\tan(34.08)\times\tan(-23.01)]$$

$$= 9.77 \text{ h}$$

Case II. 1 July

$$n = 31 + 28 + 31 + 30 + 31 + 30 + 1$$

$$= 182$$

$$\delta = 23.45 \times \sin\left[\frac{360}{365}(284 + 182)\right]$$

$$= 23.12^{o}$$

$$t_d = \frac{2}{15}\cos^{-1}[-\tan(34.08 \times \tan(23.12)]$$

$$= 14.24 \text{ h}$$

- **Calculate the hour angle at sunrise and sunset on 21 June and 21 December for a surface inclined at an angle of 10º and facing due south ($\gamma = 0$). The surface is located in Mumbai (19º67′ N, 72º51′ E).**

Case I. 21 June

$$n = 31 + 28 + 31 + 30 + 31 + 21$$

$$= 172$$

$$\delta = 23.45\sin\left[\frac{360}{365}(284 + 172)\right]$$

$$= 23.45^{o}$$

For sunrise, we have $\theta = 0$, which gives

$$\omega = \cos^{-1}[-\tan(\lambda - \beta) \times \tan\delta]$$

$$= \cos^{-1}[-\tan(19.12 - 10))\tan(23.45)]$$

$$= \times\ 94°$$

Case II. 21 December

$$n = 365 - 10 = 355$$

$$\delta = 23.45\sin\left[\frac{360}{365}(284 + 355)\right]$$

$$= -23.39$$

For sunset, we have

$$\omega = \cos^{-1}[-\tan(\lambda - \beta)\tan\delta]$$

$$= \cos^{-1}[-\tan(19.12 - 10)\tan(-23.29)]$$

or $\qquad \omega = -86°$

2.9 INTENSITY OF TERRESTRIAL RADIATION

- **Explain various radiation reaching earth's surface.**
- **Differentiate between beam and diffuse radiation.**
- **Discuss decentralized and dispersed generation.** **(UPTU 2010, 2011)**

Radiation reaching from extraterrestrial region to earth's surface is called beam radiation. The intensity of beam radiation normal to the direction of beam's propogation is called normal intensity. The normal intensity of beam radiation can be given as

$$I_{iv} = I_{ext} \times e^{-T_R / 0.9 + 9.4 \sin \alpha}$$

where I_{ext} is the intensity of extraterrestrial radiation in the direction of radiation and T_R is the turbidity factor.

The turbidity factor depends on (i) months and (ii) type of regions. The turbidity factor in different regions for different months of the year is shown in Table 2.1.

TABLE 2.1 Turbidity factor in different regions for different months of the year

S.No.	*Type of regions*	*Months*											
		1	2	3	4	5	6	7	8	9	10	11	12
1.	Mountain	1.8	1.9	2.1	2.2	2.4	2.7	2.7	2.7	2.5	2.1	1.9	1.8
2.	Flat land	2.2	2.2	2.5	3.2	3.2	3.4	3.5	3.3	2.9	2.6	2.3	2.2
3.	City	3.1	3.2	3.5	3.9	4.1	4.2	4.3	4.2	3.9	3.6	3.3	3.1

The normal intensity (I_N) and intensity normal to horizontal surface are shown in Figure 2.15.

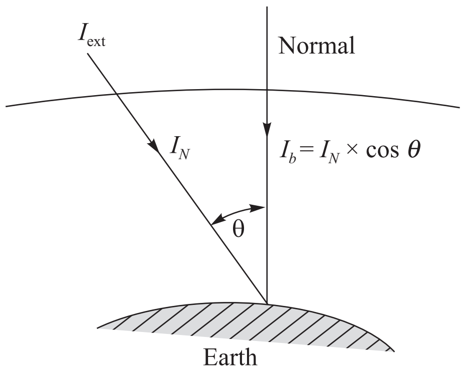


Figure 2.15 Direction of sunshine on the earth's surface.

The beam radiation (I_b) and diffuse radiation (I_d) on horizontal surface can be given by

$$I_b = I_N \cos \theta_z$$

$$I_d = \frac{1}{3}(I_{ext} - I_N)\cos\theta_z$$

Total or global radiation consists of (i) beam radiation, (ii) diffuse radiation and (iii) reflected radiation. Total radiation is given by

$$I_G = I_b \times R_b + I_d \times R_d + R_r(I_b \times I_d)$$

where R_b, R_d and R_r are conversion factors for beam, diffuse and reflected components.

2.10 SOLAR RADIATION DATA

- **What do you understand by solar radiation data? What is the need of solar radiation data?**

To design a solar energy system or to evaluate the potential of any solar application at any place, it is necessary to have (i) monthly average, (ii) daily solar radiation data on a horizontal surface consisting of both global and diffuse radiation and (iii) daily solar radiation data with certain tilt angles. The typical daily solar radiation data on clear and cloudy days as measured on a horizontal surface are as shown in Figure 2.16.

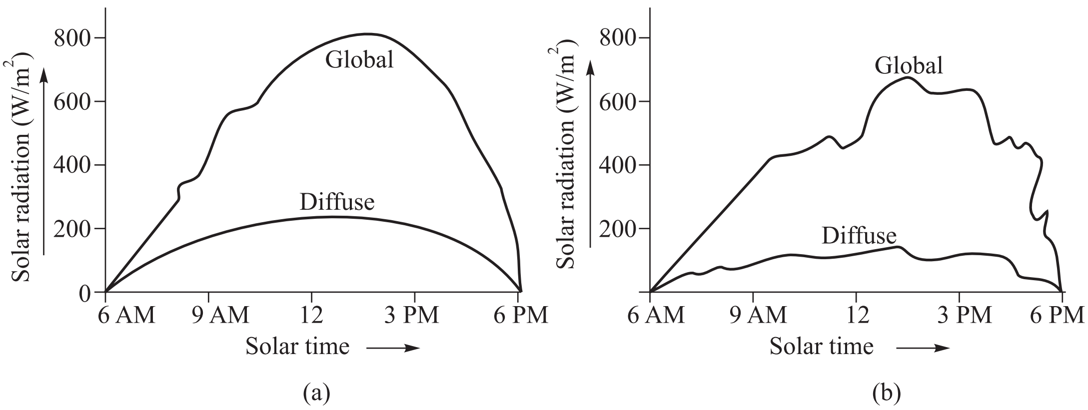


Figure 2.16 Daily variation of global and diffuse radiation on a horizontal surface. (a) Clear day and (b) Cloudly day.

Monthly average of daily radiation is obtained by averaging the daily radiation for a month. The radiation also depends on the tilt of the surface. The monthly average depends on (i) hourly variation of global and diffuse radiation, (ii) amount of radiation received per day and (iii) the number of sunshine hours per day. A general idea of the availability of solar radiation can be obtained with the help of solar radiation maps which are drawn to show the distribution of the annual mean daily global solar radiation (kWh/m^2/day). A typical solar radiation map is shown in Figure 2.17.

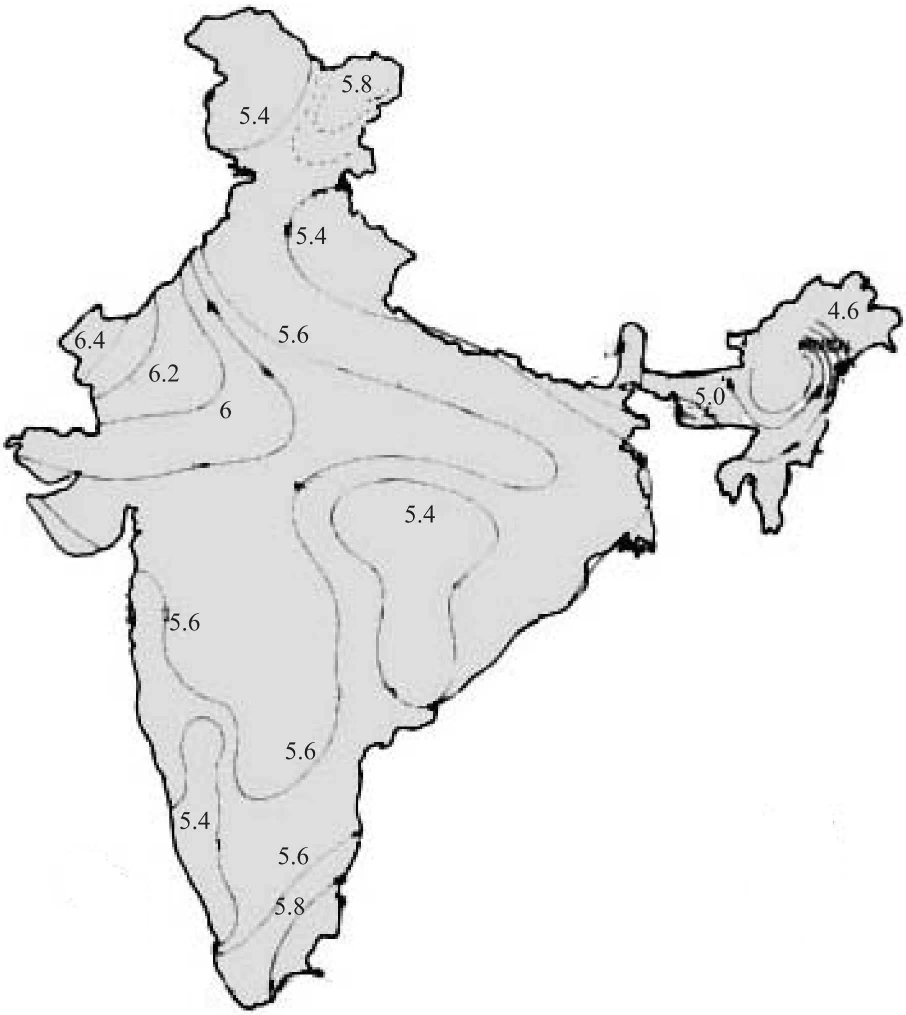


Figure 2.17 Solar radiation map.

2.10.1 Monthly Average Daily Global Radiation ($\bar{H}_g$) on Horizontal Surface

- **Write briefly about average daily global radiation.**

The monthly average daily global (total) radiation $(\bar{H}_g)$ on horizontal surface is determined from (i) monthly average daily extraterrestrial radiation $(\bar{H}_0)$ on horizontal surface, (ii) monthly average daily hours of bright sunshine $(\bar{n})$ and (iii) monthly average of maximum possible daily hours of sunshine $(\bar{N})$. It is given by

$$\frac{\bar{H}_g}{\bar{H}_0} = a + b\left(\frac{\bar{n}}{\bar{N}}\right)$$

where a and b are the regresssion parameters which are constant for a particular location.

2.10.2 Monthly Average Daily Diffuse Radiation on Horizontal Surface

- **Write short note on monthly average daily diffuse radiation.**

Monthly average daily diffuse radiation $(\bar{H}_0)$ on a horizontal surface can be determined from (i) monthly average daily global radiation and (ii) monthly average clarity index $(\bar{k}_T)$, which is the ratio of monthly average of daily global radiation to the monthly average of daily extraterrestrial radiation. The monthly average of the daily diffuse radiation can be given as

$$\frac{\bar{H}_d}{\bar{H}_g} = 1.194 - 0.838\ \bar{k}_T - 0.0446\ \frac{\bar{n}}{\bar{N}}$$

2.10.3 Monthly Average Daily Global Radiation on Tilted Surface $(\bar{H}_T)$

- **Explain monthly average daily global radiation on tilted surface.**

The monthly average daily global radiation on tilted surface $(\bar{H}_T)$ can be given as

$$\bar{H}_T = (\bar{H}_g - \bar{H}_d)\,\bar{R}_b + \bar{H}_d\left(\frac{1+\cos\beta}{2}\right) + \bar{H}_g\rho\times\left(\frac{1+\cos\beta}{2}\right)$$

where $\bar{R}_b$ is the conversion factor for monthly average daily beam radiation.

- **Estimate the average daily global radiation on a horizontal surface at Baroda (22° N, 73°10′ E) during the month of March if the average sunshine hour per day is 9.5. Assume a = 0.28 and b = 0.48. Also assume $H_0 = \bar{H}_0$.**

The average daily global radiation $(\bar{H}_g)$ on horizontal surface depends on monthly average of the daily extraterrestrial radiation $(\bar{H}_0)$ according to the following relation:

$$\frac{\bar{H}_g}{\bar{H}_0} = a + b\times\frac{\bar{n}}{\bar{N}}$$

where $\bar{n}$ is the monthly average of the sunshine hours per day at the location and $\bar{N}$ is the monthly average of maximum possible hours per day at the location.

The declination angle is given by

$$\delta = 23.45 \sin \left[\frac{360}{365}(284+n)\right]$$

For 16 March, the value of n is

$$n = 31 + 28 + 16 = 75$$

$$\delta = 23.45 \sin \left[\frac{360}{365}(284+75)\right]$$

$$= -2.42°$$

Sunrise hour angle is given by

$$\omega = \cos^{-1} (-\tan \lambda \times \tan \delta)$$

$$= \cos^{-1} [-\tan 22 \times \tan (-2.42)]$$

$$= 89.02$$

Day length is given by

$$\bar{N} = \frac{2}{15} \times \omega$$

$$= \frac{2}{15} \times 89.02$$

$$= 11.87 \text{ h}$$

$$H_0 = \frac{24}{\pi} \times I_{SC} \left(1 + 0.033 \cos \frac{360n}{365}\right) [\omega \sin \lambda \times \sin \delta + \cos \lambda \cos \delta \sin \omega]$$

$$= \frac{24}{\pi} \times 1353 \left(1 + 0.033 \cos \frac{360 \times 75}{365}\right)$$

$$\times \left(\frac{89.02}{180} \times \pi \times \sin 22 \times \sin (-2.42) + \cos 22 \times \cos (-2.42) \sin 89.02\right)$$

$$= \frac{24}{\pi} \times 1353 \times (1 + 0.277) [1.55 \times 0.374 \times (-0.0422)$$

$$+ 0.927 \times 0.999 \times 0.9998]$$

$$= 10341 \times 1.277 (0.926 - 0.024)$$

$$= 11{,}911$$

$$\frac{\bar{H}_g}{H_0} = a + b \times \frac{\bar{n}}{\bar{N}}$$

$$= 0.28 + 0.48 \times \frac{9.5}{11.87}$$

$$= 0.664$$

$$\therefore \quad \bar{H}_g = 0.664 \times 11{,}911 = 7909 \text{ kJ/m}^2$$

- **Calculate the day length in hours in Mumbai on 1 December if latitude = 19.116 and declination angle = –22.108°.**

$$t_d = \frac{2}{15} \times \cos^{-1} (-\tan \lambda \times \tan \delta)$$

$$= \frac{2}{15} \times \cos^{-1} [-\tan 19.116 \times \tan (-22.108)]$$

$$= \frac{2}{15} \times 81.92$$

$$= 10.9 \text{ h}$$

- **Find the solar altitude angle at 2 h after local solar angle on 1 June for place located at 26.75° N latitude. Also, determine the sunrise and sunset hours as well as the day length.**

$$n = 31 + 28 + 31 + 30 + 31 + 1$$

$$= 152$$

$$\delta = 23.45 \sin \left[\frac{360}{365}(284 + n)\right]$$

$$= 23.45 \sin \left[\frac{360}{365}(284 + 152)\right]$$

$$= 22°$$

Now hour angle is given by

$$\omega = 2 \text{ h} \times 15°$$

$$= 30°$$

$$\sin \alpha = \sin \lambda \sin \delta + \cos \lambda \cos \delta \cos \omega$$

$$= \sin 26.75 \times \sin 22 + \cos 26.75 \times \cos 22 \times \cos 30$$

$$= 0.553$$

$$\therefore \quad \alpha = 72.4°$$

$$t_d = \frac{2}{15} \cos^{-1} (-\tan \lambda \times \tan \delta)$$

$$= \frac{2}{15} \cos^{-1} (-\tan 26.75 \times \tan 22)$$

$$= 10.40 \text{ h}$$

The sunrise is at $\left(12 - \frac{10.4}{2}\right)$ h

$$= (12 - 5.2) \text{ h}$$

$$= 6.8 \text{ h} = 6 : 48 \text{ AM}$$

The sunset is at $= (12 + 5.2)$ h

$$= 5 : 12 \text{ PM}$$

- **Calculate the zenith angle of the sun at a place (26.75° N) at 9.30 on 16 February.**

$$\omega = (9.30 - 12) \times 15 = -37.5°$$

$$n = 31 + 16 = 47$$

$$\delta = 23.45 \sin \left[\frac{360}{365}(284 + n)\right]$$

$$= 23.45 \sin \left[\frac{360}{365}(284 + 47)\right]$$

$$= -12.95$$

$$\cos \theta_z = \cos\delta \cos \lambda \cos \omega + \sin \delta \times \sin \lambda$$

$$= \cos (-12.95) \times \cos (26.75) \times \cos (-37.5) + \sin (-12.95) \times \sin (26.75)$$

$$= 0.589$$

$$\therefore \quad \theta_z = 53.92$$

- **Calculate the angle made by beam radiation with the normal to a flat plate collector on 1 December at 0900 h (LAT). The collector is located at a place (28° 35′ N, 77° 12′ E) and it is tilted at angle of 36° with the horizontal. It is also pointing due south.**

As collector is pointing due south,

$$\gamma = 0$$

For 1 December, $n = 365 - 30 = 335$

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + n)\right]$$

$$= 23.45 \sin\left[\frac{360}{365}(284 + 335)\right]$$

$$= -22.11°$$

At 0900, hour angle $\omega = (9 - 12) \times 15$

$$= -45°$$

Now

$$\cos\theta = \sin\delta \times \sin(\lambda - \beta) + \cos\delta \times \cos\omega \cos(\lambda - \beta)$$

$$= \sin(-22.11) \times \sin(28.58 - 36) + \cos(-22.11) \times \cos 45 \times \cos(28.58 - 36)$$

$$= 0.6982$$

$$\theta = 45.7°$$

- **Calculate hour angle at sunrise and sunset on 21 June and 21 December for a surface tilted at 10° and facing due south. The location has latitude 19° 07′ N and longitude 72° 51′ E.**

Case 1. 21 June

$$n = 31 + 28 + 31 + 30 + 31 + 21 = 172$$

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + 172)\right]$$

$$= 23.45°$$

$$\omega = \cos^{-1}[-\tan(\lambda - \beta) \times \tan\delta]$$

$$= \cos^{-1}[-\tan(19.12 - 10) \times \tan 23.45]$$

$$= 81.4$$

2.11 MEASUREMENTS OF SOLAR RADIATION DATA

- **Explain the working of any one of the following with the help of neat sketch (a) Pyrometer (b) Pyrheliometer**

or

- **Differentiate between beam and diffusion radiation. Describe a type of instrument to measure beam radiation with a neat sketch.**

Solar energy reaching earth's surface consists of two components: direct solar energy and diffuse solar energy. Direct solar energy is the energy reaching earth's surface with the sun's beam. The sun's beam has high heat content which may cause sun's burns. It is also described as shadow producing radiation. Diffuse solar energy is formed as the result of the atmosphere attenuation, scattering and beam's redirection. As the name suggests, it has intensity much lower than beam's intensity but it propagates uniformly in all directions. The difference between beam and diffuse radiation is given in Table 2.2. Figure 2.18 shows the method of

TABLE 2.2 Difference between beam and diffuse radiation

Beam radiation	*Diffuse radiation*
It is the radiation reaching directly from sun	It is the radiation reaching after attenuation, scattering and redirection
It has unidirection propagation	It has uniform propagation in all direction
It is very intense radiation and it can produce sun burns and shadow	It is mild radiation. Typical values of daily diffuse radiation is 1–20 MJ/m^2
It is available highest during near sky days	It has usually highest values during the cloudy conditions.

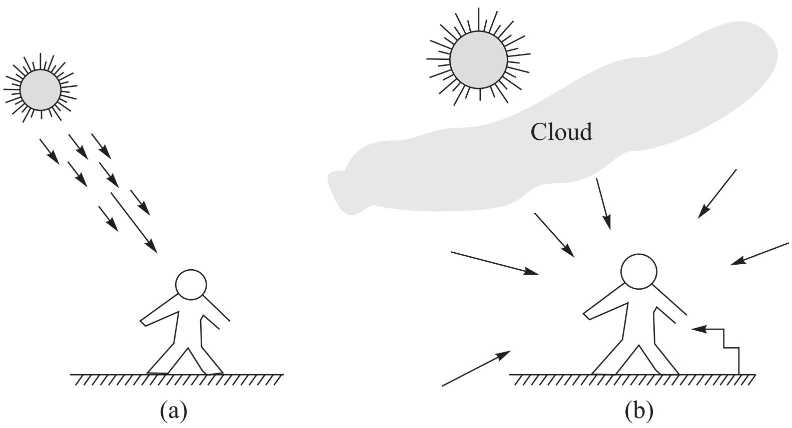


Figure 2.18 (a) Beam and (b) Diffuse radiation.

propagation of beam and diffuse radiation. The combination of both forms of solar energy incident on a horizontal plane at earth's surface is called global solar energy, which is given by

$$H_g = H_d + H_b \cos \theta_z$$

The solar radiation data can be measured in the following way:

(i) **Global radiation.** It can be measured using a pyranometer. Pyranometer is a Greek word composed of Pyr (fire) + ano (something above) + meter (measurement), which means "measuring fire from above", that is, measuring sun's radiation.

(ii) **Diffuse radiation.** It is also measured by pyranometer using a shading ring to stop direct beam radiation to the instrument so that the instrument measures only diffuse radiation.

(iii) **Beam radiation.** It is measured using a pyrheliometer. The instrument has a long narrow tube to collect only beam radiation from the sun.

(iv) **Sunshine recorder.** The sunshine hours in a day are measured using a sunshine recorder.

Pyranometer

A pyranometer is radiation energy measuring device which is designed to measure global or total radiation usually on a horizontal plane but it can also be used to measure on an inclined plane. When instrument is shaded using a shading ring to prevent beam radiation reaching its detector, the pyranometer in this condition can measure only diffuse radiation. The instrument consists of a thermopile whose sensitive surface forms its hot junction. This surface is blackened circular in shape and exposed to radiation. So that the surface should respond to radiation of all wavelengths so as to absorb them as a black body. The temperature of hot junction increases depending on amount of the incident radiation energy absorbed by it. The cold junction of the thermopile is completely shaded to prevent the radiation reaching (shown as white). The sensing element is covered by two concentric hemispherical glass domes to shield it from wind and rain. This also helps to reduce or prevent heat inflow to the detector by the convection heat transfer from air. The instrument is protected from direct solar radiation by mounting a circular guard plate at the level of detector which is also painted white to prevent the absorption of any solar radiation. The instrument can be accurately levelled by means of three levelling screens provided at its base. Inside the instrument, a tube containing silica gel is provided to keep the interior of the instrument dry without the adverse effect of moisture; that is, moisture should not be deposited inside the glass of the domes. The pyranometer is also provided with a shadow band or occulting disc to prevent the direct beam radiation from reaching the sensing element and it is used when instrument is required to measure diffuse radiation. The temperature difference between the hot and the cold junction is the function of radiation falling on the sensitive surface (black junction). The thermopile is designed to measure radiation in linear manner (Figure 2.19). The instrument has a voltage output of approximately 9 μV/(W/mV) which is recorded on a chart paper by a recorder. The daily values of radiation is recorded on hourly basis and a pyranogram is obtained which is a graph of radiation incident versus hour lines.

Pyrheliometer

It is an instrument to measure beam radiation. It has a narrow long tube called collimator tube to collect beam radiation from the sun at normal incidence. The long collimator tube ensures that a beam radiation having field of view limited to a solid angle of 5.5° should be collected. The collimator tube is further blankened from inside and provided diaphragm along the

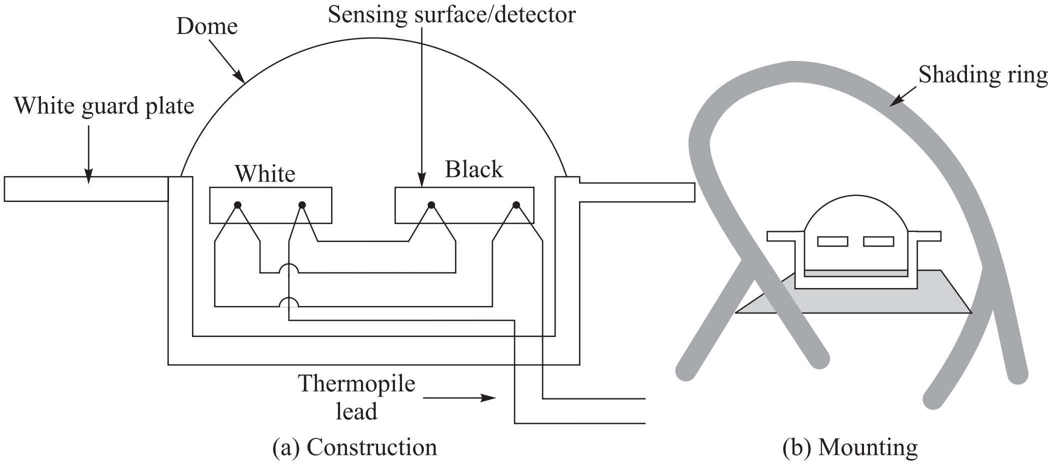


Figure 2.19 Construction of the pyranometer.

length to absorb any radiation entering the tube but incident at any angle outside the designed angle of 5.50°. At the base of the collimator tube, a wire-wound thermopile having sensitivity of about 8 μV/(W/m^2) is positioned which has impedence of about 200 Ω . The tube is sealed with dry air with the help of silica gel to avoid any absorption of beam radiation owing to presence of moisture in the air. A tracker is provided in the instrument to keep the collimator tube continuously face the sun rays for the measurement (Figure 2.20).

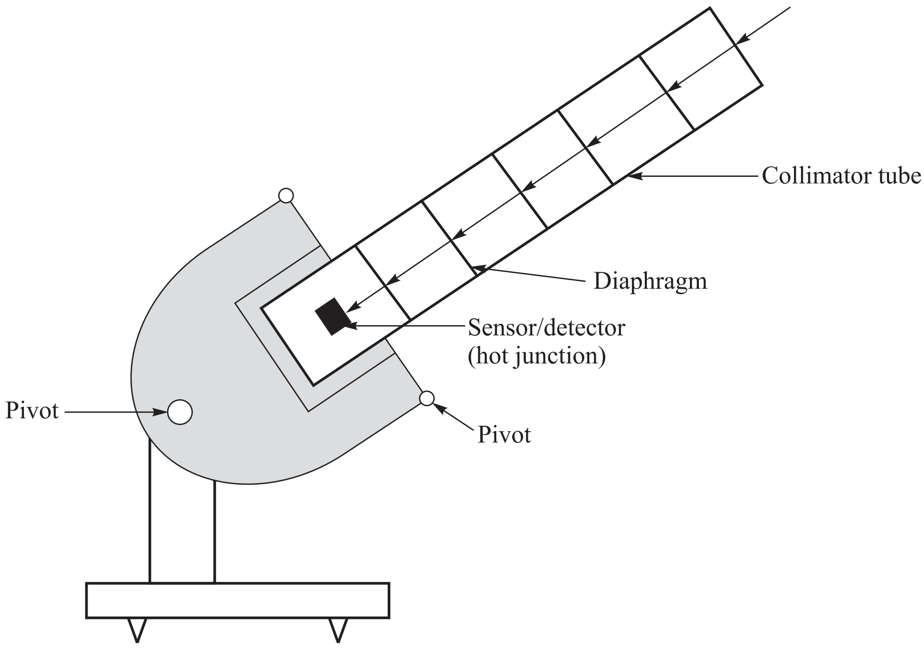


Figure 2.20 Construction of a pyrheliometer.

Three types of pyrheliometers are usually used to measure the incident beam radiation, which are:

- The Angstrom compensation pyrheliometer
- The Abbot silver disc pyrheliometer
- Eppley pyrheliometer.

Angstrom compensation pyrheliometer

The instrument has a thin blackened strip besides the detector made of a similar strip. The detector is exposed to the beam radiation while this strip is kept shaded so that it has no heating effect from the beam radiation. However, this strip is heated electrically using an electric circuit so that the strip can achieve the same temperature which is present at the sensitive solar detector strip owing to the incidence and absorption of solar beam radiation. The leads of thermopile are connected in opposition through a sensitive galvanometer to find null position by testing the presence of equality of temperature at both the strips. The beam radiation energy (H_b) at the place can be determined by the following equation:

$$H_b = k \times i^2$$

where i is the heating current in ampere and k is the instrument constant depending upon resistance (R), width of strip (w) and absorbing coefficient (α) that is, $k = \left(\frac{R}{w \times \alpha}\right)$.

The electrical circuit for Angstrom compensation Pyrheliometer is shown in Figure 2.21.

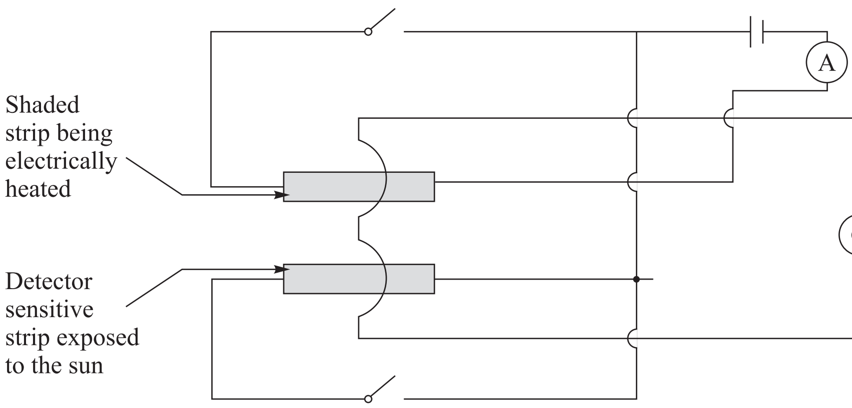


Figure 2.21 Electrical circuit for Angstrom compensation pyrheliometer.

Sunshine recorder

The instrument is used to measure the duration of bright sunshine hours in a day. It mainly consists of a glass sphere (diameter = 10 cm) mounted on its axis parallel to the axis of earth within a spherical section called bowl as shown in Figure 2.22. The bowl and glass sphere are arranged in such a way that sun's rays are focused sharply as a spot on recording paper card held in a groove in the bowl. The card is made of a special coated paper with the printed time scale. The paper card has the property to burn a spot wherever sun's rays fall on it. As the sun moves, the focused bright sun's rays burn a path along the card paper. The length of the trace formed by the burn spots on the card paper is the measure of the duration of sunshine hours in a day. To take care of different seasons of the year, three overlapping pair of grooves to fix the card paper are provided in the bowl of the instrument.

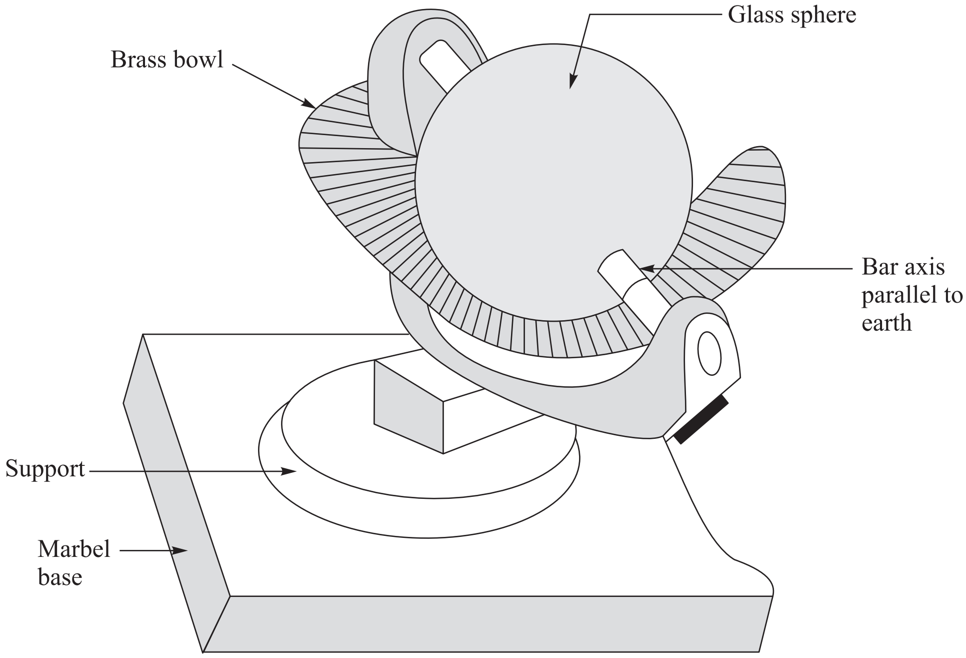


Figure 2.22 Sunshine recorder.

CHAPTER 3

Solar Energy

3.1 INTRODUCTION

Solar energy is a clean, cheap and abundantly available renewable energy. Solar energy can be used in two ways: (i) directly as thermal energy and (ii) indirectly using solar photovoltaic cells to convert it to electricity. In cold climate region or other regions in winter, a large amount of thermal energy is required to heat air to maintain comfort conditions in space and to heat water for washing, cleaning and drying, both for domestic and industrial needs. Solar energy collectors are the devices similar to heat converter which are used to obtain thermal energy from solar energy. Solar energy is available during daytime from sunrise to sunset. Solar energy of 5–7.5 kWh/m^2 is commonly available in most places in India. The solar energy can be used either in solar power plant or in solar photovoltaic (SPV) cells to get electricity. Indian Renewable Energy Development Agency and the Ministry of Non-Conventional Energy Sources are working continuously to intall solar energy in more than a million houses in the shortest time and to increase the uses of solar energy for (i) domestic lighting, (ii) solar water heating, (iii) street lighting, (iv) village electrification, (v) railway signals, (vi) desalination of saline water, (vii) water pumping, (viii) space heating, (ix) solar cooking, (x) space cooling, (xi) solar greenhouse and (xii) powering of remote telecommunication stations.

3.2 SOLAR COLLECTORS

- **Why is a solar collector needed?**

Solar energy reaching earth's surface has small intensity of about 5–7.5 kWh/m^2. Hence, for any worthwhile application, sufficient solar energy should be collected from a large ground area with the help of many solar collectors. Solar collector is a device for collecting solar radiation and then transferring the absorbed energy to a fluid passing through it. A solar collector absorbs solar energy in the form of heat and simultaneously transfers this heat to a fluid so that the heat can be transported by the fluid. The transport fluid takes this transferred heat from the collector and delivers it to a thermal storage tank, boiler or heat exchanger so that it can be utilized in a solar thermal system. Hence, solar collector is essential and it forms the first basic unit in a solar thermal system.

3.2.1 Classification of Solar Collectors

- **How are solar collectors classified? What are the important features of a solar collector?**

or

- **Explain (i) collector efficiency, (ii) concentration ratio and (iii) temperature range.**

or

- **Enumerate different types of concentrating solar collectors.**

A solar collector is a device (i) to collect and absorb solar radiation and (ii) to transfer the absorbed heat energy to the fluid (generally air or water) in contact or passing through it. There are mainly two types of solar collectors (i) non-concentrating or flat plate type solar collector and (ii) concentrating type solar collector as shown in Figure 3.1. The solar energy

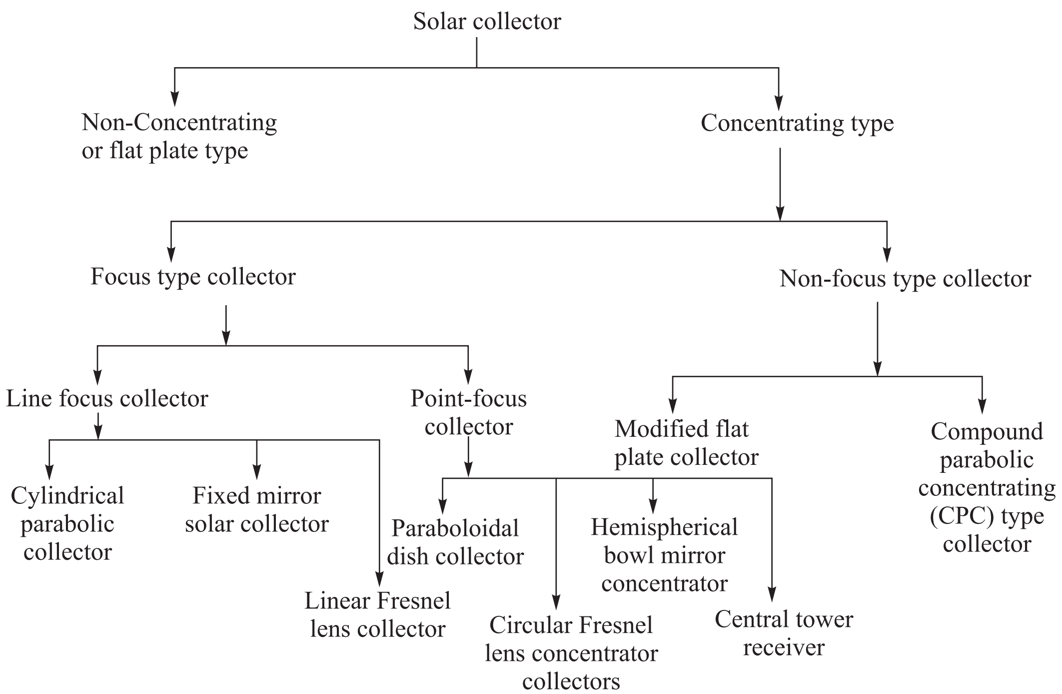


Figure 3.1 Classification of collectors.

collector with its associated absorber is the essential component of any solar collector for the conversion of solar radiation energy into more usable form of energy such as heat or electricity.

In the non-concentrating solar collectors, the collector's or radiation interceptor's area is the same as that of absorber's area. On the contrary, the intercepter's area is many times more than that of absorber's area in the concentrating type collectors. By increasing the concentration of radiation energy, much higher temperature can be obtained in the collector's fluid for transportation. Concentrating collectors can be used to generate steam of medium temperature and pressure. The concentrating collectors use different arrangements of mirrors and lenses to concentrate solar radiation for effective generation of steam in the boilers and other devices. The concentrating type solar collectors have better efficiency than that of flat plate type collectors. To improve their efficiency, the collectors should be movable by the tracking system so as to make the collectors always facing the sun when the sun moves through the sky. The line focus type collectors require one axis tracking while the point focus type collectors require two axes tracking. The line focus, point-focus and non-focus type collectors are as enumerated in the classification as shown in Figure 3.1.

While non-focus type collectors utilize both beam and diffuse radiation, the focus type collectors utilize only beam radiation as diffuse radiation cannot be focused. Concentrating collectors can increase the power flux of sunlight by hundreds of times. This class of collectors is used for high temperature applications, such as steam generation. Concentrating collectors are best suited to such climates that have a high percentage of clear sky days as cloudy days have diffuse radiation which cannot be concentrated. The main type of concentrating collectors are (i) parabolic dish collectors, (ii) parabolic trough collectors, (iii) power tower and (iv) stationary concentrating collectors. A solar photovoltaic concentrating module uses optical elements such as Fresnel lenses to increase the sunlight incidenting on it. Concentrating collector has to face sun and it needs tracking device to follow with the movement of the sun. Concentrating collectors for home or small business solar heating appliances are usually made of parabolic trough type collectors that can concentrate the solar radiation on an absorber tube or receiver which contains any fluid for heat transfer.

The important features of a solar collector are as follow:

- Collector efficiency
- Concentrating ratio (CR)
- Temperature range

Collector efficiency

It is defined as the ratio of energy actually absorbed by the collector to the energy incident on the collector. The absorbed energy by a collector is the solar energy which is transferred to the transport fluid as heat energy.

$$\eta = \frac{\text{Energy absorbed}}{\text{Solar incident energy}}$$

Concentrating ratio

It is defined as the ratio of the area of aperture of the collector system to the area of the receiver. The aperture of the system is the projected area of collector facing or normal to the sun as shown in Figure 3.2. The radiation is incident on an aperture area A_o which is then concentrating on a smaller area on receiver or absorber plate given by A_r. The concentration ratio is

$$CR = \frac{A_o}{A_r} \text{ and } CR_{max} = \frac{1}{\sin \theta_{max}}$$

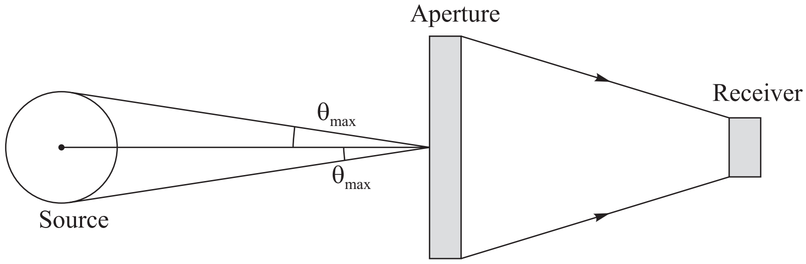


Figure 3.2 Concentrating ratio of a collector.

Temperature range

It is the range of temperature to which the heat transporting fluid is heated up by the collector. The temperature range depends upon the concentration ratio. The flat plate collectors have concentration ratio of unity as no focussing or optical concentration system is utilised in them to concentrate the solar radiation. This is the reason why the temperature range of flat collectors is less than 100°C. Line focus collectors have concentration ratio up to 100 and these collectors can have temperature range on the order of 150–300°C. Point focus collectors have very high concentration ratio (CR > 1000) and these collectors have temperature range in the order of 500–1000°C.

- **In a collector, the aperture area is 2m^2 while it has absorber area of 100 cm^2. Find its concentration ratio.**

$$\mathbf{CR} = \frac{A_a}{A_r} = \frac{2}{100 \times (100)^{-2}} = 200$$

- **A parabolic collector of length 2m has angle of acceptance (2θ) as 15°. Find the concentration ratio of the collector.**

$$CR = \frac{1}{\sin \theta_{max}}$$

But $2\theta_{max}$ = angle of acceptance = 15

$$\therefore \quad \theta_{max} = \frac{15}{2} = 7.5°$$

$$\therefore \qquad CR = \frac{1}{\sin 7.5} = 7.66.$$

3.2.2 Flat Plate Collector

- **What is a flat plate solar collector?**

or

- **Explain the principle of conversion of solar energy to heat. Explain a flat plate solar collector.**

Principle of conversion

If incident radiation is unity on a body, then radiation can be absorbed, reflected, transmitted. If absorption coefficient, reflection coefficient and transmission coefficient are α, ρ and τ, respectively, then

$$\alpha + \rho + \tau = 1$$

The absorbed part of radiation is responsible for increasing the temperature of the body. If the body gains temperature and temperature becomes τ, it also starts radiating heat to surroundings as per the Boltzmann equation ($Q_{rad} = \in \sigma T^4$ where σ is the Boltzmann constant and $\in$ is the emission coefficient). When body has equilibrium temperature,

$$\alpha \cdot H_G = \in \sigma T^4$$

where H_G is the intensity of global radiation.

The equilibrium temperature (T) depends on higher value of absorption coefficient (α), lower value of emission coefficient ($\in$) and higher value of intensity of incident radiation. The absorption coefficient can be increased by painting the body black. Emission coefficient can be reduced by (i) insulation of body and (ii) lowering of reradiation from the body by using glass cover. The intensity of radiation can be increased by using any means helping to concentrate the incident radiation.

Components of the flat plate collector

A flat plate collector consists of following essential components:

(i) **Absorber plate.** It is meant to intercept and absorb incident solar radiation. It is primarily a blackened heat absorbing plate usually made of copper, aluminium or steel. It may also be given a coating to minimise the emission of heat from its surface.

(ii) **Transparent cover.** It is made of one or more transparent sheets of glass or plastic. It is placed above the absorber plate. The cover allows radiation to reach the absorber plate but it prevents any reradiation and heat loss due to convection.

(iii) **Fluid tubes or channels.** Fluid tubes or channels are arranged in thermal contact with the absorber plate so that heat can be transferred from the absorber plate to the fluid in the tubes or channels.

(iv) **Thermal insulation.** The thermal insulation is provided under the absorber plate and fluid tubes to minimise any heat loss by transmission or convection from the absorber plate and fluid tubes.

(v) **Tight container or box.** All the above components of the collector are protected by a tight container or box as shown in Figure 3.3.

The characteristic features of a flat plate collector are as follows:

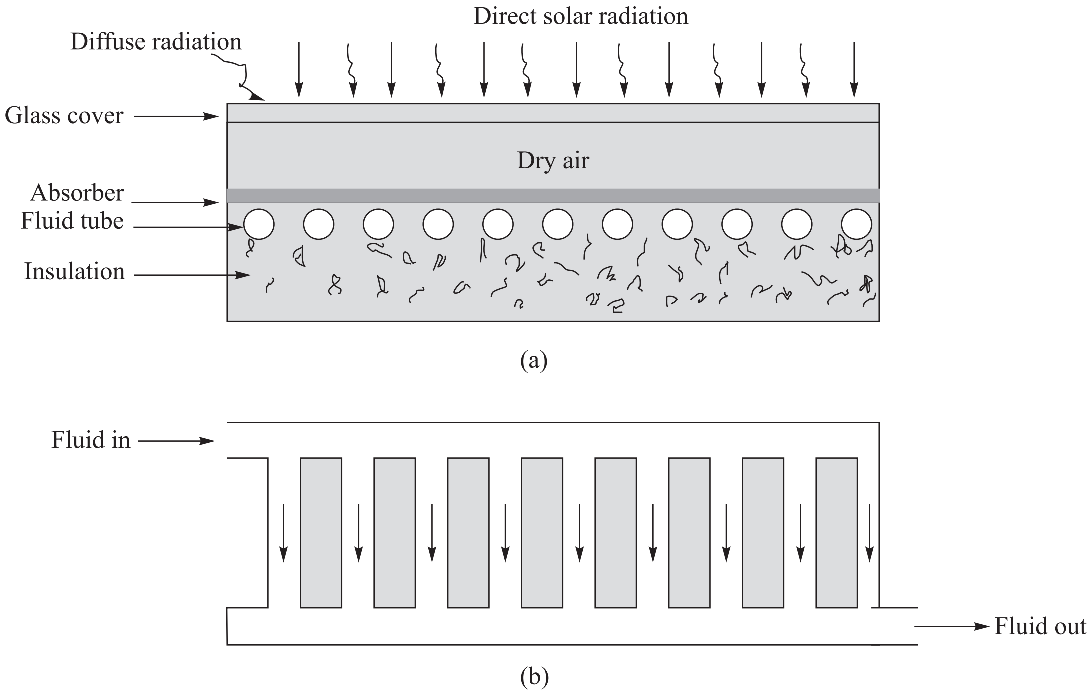


Figure 3.3 Flat plate solar collector. (a) Layout of transparent cover, absorber and fluid tubes. (b) Fluid tube connection and fluid flow.

(i) It absorbs both direct and diffuse solar radiation.

(ii) It does not need any sun tracking system. Hence, it is mechanically stronger than other collectors which require tracking system.

(iii) It has simple construction requiring a little maintenance.

3.2.3 Modified Flat Plate Collector

- **Explain modified flat plate collector.**

It is a modified form of the flat plate collector as it has plain reflectors at its edges to reflect additional radiation to the absorber or receiver and so there is some concentration of solar radiation at the receiver. The mirror reflectors are called booster mirrors which increase the acceptance angle and concentration ratio of the flat plate reflector from 1 to 4. The arrangement of the reflecting mirrors is shown in Figure 3.4.

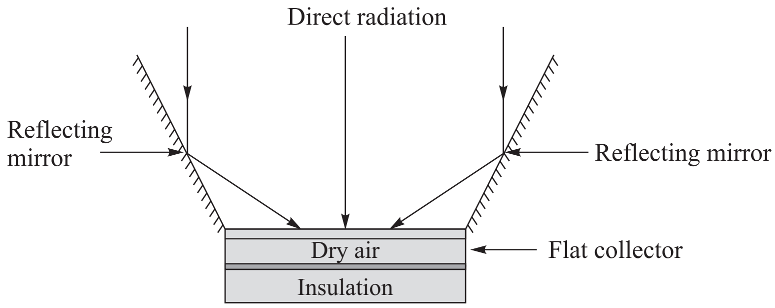


Figure 3.4 Modified flat plate collector.

3.2.4 Compound Parabolic Concentrator

- **Write briefly about compound parabolic concentrator.**

The compound parabolic concentrator (CPC) is mainly a flat collector having two parabolic mirror reflectors attached at the edge of the flat plate collector as shown in Figure 3.5.

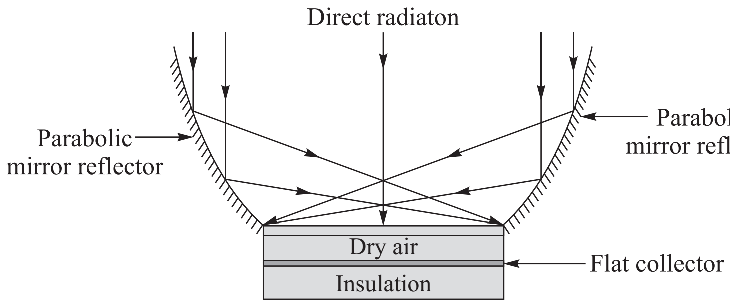


Figure 3.5 Compound parabolic concentrator.

The parabolic mirrors are so adjusted that the focus of one mirror is located at the bottom end of the other mirror in contact with the receiver. The arrangement helps in increasing the acceptance angle. The concentration ratio achieved by this type of collectors ranges from 3 to 7.

3.2.5 Cylindrical Parabolic Concentrator

- **Describe a line focal concentrator.**

  or
- **Describe a one-axis tracking collector.**

  or
- **Describe briefly a cylindrical parabolic concentrator.**

Cylindrical parabolic concentrator or parabolic trough collector consists of a cylindrical parabolic trough reflector with a metallic fluid tube or receiver tube containing fluid at its focal line as shown in Figure 3.6. In order to have better absorption of solar radiation, the fluid tube is blackened at outer surface. The concentrated solar radiation reaching the fluid tube heats up the transport fluid flowing through it. The collector with such concentrator has to be oriented to any of the following three directions: (i) East–West, (ii) North–South and (iii) Polar. Hence, such collector needs one-axis tracking system which can move the collector as per the sun's movements in sky. These types of collectors have the concentration ratio in the range of 5–30.

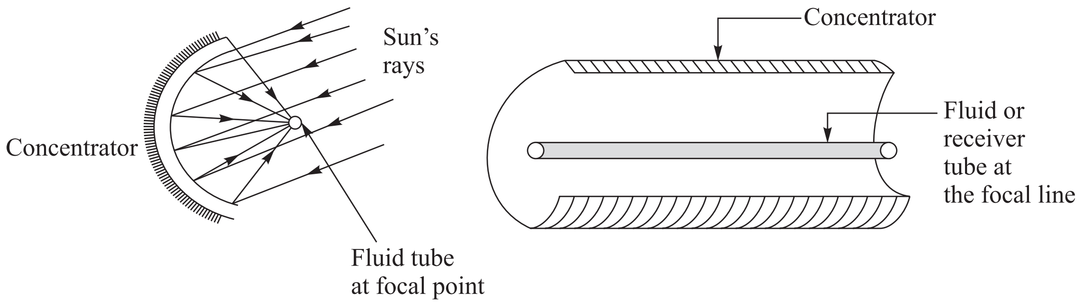


Figure 3.6 Cylindrical parabolic concentrator. (a) Focussing of sun's rays. (b) Arrangement of cylindrical concentrator and fluid tube.

- **A cylindrical parabolic concentrator is 9 m long and 2 m wide. The diameter of absorber tube is 10 cm. Find the concentration ratio.**

$$A_c = 2 \times 9 - 0.1 \times 9 = 17.1 \text{ m}^2$$

$$A_r = \pi D \times 9 = 3.14 \times 0.1 \times 9 = 2.82 \text{ m}^2$$

Now

$$\text{CR} = \frac{A_c}{A_r}$$

$$= \frac{17.1}{2.82} = 6.06$$

3.2.6 Linear Fresnel Lens Collector

- **Write short note on linear Fresnel lens collector.**

or

- **Describe a mirror strip solar collector.**

In this type of collectors, a concentrator in the form of Fresnel lens is used. The Fresnel lens consists of fine and linear grooves formed on one of the surfaces of some refracting materials sheet while its other surface is flat. The grooves provided on the sheet are designed in such a manner that these behave similar to spherical lens to every incident light rays. The incident radiation, therefore, converges on the focal line of the lens system where fluid tube is provided as shown in Figure 3.7. The heat is transferred to the transport fluid flowing in the fluid tube. A concentration ratio ranging from 10 to 30 is achieved. The temperature range of such collectors varies from 150 to 300°C.

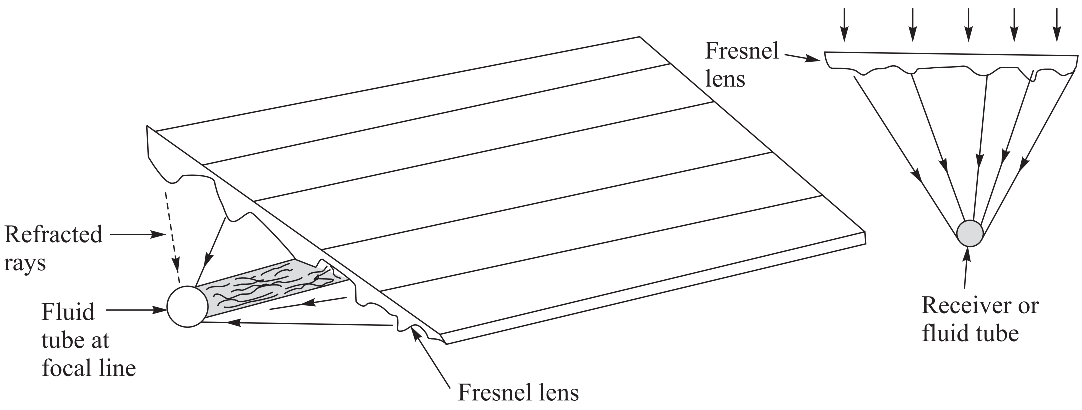


Figure 3.7 Linear Fresnel lens collectors.

3.2.7 Fixed Mirror Solar Concentrator

- **Explain fixed mirror solar concentrator.**

or

- **Describe a collector having tracking receiver or fluid tube.**

The concentrator consists of a number of long narrow mirror strips fixed on the circumference of a certain reference cylinder with a tracking receiver or fluid tube moving at the same circular circumference or focal circle as shown in Figure 3.8. The mirrors are arranged in

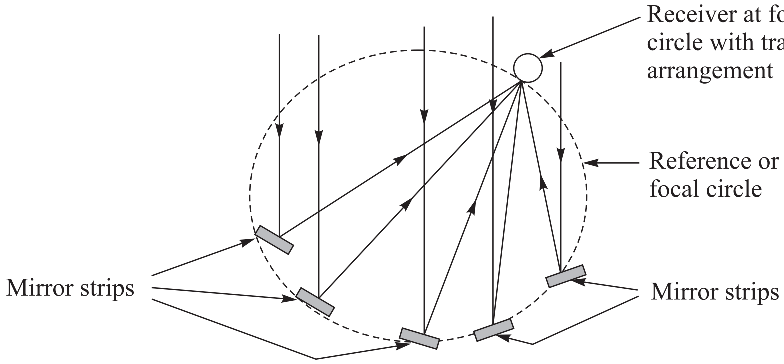


Figure 3.8 Fixed mirror solar concentrator.

such a manner that the incident radiation on them is focused on the receiver tube on their common focal circle. The receiver tube is made to move along the focal circle by a tracking device as per the movement of the sun in the sky. The concentration ratio of the concentrator is equal to the number of mirrors used for the concentration of radiation.

3.2.8 Paraboloidal Dish Collector

- **Describe any of the point-focus collector**

or

- **Why is two axes tracking required for a point-focus collector?**

or

- **Write a short note on paraboloidal dish collector.**

A point-focus collector has a dish of the shape of a paraboloidal, that is, the surface produced when a parabola is rotated about its axis. The paraboloidal surface can concentrate all incident radiation parallel to its axis to a point focus where the receiver tube is positioned. In order to ensure proper incidence of radiation, the parabolic dish collector should be provided with two axes tracking: (i) by rotating the support structure about the vertical axis for dish alignment and (ii) the dish is rotated about a horizontal axis for elevation tracking as shown in Figure 3.9. This type of collectors can have concentration ratio ranging from 10 to 1000 which helps to produce temperature up to 3000°C.

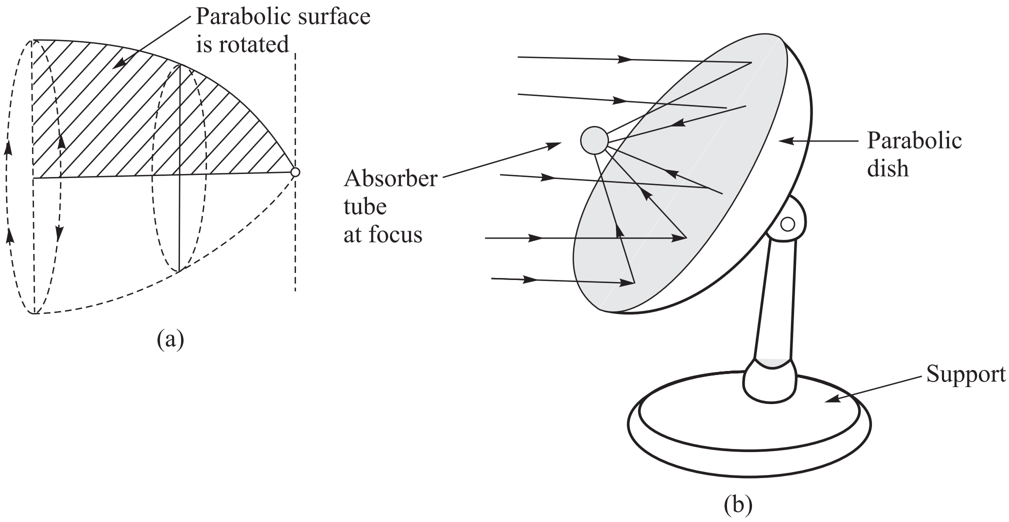


Figure 3.9 Paraboloid point focus solar collector. (a) Generation of paraboloid surface. (b) Parabolic surface concentrating radiation.

3.2.9 Hemispherical Bowl Mirror Concentrator

- **Describe a hemispherical bowl mirror concentrator. How does its tracking differ from that of paraboloid point focus concentrator?**

The hemispherical bowl mirror concentrator is a point focus concentrator in which reflector remains stationary and the receiver is made to track about two axes as per the movement of the sun in the sky so that solar radiation can be converged at the receiver kept at the focal point. The hemispherical fixed mirror, absorber with two axes tracking system and supporting structure of the collector are as shown in Figure 3.10. All the sun rays entering the hemisphere after reflection are concentrated at focal point. The absorber should be moved in such a way that it is always at the converging point of the sun rays after the reflection.

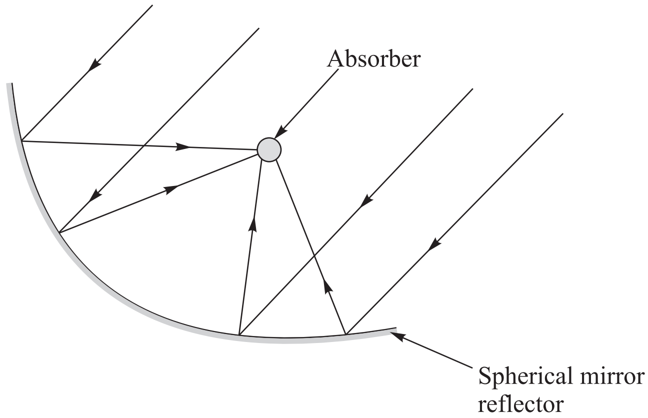


Figure 3.10 Hemispherical bowl mirror concentrator.

3.2.10 Circular Fresnel Lens Concentrator

- **Describe circular Fresnel lens concentrator.**

The principle of working of this type of collector is similar to the linear Fresnel collector and the only difference is that this type of collector is designed to concentrate the radiation at one focal point instead of line focus. These Fresnel lenses concentrators are used where high concentration of radiation is required, for examples, with silicon solar cell receiver. The concentrator has a number of thin circular zones with fine grooves so designed that the lens concentrator behaves optically as a thin spherical lens. The sun rays are made to refract and converge at a point as shown in Figure 3.11. The concentration ratio obtained by this concentrator is very high with a value of about 2000.

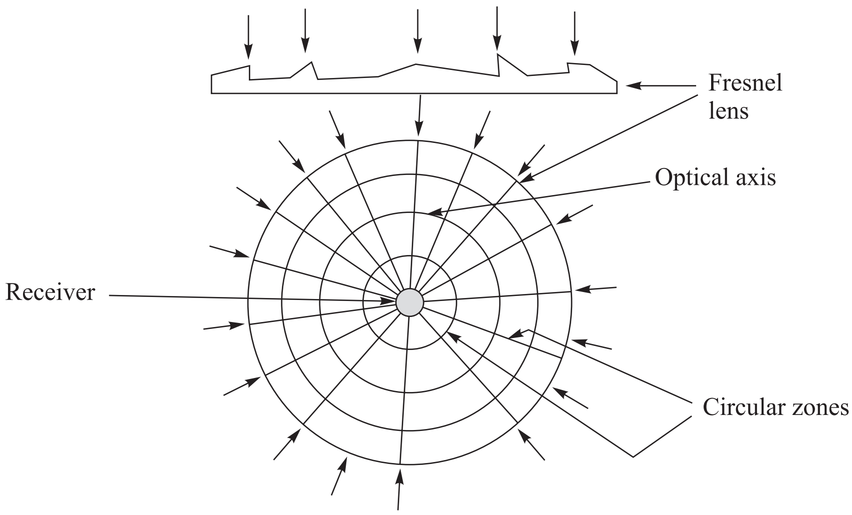


Figure 3.11 Circular Fresnel lens concentrator.

3.2.11 Central Tower Receiver Collector

- **What do you understand by central tower receiver collector?**

In this type of collectors, the receiver is located at the top of a tower and solar radiation is reflected on it from a large number of independently controlled flat mirrors called heliostats. The heliostats can be moved independently about two axes so that the reflected solar radiation is always directed towards the absorber mounted on the tower as shown in Figure 3.12. The heliostats are spread over a large area on ground surrounding the absorber mounted on the tower. The number of heliostats can be as high as thousands and they simultaneously track the sun to reflect the solar radiation from all sides on the receiver. These heliostats together act as a very large paraboloidal dish collector. The concentration ratio as high as 3000 can be obtained by this point type concentrator called central tower receiver collector. The solar radiation at the receiver is converted into heat, which is transported to a heat engine or any other device for use.

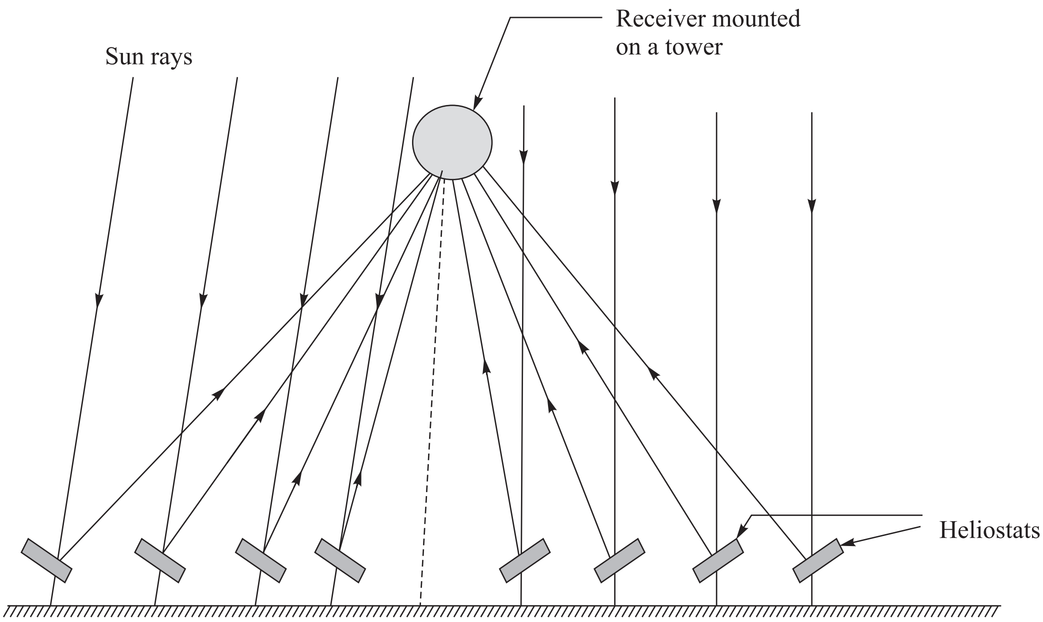


Figure 3.12 Heliostats and the receiver in a central tower receiver collectors.

3.2.12 Comparison between Flat and Focussing Collectors

- **Differentiate between flat and focussing collectors.**

The differences between flat and focussing collectors are given in Table 3.1.

TABLE 3.1 Differences between flat and focussing collectors

Flat collectors	*Focussing collectors*
The absorber area is large	Absorber area is small
Concentration ratio is 1	Concentration ratio is high varying from 4 to 3000
Temperature range is low, generally not more than 70°C	Tmperature range is high, which is up to 3000°C
It uses both beam and diffuse radiation	It uses mainly beam radiation
Simple in construction and maintenance, no tracking system is required	More complicated design and difficult maintenance, tracking system is required
Less costly	More costly
Application limited to low temperature uses	High temperature applications such as power generation
Suitable for all places as it can work in clear and cloudy days	Suitable where there are more clear days in a year

3.2.13 Orientation of Flat Plate Collector

- **Discuss the orientation of flat plate collector to get the maximum output.**

To reduce the losses owing reflection of incident radiation from the absorbing surface, it is essential that incident radiation should strike the absorbing surface at the right angle. But the incident radiation changes its direction as per the movement of the sun in the sky. The angle of incidence of the sun rays also depend on (i) latitude of the place, (ii) time of the day and (iii) time of the year. Ideally, the collector should follow the sun in order to get maximum radiation. However, this will require a huge amount of electrical energy for tracking device to keep the collector facing the sun as it moves in the sky. It is neither advisable nor economical in the context of flat plate collector having low energy output. The flat plate collectors are, therefore, kept facing south so that the maximum amount of energy can be extracted for all places in the northern hemisphere. The collector is also always kept inclined to horizontal position, with optimum inclination facing the sun so that maximum solar radiation is received throughout the day. The optimum inclination is kept as follows:

(i) In summer, inclination = lattitude –15°
(ii) In winter, inclination = lattitude +15°
(iii) Round the year, inclination = lattitude.

3.2.14 Collector Performance Testing

- **Describe the performance testing procedure of solar collectors.**

The performance testing of solar collector is carried out by comparing liquid heating by the collector using the solar radiation with the incident solar radiation on the collector. A pyranometer is used to measure the solar radiation on the plane of the collector. The steady flow of the liquid in the collector using a liquid loop is shown in Figure 3.13. The figure shows the (i) pump to circulate liquid, (ii) heat exchanger to remove heat from the liquid transferred to it by the collector, (iii) heater to maintain a constant temperature at the inlet of the collector, (iv) flowmeter to measure liquid flow, (v) valve to control flow, (vi) temperature sensors to measure inlet and outlet temperatures to the collector and (vii) collector.

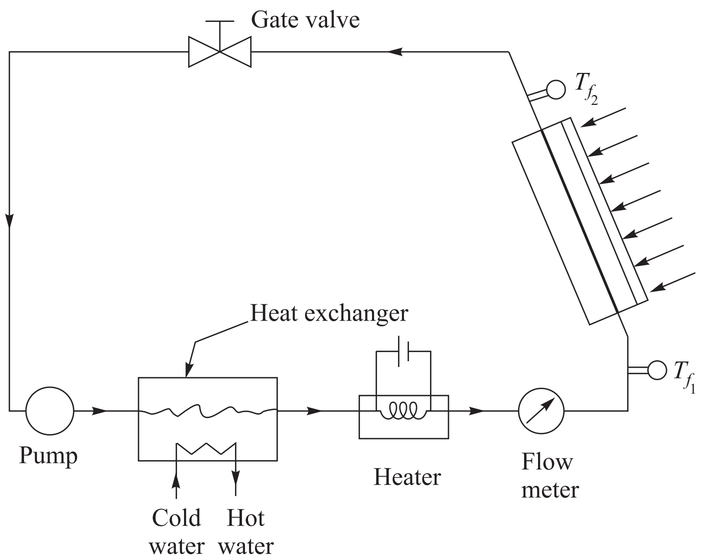


Figure 3.13 Performance testing procedure.

The liquid is heated by the collector depending upon incident solar radiation. The liquid flow is controlled by the pump and temperatures at inlet and outlet are kept constant by liquid flow and amount of heat rejected at heat exchanger or heat input by the heater. In the condition of equilibrium, the heat transferred to liquid by the collector is calculated as

$$Q_{\text{out}} = m \cdot C_p \; (T_{f_2} - T_{f_2})$$

where m is the mass of liquid flow and
C_p is the specific heat of the liquid.

If solar global radiation as measured by pyranometer is I_g and collector area is A_c, then the efficiency of the collector is given by

$$\eta_c = \frac{Q_{\text{out}}/A_c}{I_g}$$

$$= \frac{m \times C_p \; (T_{f_2} - T_{f_1})}{A_c \times I_g}$$

3.3 SOLAR ENERGY STORAGE

- **What do you understand by solar energy storage?**

or

- **Why is the storage of solar energy necessary?**

The solar energy is generally transformed into thermal or electric energy using solar devices. The solar energy is, however, available during sunshine hours, and the demand of thermal or electric energy may also exist during non-sunshine hours. Also, the maximum availability of solar energy may not coincide exactly with the demand of thermal or electric energy. The availability of solar energy is sometimes low for several days due to cloudy days, resulting in the substantial lowering of the output of thermal and electric energy from the solar radiation. Hence, it is essential to store energy output (thermal and electric) from solar devices during high insolation (in = incident, sol = solar and ation = radiation) times which is used afterwords to meet the thermal and electric load demand during peak demand times. During low insolation times, solar energy storage system enables delivery of more power than what is generated by the solar electric or thermal plant, and so it enables to match the generation of energy with the load demand.

3.3.1 Classification of Solar Energy Storage System

- **How can classification of solar energy storage systems be done? Explain them briefly.**

The solar energy storage systems can be classified as follows:

- Thermal energy storage system
- Chemical energy storage system
- Electrical energy storage system
- Hydrogen energy storage system
- Electromagnetic energy storage system
- Biological storage system

Thermal energy storage

Thermal energy storage can be (i) sensible heat storage by the virtue of heat capacity and the change in temperature of the material and (ii) latent heat storage by the virtue of latent heat necessary to change the phase of the storage medium.

Chemical energy storage

Lead acid batteries are the most commonly used means in chemical energy storage system. The advantages are (i) good working efficiency (up to 80%), (ii) low cost, (iii) rapid change from charging to discharging mode and (iv) slow discharge rate. A storage battery takes electrical energy generated by solar radiation and stores it as chemical energy. It later supplies electric energy by converting this stored energy.

Electrical energy storage

A capacitor is used to store electrical energy in an electrostatic field when it is charged. The capacitor of large capacity is required to store a significant amount of energy.

Hydrogen energy storage

The electrical energy is used to decompose water by the electrolysis reaction into hydrogen and oxygen. These substances can be recombined to release the stored energy when required.

Electromagnetic energy storage

The electrical energy is used to store energy in a magnetic field. The resistance of the coil wire is made almost negligible so that the stored energy in the coil is not dissipated out and stored energy in the magnetic field can be maintained indefinitely. The electromagnetic energy storage requires the use of superconducting materials. These materials develop almost zero resistance to electricity flow when cooled below a critical or transition temperature. This method of storing electromagnetic energy is also called super conducting magnetic energy storage (SMES). The electric energy can be recovered when coil is discharged.

Biological storage

The solar energy is stored in plants by a process known as photosynthesis. Photosynthesis is the process in which organic compounds are formed in green plants using carbon from atmospheric carbon dioxide in the presence of sunlight. The plants on decaying form biomass which can be converted into various types of solid, liquid and gaseous fuels.

3.3.2 Sensible Heat Storage

- **What are the main advantages and disadvantages of sensible heat storage with water as storage media? Compare them with those of solid media storage.**

Sensible heat storage

Thermal energy is stored in this types of storage by virtue of heat capacity and temperature difference developed during charging and discharging. The temperature of the storage material rises when thermal energy is absorbed and temperature drops when thermal energy is taken out. In this storage, the charging and discharging can be performed reversibly for an unlimited number of times. The sensible heat storage can be liquid media storage and solid media storage. Water is considered as the most suitable media for storage below 100°C. Liquids such as oils, liquid metals and molten salts are also used as liquid media storage.

The water thermal energy storage can be short term and long term. A short-term thermal energy storage system has a well-insulated storage tank as shown in Figure 3.14. The storage in such tank is economical for few days only as heat losses over long duration make the storage uneconomical. Long-term sensible heat storage by water is possible in underground reservoirs having special insulation. In this system, water is heated in charging mode by passing it through a heat exchanger and then it is stored in an underground reservoir. In the discharge mode, the hot water is made to flow back through the heat exchanger, where it releases the stored energy as shown in Figure 3.15 but with reverse circulation.

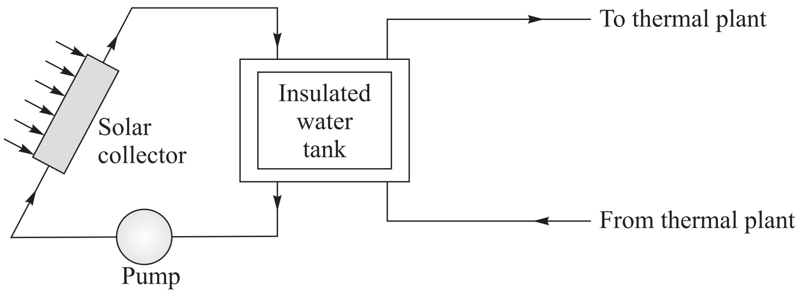


Figure 3.14 Short-term sensible heat storage by water.

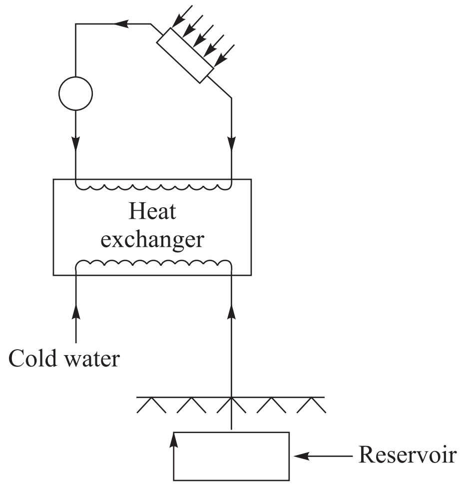


Figure 3.15 Long-term sensible heat storage by water.

Advantages. Water has the following advantages:

- It is abundantly available.
- It is inexpensive.
- It has high specific heat which enables to store more heat per unit mass.
- It has low viscosity requiring less energy to pump through the pipe system.
- It can be used for both storage and working medium.
- It is stable.
- It has no harmful effect.

Disadvantages. Water has the following disadvantages:

- It has limited temperature range of 0–100°C.
- It results in the corrosion of pipes.
- It can leak easily as it has low surface tension.

Solid media storage or packed media storage

This type of storage has a bed of loosely packed solid materials such as rocks, sand, concrete, pebbles and metals to store sensible heat. A fluid such as air is circulated through the bed to add or remove heat from the storage. This type of solid media storage has no limitations such as (i) low temperature due to freezing and (ii) high temperature due to vapourizing as applicable in the case of liquid media storage. A typical packed bed storage unit is shown in Figure 3.16. It consists of a container, a screen to support the bed, inlet duct and outlet duct. The charging or adding of heat is done by passing hot air through the bed in one direction and the removable of heat is done by passing the normal air through the bed in the opposite direction.

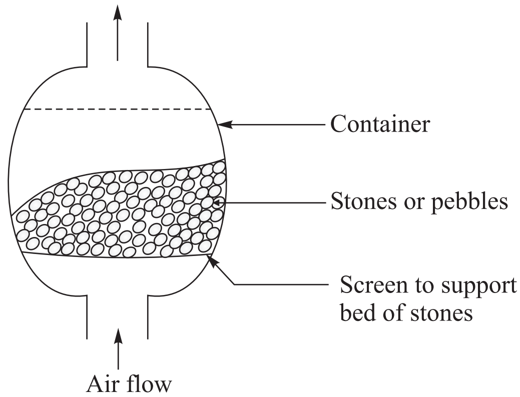


Figure 3.16 Solid media storage.

Advantages. The advantages of solid media storage are as follows:

- Stones or pebbles are abundantly available
- Low cost
- Non-combustible
- Easy to handle
- Possibility of high storage temperature
- No freezing point during heat removal
- No corrosion problem
- No requirement of heat exchanger

Disadvantages. The disadvantages are as follows:

- The size of the storage container should be large
- Simultaneously charging and discharging of energy is impossible
- Large pressure drop needs high capacity air blower

3.3.3 Latent Heat Storage

- **Why solid–gas and liquid–gas phase changes are not considered suitable for latent heat storage?**

or

- **What are the main problems associated with the use of salt hydrate as latent heat storage?**

In the latent heat storage, heat energy is stored by virtue of latent heat which is required to bring about phase change of storage medium. The heat required to bring about phase change of a material is much larger compared to sensible heat change of the same material. The phase change of a material also involves absorption or release of a large quantity of heat energy at constant temperature, which is impossible in the case of sensible heating and cooling. Therefore, latent heat storage system is more compact for a certain heat storage compared to sensible heat storage system. The phase change which can be used for storage system are solid–solid, solid–gas, solid–liquid and liquid–gas. Solid–gas and liquid–gas transformation involves large volume changes, thereby making such storage systems impractical and complex. However, solid–solid transition involves transformation of the material from one crystalline form to another, thereby resulting in the transformation with small volume changes. Hence, such storage systems are practical and preferred in spite of small changes in latent heat possible during transformation.

For phase-change storage media, salt hydrates called Glauber's salt ($Na_2SO_4 \cdot 10H_2O$) are preferred. These have solid–liquid transformation. Besides hydrates, paraffins ($C_{18}H_{36}$) and non-paraffins (ester, fatty acids, alcohols and glycols) are also suitable for such storage. The hydrate crystals have water of crystallization and these can be represented by $X(Y)_n \cdot mH_2O$ (one atom of X, n atoms of Y and m molecules of water in one crystal). When hydrate crystals are heated to transition temperature, these crystals release their water of crystallization and anhydrous salt (hydrates without water) get dissolved in the released water. The reaction is as follows:

$$\underset{\text{(crystal)}}{X(Y)_n \cdot mH_2O} + \text{heat} \rightarrow \underset{\text{(anhydrous salt)}}{X(Y)_n} + \underset{\text{(water)}}{mH_2O}$$

The problems faced with the use of salt hydrate for latent heat storage are as follows:

(i) The released water of crystallization is insufficient to dissolve all the solid salt produced on heating. The anhydrous salt settles down at the bottom of the container. The recrystallization becomes impossible on removal of heat. The process becomes irreversible and performance degradation takes place.

(ii) Mechanical means (vibration or stirring), the suspension media or thickening agents have to be used to make the system work in reversible manner without performance degradation. The problem can also be resolved by limiting vertical height of the container.

(iii) Heat of fusion is small (251 kJ/kg).

- **Glauber's salt is used as medium for phase-change storage in a solar heating system. Determine how much energy is stored per unit mass of the salt when the salt is heated from 25° to 50°C. Specific heat of salt crystal is 1.95 kJ/(kg K) and of anhydrous salt solution is 3.55 kJ/(kg K). Take melting point of salt as 32°C and latent heat as 250 kJ/kg.**

1. Heat for sensible heating $Q_1 = C_s \times (T_m - T_1)$

$$C_s = 1.95 \text{ kJ/(kg K)}$$

$$T_m = 32°\text{C}$$

$$T_1 = 25°\text{C}$$

$$Q_1 = 1.95 \times (32 - 25) = 13.65$$

2. Heat for phase change (Q_2) = 250 kJ/kg

3. Heat for sensible heating $Q_3 = C_l \, (T_2 - T_m)$

C_l = Specific heat of liquid

T_2 = Final temperature

$Q_3 = 3.55\ (50 - 32) = 63.99$

Energy storage per kg $= Q_1 + Q_2 + Q_3$

$= 13.65 + 250 + 63.99$

$= 327.64$ kJ

3.4 SOLAR POND

- **With the help of schematic diagram, explain the working of solar pond electric power plant.**

or

- **What is meant by solar pond? Explain.**

or

- **Describe a working of solar power plant.**

or

- **Explain the principle of working of solar pond.**

Principle. In ordinary pond, when water is heated up by the sun rays, the heated water rises to the top of the pond. The hot water loses heat to the atmosphere, and so the net temperature at the top of the pond remains nearly at atmospheric temperature. The solar pond technology ensures that heated brine water remains at the bottom of the pond due to more brine concentration and density in it.

The solar pond serves the dual purpose of a large flat collector and a thermal storage system. It consists of a large size brine pond (depth of about 1 m) which has salt concentration gradient in such a way that the most concentrated and dense part of the brine solution is at the bottom of the pond and brine concentration gradually reduces from bottom to top of the pond based on the variation of brine solution density. A solar pond has three zones as shown in Figure 3.17. The top zone is surface zone which has the least salt content and its temperature is the atmospheric temperature. The bottom zone has the maximum salt content and it has a high temperature (70–85°C). This is the zone that collects and stores the solar energy as heat energy. In between these two zones there is the gradient non-convective zone.

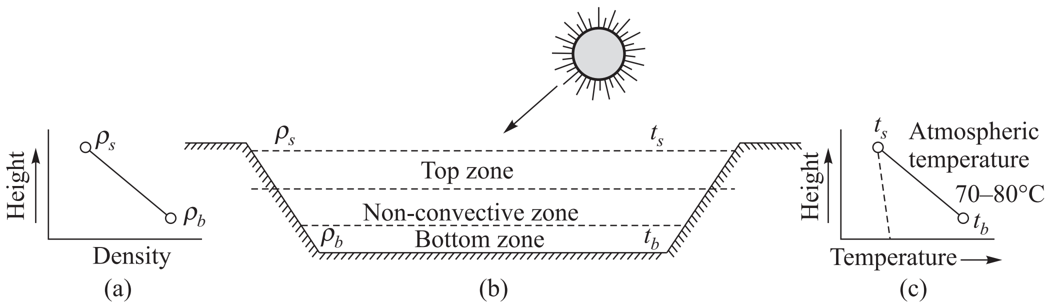


Figure 3.17 The concept of solar pond. (a) Variation of density, (b) The three zones in the pond, (c) Variation of temperature.

The hot brine solution from the bottom of solar pond is taken out without disturbing the brine gradient existing in the solar pond. This solution is taken to heat exchanger to remove heat from the brine solution by evaporating a refrigerant in the evaporator. These vapours are used to run a turbine which is coupled to a generator to generate power. The refrigerant vapours exiting from the outlet of the turbine are condensed to liquid state in a condenser and pumped to heat exchanger. Solar pond electric power plant is shown in Figure 3.18.

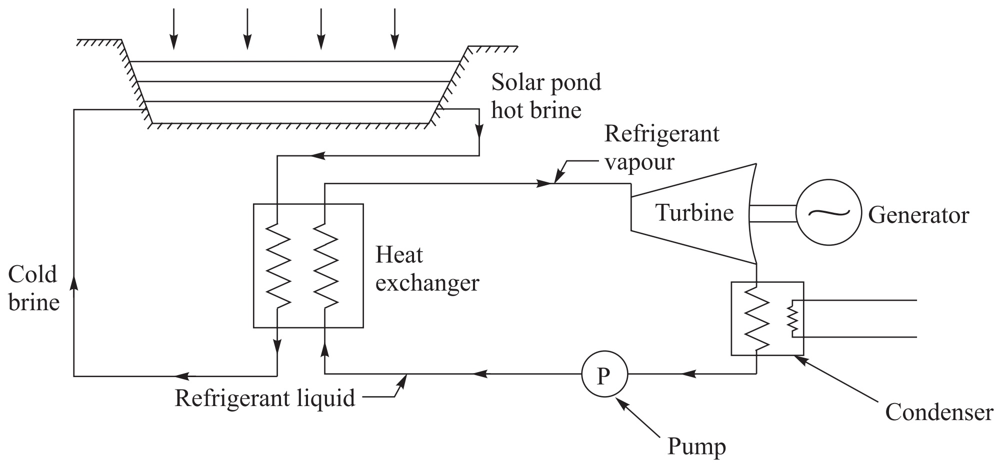


Figure 3.18 Layout of a solar pond electric power plant.

3.5 SOLAR WATER HEATER

- **With the help of a neat sketch, explain the working of a solar water heater.**

or

- **Describe a solar water heating system.**

A small capacity water heating system with natural circulation is as shown in Figure 3.19. It is suitable to supply hot water for domestic purposes. It has two main components which include (i) flat plate collector to convert solar radiation into heat energy and (ii) water storage tank to store hot water. The tank is located above the level of collector. Heat is transferred to the water in the solar collector and hot water rises to flow in the water tank. The hot water enters the top of the water tank and cold water from the water tank moves out from the bottom of the tank so as to enter the inlet of the collector. The natural circulation of water is established from the collector to water tank and then from water tank to the collector. The hot water for use is withdrawn from the top of tank, which is replaced by cold water entering at the bottom of the tank. Water heating system is also provided with an auxiliary heating system so that the system can also work during cloudy and rainy days when sufficient solar radiation is unavailable.

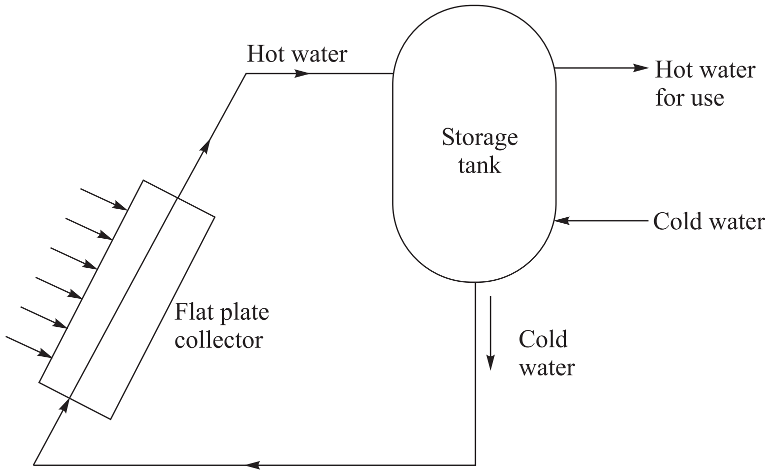


Figure 3.19 Small capacity water heating system with natural circulation.

3.6 SOLAR THERMAL PUMP

- **Explain the working of the solar thermal water pump with the help of a neat sketch.**

or

- **What are the features of solar energy which make it attractive for water pumping in irrigation?**

or

- **Explain the working of solar pumping.**

Solar pumping utilizes the mechanical power generated by the solar radiation to run the water pump. Solar energy offers several beneficial features which make its utilisation in irrigation pumping quite attractive. The features are as follows:

(i) The need for pumping arises most during the summer months when solar radiation is intense.
(ii) Pumping can be carried out intermittently without any problem.
(iii) Surplus pumped water can be stored in a reservoir or tank.
(iv) The requirement of water decreases during periods of low radiations when solar pumping decreases. Evaporation losses reduce during cloudy days. Rainwater is also available during rainy days.
(v) There is relatively inexpensive running and maintenance cost.

The solar pump is similar to solar heat engine working in low-temperature range. The source of heat is a solar collector. The heat is transported to a heat exchanger where heat is transferred to a refrigerant of low boiling point. The refrigerant evaporates and high-pressure vapour is taken to a turbine to do useful mechanical work by running the solar pump as shown in the Figure 3.20. The outlet refrigerant vapour from turbine is condensed and taken to heat exchanger using feed pump for reuse.

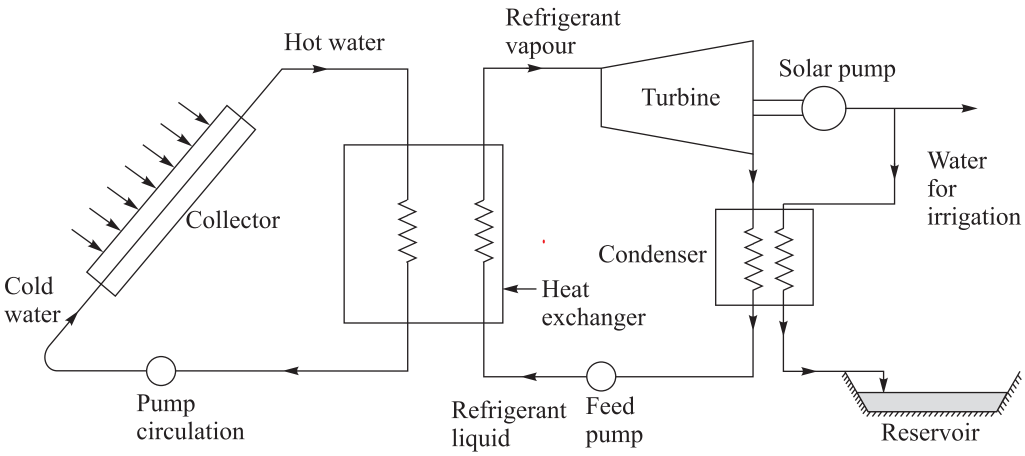


Figure 3.20 Solar water pump.

3.7 SOLAR FURNACE

- **Explain the working of a solar furnace with the help of a neat sketch.**

or

- **What are the main advantages and disadvantages of a solar furnace?**

or

- **What is the maximum temperature obtained in a solar furnace?**

Principle. Solar furnace is used to study the properties of the materials, such as physical, mechanical, chemical and electrical properties at high temperatures. The focussing type solar collectors can concentrate solar radiation over a small area in a furnance for heating of materials being tested. It is possible to obtain high temperatures which can be about 3500°C.

The solar furnace has basically two main components: (i) a concentrator with arrangement to position testing materials at its focus and (ii) a system of a large number of small heliostats. The large number of heliostats are located and positioned in such a manner that they direct solar radiation onto a paraboloidal collector (Figure 3.21). The solar radiation after reflection

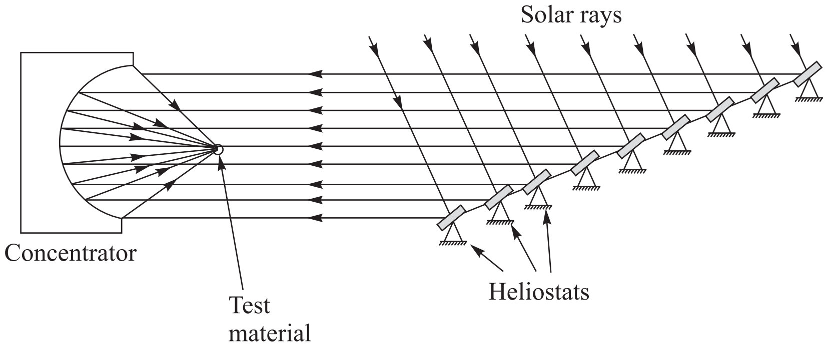


Figure 3.21 Solar furnance using heliostats and paraboloidal concentrator.

from the heliostats moves parallel to the optical axis of the concentrator. The heliostats are provided with the systems of sun tracking. The concentrator focuses the incoming solar rays on to the test material to heat up.

The advantages of a solar furnance are as follows:

(i) It gives pure heating without contamination.
(ii) It provides easy control of temperature.
(iii) No adverse effect is produced on the test material by the sun rays.
(iv) It has simple working principle.
(v) It provides an easy observation of test material while heating.
(vi) It gives high rate of heating by intense radiation concentrated at a point.

The disadvantages are as follows:

(i) It can be used during sunshine hours.
(ii) The cost of equipment is high.
(iii) Materials with small area can be only heated and tested.

3.8 SOLAR PASSIVE HEATING

- **What do you understand by solar passive heating?**

or

- **How is passive heating assured by building design?**

or

- **Write briefly about the solar house.**

Solar energy can be used for passive heating of buildings to maintain comfortable temperature inside the buildings. Passive heating of buildings does not require any mechanical device. This heating consists of natural processes such as convection, radiation and conduction which are used to transport heat in the space. The heating necessitates a suitable building design to ensure natural flow of heat in the space inside building. Such specially designed building is called solar house.

In the northern hemisphere, the sun rays come from south direction. Hence in order to achieve solar passive heating in cold regions, south facing wall is made thick using concrete or stones to store the maximum heat energy from the incident solar radiation. The entire south wall is further provided with a plastic or glass sheet covering with an air gap in between the wall and the sheet covering. The incident solar radiation after passing through the sheet covering is absorbed by the thermal storage wall. The warm air in air gap rises and enters into the space inside the building to be heated as shown in Figure 3.22. The warm air enters into the space from the upper inlet vents and cold air is removed from the space from the lower outlet vents.

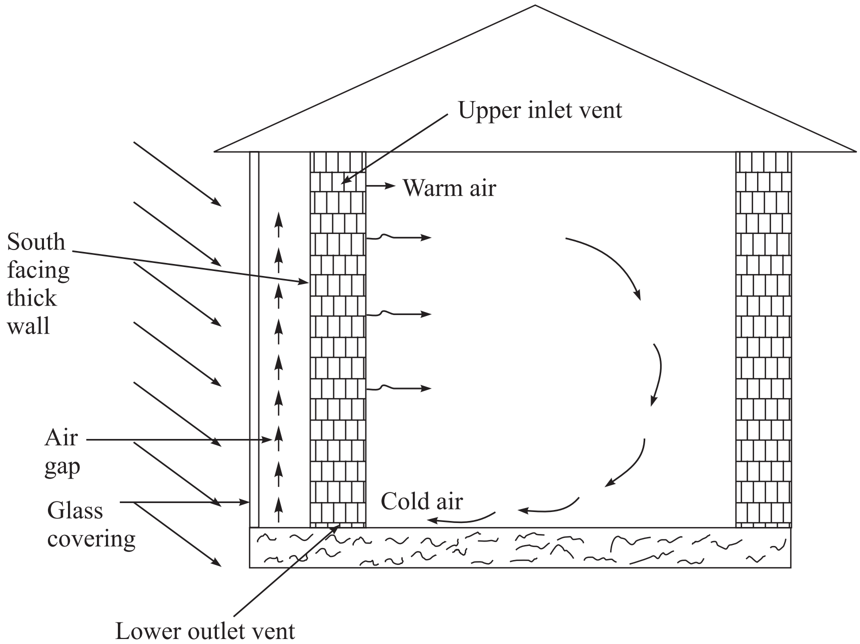


Figure 3.22 Solar passive space heating.

There is another method to provide solar passive space heating, which is shown in Figure 3.23. In this method, a flat plate collector is provided to face south. The collector is provided with rock bed type storage system. During sunshine hours, the collector transfers and stores heat energy from incident solar radiation into the rock bed storage system. The available stored energy in the rock bed is used later at night when air is passed through the rock bed, and so warm air enters into the space to be heated.

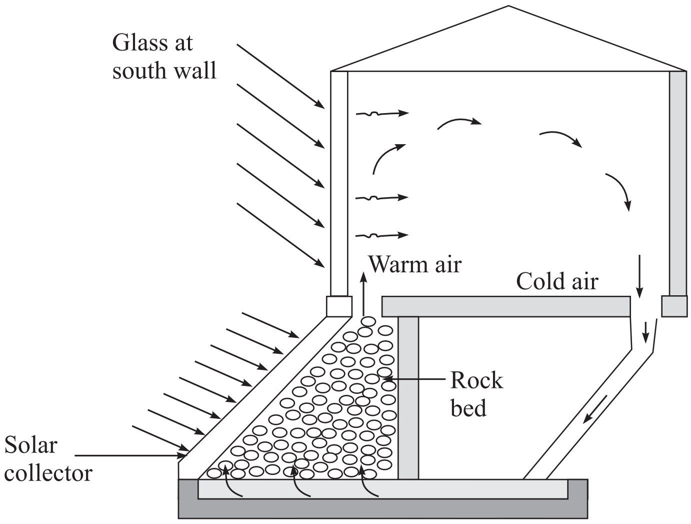


Figure 3.23 Passive solar heating using solar collector.

3.9 SOLAR PASSIVE SPACE COOLING

- **For solar passive space cooling, the best approach is to reduce unnecessary heat loads entering the space inside the building. Comment.**

The heat tends to enter a building in the following ways:

(i) Direct sunlight heat which can be reduced by using shading and providing venetian blinds to glass windows and doors.
(ii) Conduction of heat through walls, roof and floor. It can be reduced by providing insulation. Maximum heat is conducted through the exposed roof which has to be provided a false ceiling with a good insulating materials to reduce the conduction of heat from it.
(iii) Infiltration of outside hot air. It can be reduced by proper sealing of the space and reducing the openings of doors and windows.

The methods to reduce or prevent heating of the space are as follows:

(i) Shading of glass area and the walls
(ii) Providing air circulation or ventilation so that warm air is driven out and cool air from outside is sucked into the space using chimney effect as shown in a Figure 3.24
(iii) Providing a pond on the roof to reduce radiation heating and achieve cooling below the pond
(iv) Providing black plastic bags on a metallic roof which helps in radiating out the heat from the space during night-time
(v) Providing ground coupling or basement construction to maintain temperature of the space close to ground temperature.

The ground temperature is always lower than surrounding atmospheric temperature

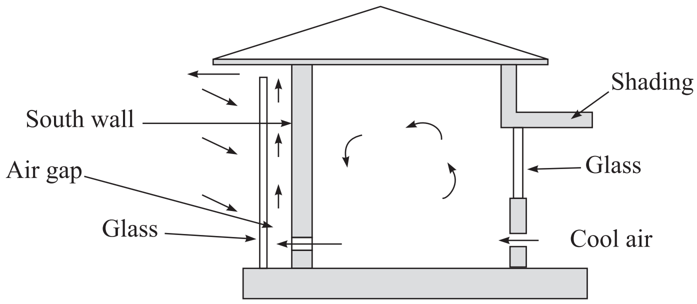


Figure 3.24 Solar passive cooling through ventilation.

3.10 SOLAR REFRIGERATION AND COOLING SYSTEM

- **Explain a method of active cooling of a space by solar radiation.**

or

- **Compare the relative merits and demerits of lithium bromide and water aqua ammonia vapour absorption cooling system.**

or

- **Explain solar vapour absorption system for cooling.**

A simple solar operated absorption refrigeration system to cool a space is as shown in Figure 3.25. The hot water transported from a flat plate collector is passed through a generator

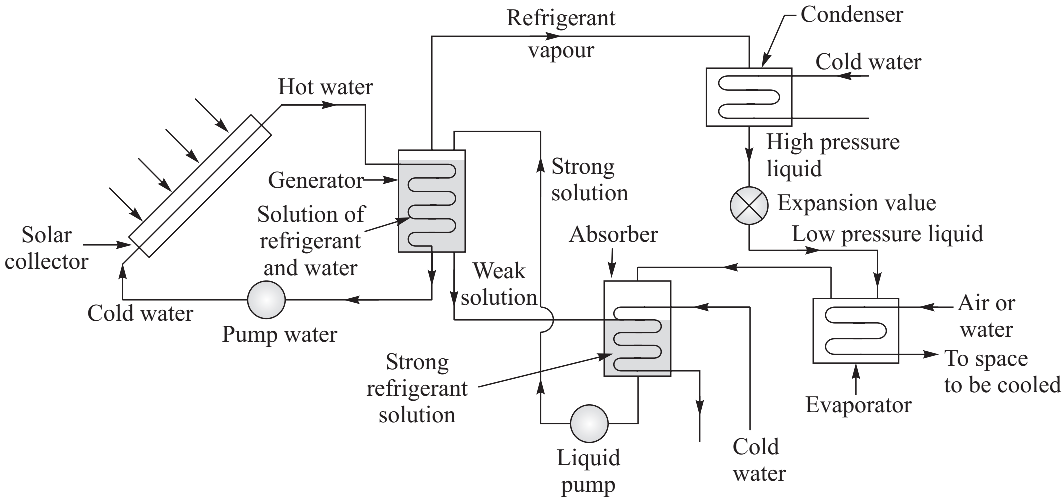


Figure 3.25 Solar absorption refrigeration system.

which is a heat exchanger. The heat is transferred to a refrigerant and absorber solution. The refrigerant can be ammonia or water while absorber is water or lithium bromide which generates refrigerant vapours at high pressure. The high-pressure vapours are condensed into high-pressure liquid in the condenser. The high-pressure refrigerant liquid is throttled to low pressure and temperature by an expansion valve. The low pressure refrigerant takes heat from the evaporator and vapouries, thereby cooling air or water which can be used for cooling the space inside the building. The refrigerant vapour is ultimately absorbed into the weak solution taken from generator to the absorber, thereby converting it into strong solution of the refrigerant. The strong solution is pumped from the absorber to the generator for the repeat of the refrigeration cycle.

Lithium bromide–water system

Water is refrigerant and lithium bromide is absorber. The absorber has pressure of 0.1 atm and temperature of 90°C while evaporator has pressure of 0.008 atm and temperature of 4°C.

Merits

(i) It is a comparatively simple system.
(ii) It has high coefficient of performance.
(iii) It requires less power for pumping water from absorber to generator due to lesser pressure in the generator.
(iv) Water as refrigerant has more latent heat of vapourisation.
(v) Lithium bromide is non-volatile which helps to prevent water vapour from going out of generator to condenser.

(vi) Solution is non-toxic.
(vii) Solution is non-inflammable.

Demerits

(i) As it can develop low temperature of 4°C only in evaporator. The system can be used for only air conditioning purpose.
(ii) The solution is corrosive.
(iii) Maintaining very low pressure in the evaporator and absorber is problematic.
(iv) Condenser has to be water cooled. Air cooling of condenser is not possible.

Aqua-ammonia absorption system

It has ammonia as refrigerant and water as absorber. The generator has pressure of 10 atm and temperature of 120°C, while evaporator has pressure of 1 atm and temperature of –5°C.

Merits

(i) It is suitable for both air conditioning and refrigeration.
(ii) Condenser can be air or water cooled.
(iii) The absorber is water, which is non-toxic and inflammable.

Demerits

(i) A rectifier is require to separate water entering into condenser.
(ii) High pumping power to pump refrigerant from the absorber to the generator is required.
(iii) Ammonia is inflammable.
(iv) Ammonia is toxic.

3.11 SOLAR VAPOUR COMPRESSION REFRIGERATION AND COOLING

- **Describe a solar cooling system based on vapour compression system.**

or

- **Can a vapour compression system be used for heating?**

or

- **What is solar air conditioning?**

Vapour compression system can be used for both cooling and heating. If the vapour compression system takes heat from space and releases to atmosphere, it is working as cooling system. On the other hand, if the vapour compression system takes heat from atmosphere and releases the same into the space, it is working as heat pump. The vapour compression system working with solar radiation to cool a space is shown in Figure 3.26. Solar power is converted into mechanical work using turbine which then runs a compressor coupled with it. The compressed refrigerant is expanded into evaporator, providing the requisite cooling.

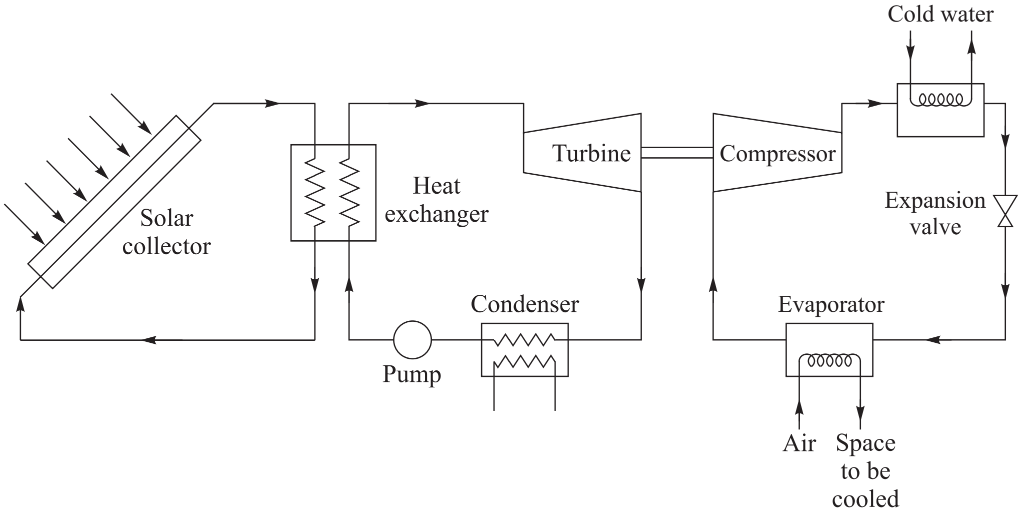


Figure 3.26 Solar vapour compression refrigeration system.

3.12 SOLAR COOKERS

- **Describe solar cooker.**

or

- **What is the main advantage of using a glass cover in a box-type cooker?**

A solar cooker consists of (i) an insulated box of blackened aluminium in which utensils with food materials can be kept, (ii) reflector mirror hinged to one side of the box so that the angle of reflector can be adjusted and (iii) a glass cover consisting of two layers of clear window glass sheets which also serves as the box door as shown in Figure 3.27.

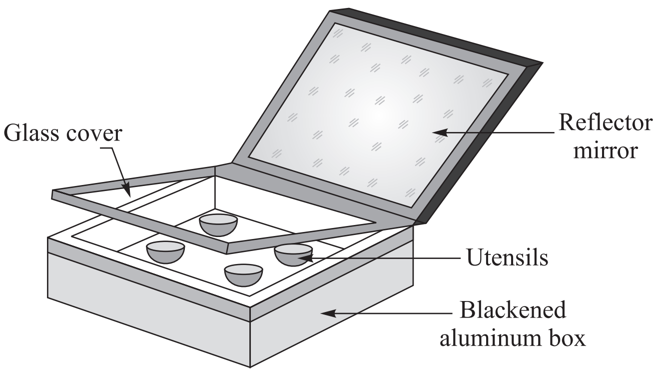


Figure 3.27 Solar cooker.

The box is kept in such a way that solar radiation falls directly on the glass cover and reflector mirror is also adjusted in such a way that additional solar radiation after mirror reflection is also incident on glass cover. The glass cover traps heat owing to the greenhouse effect, that is, short-wavelengths radiation can pass inside the box but long-wavelengths radiation coming out from the box is entrapped in the box, thereby providing more heating effect. The air temperature obtained inside the box ranges from 140 to 160°C. This provides sufficient heat for boiling and cooking purposes.

3.13 SOLAR DISTILLATION

- **What do you understand by solar distillation?**

The process to convert saline water into pure water using solar radiation is called solar distillation. A solar device used for this purpose is called solar still. A solar still consists of a shallow blackened basin filled with saline or brackish water to be distilled. It is covered with sloping transparent roof as shown in Figure 3.28. The sun rays can pass through transparent roof and these rays are absorbed by the blackened surface of the basin, thereby increasing

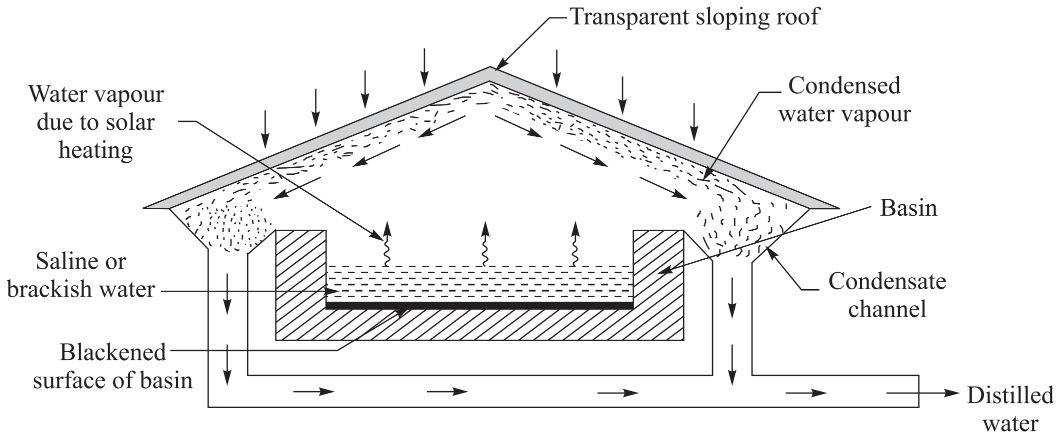


Figure 3.28 Working of a solar still.

the temperature of water. The water in basin evaporates due to solar heat and rises to the roof. The water vapour cools down and condenses at the undersurface of the roof. The water drops or condensed water slip down along the sloping roof. The condensed water is collected by the condensate channel and drained out from the solar still.

3.14 SOLAR THERMAL POWER PLANTS

- **Describe the working of a solar power plant.**

The solar thermal power plants can use different systems, such as

(i) Low temperature solar power plant using flat plate collectors
(ii) Low temperature solar power plant using solar pond
(iii) Medium temperature solar power plant using focussing collectors
(iv) High temperature solar power plant which can be

- Distributed collector system called solar farms
- Central receiver system or tower power plant

The principle of these plants is the same, which involves transportation of heat generated by the absorption of solar radiation. In medium and high temperature solar plants, steam is generated which is made to run a turbine with a generator coupled to it. In a low temperature solar system, transported heat is used to (i) generate vapour of low boiling point refrigerant using a heat exchanger and (ii) to run a turbine coupled with generator using refrigerant vapour. A central tower receiver solar power plant is shown in Figure 3.29.

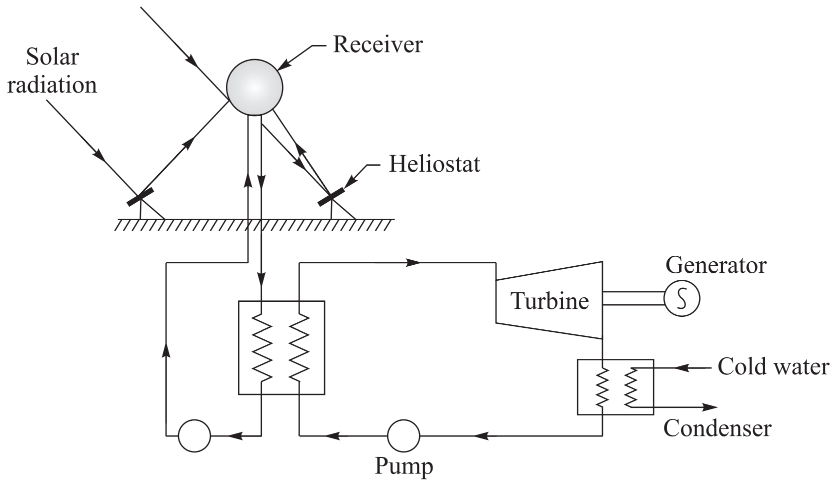


Figure 3.29 The working of a central tower receiver power plant.

3.15 SOLAR GREENHOUSE

- **What is a greenhouse?**

or

- **How is adequate supply of carbon dioxide maintained in a greenhouse?**

or

- **What is the purpose of using double layers of transparent glass sheet in a greenhouse?**

A greenhouse is a shed or enclosure in which a proper environment is provided to enable the growth and production of vegetables and flowering plants even during adverse and severe climatic conditions prevailing outside. Any vegetable or flowering plants can be grown throughout the year if suitable environmental conditions are provided.

In a greenhouse, visible light, carbon dioxide and water are provided as required for photosynthesis process. The photosynthesis process can be given as

$$\text{Light energy} + CO_2 + \text{water} = \text{Carbohydrate} + O_2$$

The carbohydrate produced in photosynthesis is used by plants during resporation process for growth. The respiration process can be given as

$$\text{Carbohydrate} + O_2 = CO_2 + \text{energy} + \text{water}$$

A typical greenhouse is shown in Figure 3.30. To ensure enough sunlight inside the greenhouse, sufficient glass or transparent plastic sheet is provided in roof and walls in the greenhouse facing the sun. For roof, two layers of glass or plastic sheets are provided with small air gap in between to obtain proper thermal insulation. The air gap helps in entrapping the solar radiation inside the greenhouse as it prevents the passing out of long-wavelength radiation from inside of the greenhouse to the atmosphere. Adequate presence of carbon dioxide is ensured by (i) supplying outside air (ii) using organic manure (iii) combustion of sulphur-free fossil fuels and (iv) carbon dioxide gas.

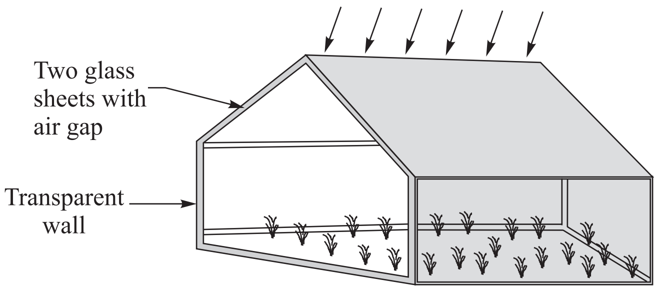


Figure 3.30 Greenhouse for cold climate.

CHAPTER 4

SOLAR PHOTOVOLTAIC SYSTEM

4.1 INTRODUCTION

Photovoltaic (PV) system is a method of generating electrical power by converting solar radiation into direct electricity with the help of semiconductors that exhibit the photovoltaic effect. The photovoltaic power generation employs solar panels constructed of a number of solar cells made-up of a photovoltaic material. Owing to the growing demand for renewable energy sources, the technology of manufacturing of solar cells and photovoltaic arrays has improved considerably in recent times. Driven by advances in technology and increase in production of solar cells, the cost of solar cells has declined considerably. The cost of electricity from photovoltaic is currently competitive with what is produced by conventional methods. More than 100 countries use solar photovoltaic technology. Solar photovoltaic power generation with a capacity of 40,000 MW has been installed worldwide. After the 1960, the silicon solar cell has become the standard energy source for application in space.

4.2 SOLAR CELL FUNDAMENTALS

- **What do you understand by (i) Valence band, (ii) Conduction band, and (iii) Forbidden band?**

The electrons in the outermost shell of an atom are called valence electrons. The band occupied by valence electrons is called valence band. The highest permitted band is called the conduction band, which is at higher energy level than the valence band. The electrons in this band move freely. The energy gap in between the conduction band and the valence band is called forbidden band as electrons cannot exist in this band (Figure 4.1).

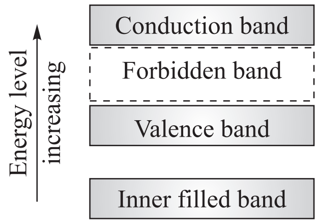


Figure 4.1 Energy level of electrons.

- **How do you differentiate between a conductor, an insulator and a semiconductor?**

No forbidden band exists between the valence band and the conduction band in a conductor. The electrons can move easily from valence band to conduction band. However, forbidden band exists both in insulator and semiconductor. The forbidden band in insulator is more wide (more energy gap between valence and conduction bands) compared to semiconductor. Insulator cannot conduct electricity owing to wide energy gap existing between valence and conduction bands (Figure 4.2).

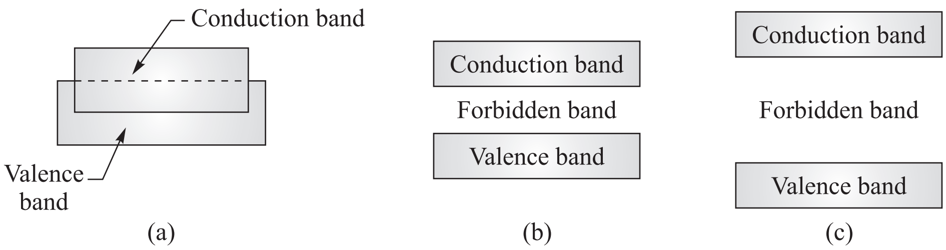


Figure 4.2 Difference between a conductor, a semiconductor and an insulator. (a) Overlapping of bands in conductors (b) Narrow gap in between bands in semiconductors (c) Wide gap in between bands in insulator.

4.2.1 Semiconductors

- **What are *n*-type semiconductors?**

An *n*-type semiconductor is formed when arsenic impurity (valence 5) is introduced into a pure germanium (valence 4). Arsenic atom forms four covalent bonds with neighbouring germanium atoms and the fifth electron of arsenic atom remains free. Therefore, impure germanium atom has excess of electrons which act as charge carries. Such semiconductors are called *n*-type semiconductors.

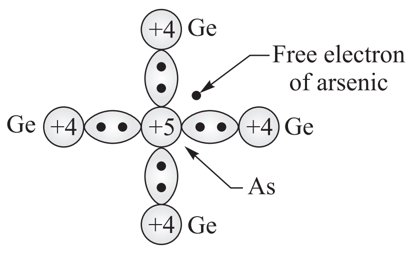


Figure 4.3 An *n*-type semiconductor.

• What are *p*-type semiconductors?

If aluminium (valency 3) is introduced as impurity in pure germanium (valency 4), then only three electrons are available in aluminium atom to form the covalent bond with germanium atoms. There is one electron short for forming fourth bond which appears empty space in the structure. Empty space is called hole. Hence, impure germanium has an excess of holes which act as charge carriers. Such semiconductors are called *p*-type semiconductors.

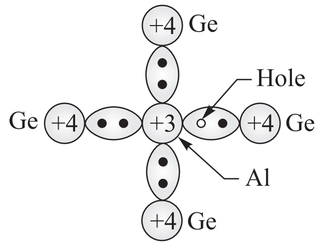


Figure 4.4 A *p*-type semiconductor.

• What happens when *p-n* junction is formed?

An *n*-type semiconductor has free electrons as charge carriers while a *p*-type semiconductor has free holes as charge carriers. When *p-n* junction is formed, electrons from the *n*-type semiconductor and holes from the *p*-type semiconductor tend to diffuse to their opposite sides.

• What is the depletion layer in *p-n* junction?

Near *p-n* junction, holes from *p*-region and electrons from *n*-region diffuse to opposite sides where they meet opposite carriers and get cancelled. As a result, a thin layer is formed at the junction which is free from all charge carriers. This layer is called the depletion layer.

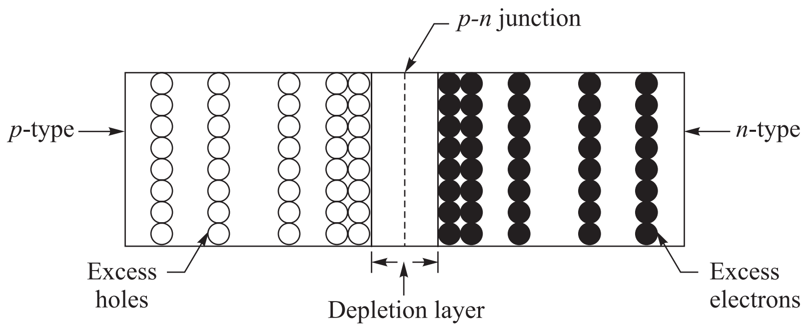


Figure 4.5 Depletion layer.

• What is the potential barrier at the *p-n* junction?

Electrons diffuse into *p*-region and holes diffuse into *n*-region. Such diffusion sets up a potential difference across the junction, thereby stopping further diffusion of holes and electrons into *n*-region and *p*-region, respectively. This electric field opposing the movement of carriers is called the potential barrier. Hence, some electromotive force (e.m.f.) in way of battery (forward biased) is required to move these charge carriers against the potential difference.

4.2.2 Photovoltaic Effect

- **What do you understand by photovoltaic effect?**

or

- **What is the principle of solar photovoltaic?**

Photovoltaic effect is a process in which two dissimilar materials in close contact produce an electrical charge when struck by light or any other radiant energy. When light strikes crystals such as silicon or germanium (*p-n* junction) in which electrons are usually not free to move from *n*-region to *p*-region due to the potential barrier, the light provides the energy (e.m.f.) needed to free some electrons from the bound condition depending on the absorption of solar energy (Figure 4.6). Free electrons cross the junction between two dissimilar crystals more easily in one direction than in the other, giving one side of the junction a negative charge, and this results in a negative voltage with respect to the other side, as in the case of a battery in which one electrode has negative voltage with respect to the other. The photovoltaic effect can continue to provide voltage and current as long as light falls on the junction of two materials.

- **What is solar power?**

Solar power is the production of electricity directly from sunlight. The solar photovoltaic (PV) power is produced using photovoltaic effect so that when sunlight strikes a solar voltaic cell, it releases electrons from the *p-n* junction of the cell and pushes these electrons across a potential barrier or electric field at the junction. These electrons then travel through an external circuit to return to their usual state and in this process create electric power.

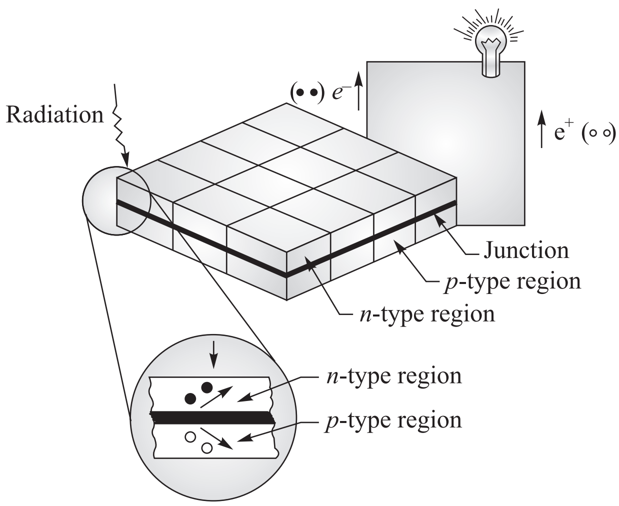


Figure 4.6 Generation of "emf" across junction to move the charge carriers.

The photovoltaic effect is the basic physical process through which a PV or solar cell converts sunlight into electricity. Sunlight is composed of energy packets called photons.

These photons contain different amounts of energy that correspond to different wavelengths of the solar spectrum. When photons strike a PV cell, they may be reflected, absorbed or can pass through the *p-n* junction. The absorbed photons in the *p-n* junction generate electricity.

A solar cell is essentially a *p-n* junction with a large surface area. The *n*-type material is kept thin to allow light to pass through it and strike the *p-n* junction. The light travels in packets of energy called photons. The generation of electric current takes place inside the depletion zone of the *p-n* junction. The depletion zone as explained previously is the area around the *p-n* junction where the electrons from the *n*-region diffuse into the holes of the *p*-region. When a photon of light is absorbed by one of these atems in *n*-region of silicon, it will dislodge an electron from any atom, thereby creating a free electron and hole pair. The free electron and hole pair has sufficient energy to jump out of the depletion zone. If a wire is connected from the cathode at *n*-type silicon to an anode of *p*-type silicon, electrons flow through the wire. The electron is attracted to the positive charge of *p*-type material and travels through the external load (bulb or resistance), thereby creating a flow of electric current. The hole created by the dislodged electron is attracted to the negative charge of the *n*-type material and travels to "back electrical contact". As the electron reaches the *p*-type silicon from the "back electrical contact", it combines with the hole, thereby restoring the electrical neutrality (Figure 4.7).

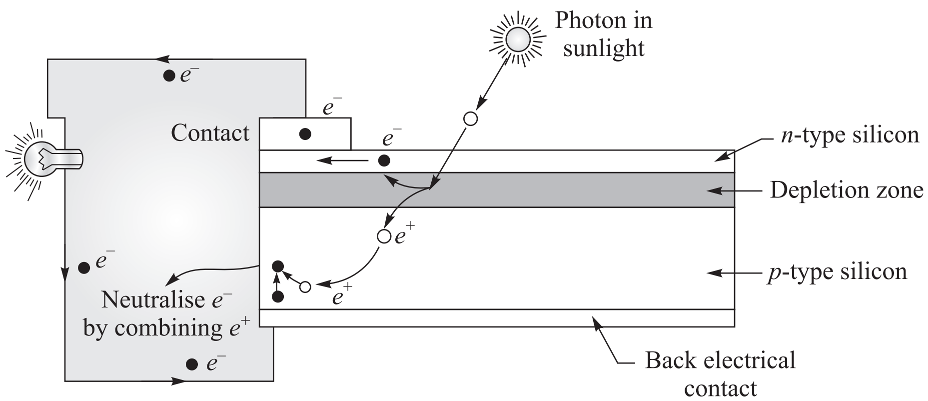


Figure 4.7 Photon generating pairs of electron and hole to move electric current in the external circuit.

4.3 SOLAR CELL, MODULE, PANEL AND ARRAY

4.3.1 Solar Cell

- **Explain the construction of a solar cell.**

The solar cell consists of (i) *p*-type silicon material layer, (ii) *n*-type silicon material layer, (iii) front metallic grid and (iv) opaque back metal contact as shown in Figure 4.8.

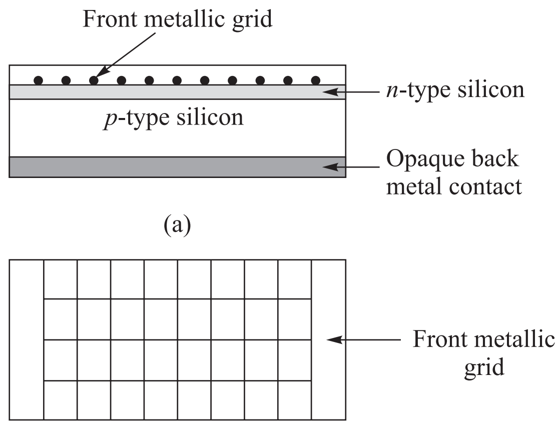


Figure 4.8 Construction of a solar cell. (a) Side view of the solar cell. (b) Top view of the solar cell.

The bulk material consists of *p*-type silicon having thickness about 100–350 µm. A thin layer of *n*-type silicon having thickness of about 2 µm is diffused on this bulk material, providing *p*-*n* junction. A metallic grid at top with *n*-type material and an opaque back metal contact at the bottom of *p*-type material are provided which also act as negative and positive terminals.

4.3.2 Solar PV Module

- **What is a solar PV module?**

A single solar cell cannot be used as such as it has (i) a very small output and (ii) no protection against dust, moisture, mechanical impacts and atmospheric harsh conditions. Suitable voltage and adequate power can be obtained by suitably interconnecting a number of solar cells. This assembly of solar cells is called solar module. Solar cells are provided with transparent cover and these are hermetically sealed for assembly into solar module. A solar module has generally 32–36 solar cells connected in series to charge a 12 V battery. It is necessary that all solar cells should match as closely as possible with each other so that peak power of the module is the algebraic sum of the peak power of individual solar cells. A typical module is shown in Figure 4.9.

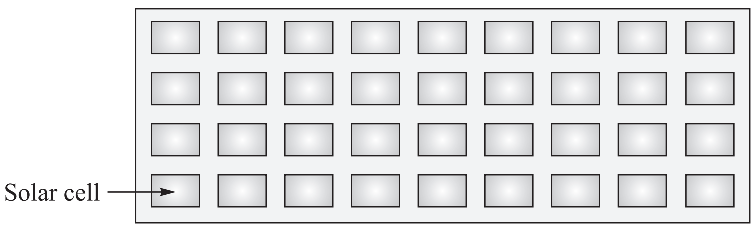


Figure 4.9 Solar PV module with 36 solar cells.

4.3.3 Solar PV Panel

- **Describe the construction of a solar PV panel.**

Solar PV panel consists of a number of solar PV modules connected in series and parallel to obtain the power of desired voltage and current. When modules are connected in series, it is desirable that each module should produce maximum power at the same current. When solar PV modules are connected in parallel, it is desirable that each module should produce maximum power at the same voltage. A frame is used to mount several modules to form a solar PV panel as shown in Figure 4.10.

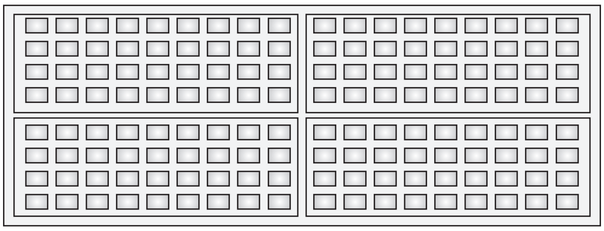


Figure 4.10 A solar PV panel of four modules.

In the panel, bypass diodes are installed across each module so that any defective module can be bypassed by the output of remaining modules. The blocking diodes are connected in series with each series string of modules which enable the output of the remaining series strings should not be absorbed by the failed string. A typical panel with the series and the parallel connections is shown in Figure 4.11.

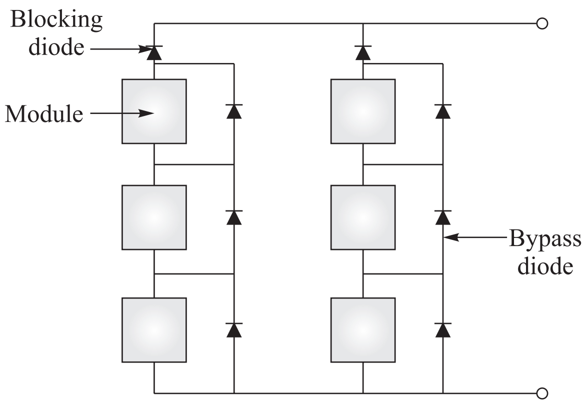


Figure 4.11 A typical panel with the series and the parallel connection.

4.3.4 Solar PV Array

- **What do you understand by a solar PV array?**

A PV array consists of a number of solar panels which are installed in an array field. The solar panels may be installed as stationary facing the sun or installed with some tracking mechanism. The installation should ensure that no panel should cast shadow on any of the neighbouring panels and those panels can be easily maintained.

4.4 SOLAR CELL CHARACTERISTICS

- **How does the *p-n* junction act as a diode, thereby facilitating flow of current when it is forward biased?**

In case the *p-n* junction is forward biased, electrons from *p*-region start moving towards the positive terminal of the battery, thereby reducing the potential barrier at the junction (Figure 4.12). This facilitates the flow of current through the *p-n* junction. In case the junction is reversed biased, the potential barrier at the junction increases, which further reduces the possibility of any flow of current through the junction. The Current–Voltage (*I–V*) characteristic of a *p-n* junction is shown in Figure 4.13.

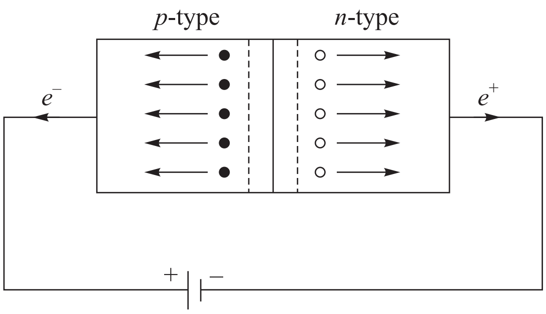


Figure 4.12 The *p-n* junction forward biased.

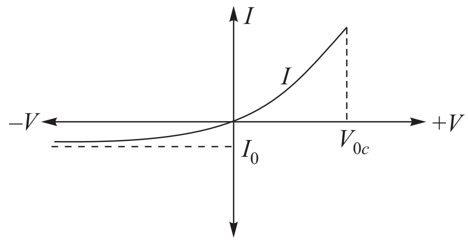


Figure 4.13 Current–Voltage characteristic of *p-n* junction when forward and backward biased.

As the voltage (V) increases, the current (I) in the junction also increases. However, there is a very small reverse saturation current (I_0) instead of zero current when reversed voltage is applied. The flow of current can be given by diode current equation (Schottky equation):

$$I = I_0 \; [e^{V/V_T} - 1]$$

where I_0 is the reverse saturation current and V_T is the voltage equivalent of temperature and it is given by

$$V_T = \frac{kI}{q}$$

Here, k is the Boltzmann constant,
T is the temperature in kelvin and
q is the charge of an electron.

4.4.1 Voltage–Current Characteristic of *p-n* Junction (Solar Cell)

- **Explain the current–voltage characteristics of a solar cell and define fill factor. What is the significance of the fill factor?**

or

- **Explain how the variation of isolation (incident solar radiation) and temperature affects the current–voltage characteristics of a solar cell.**

The current-voltage characteristics of a *p-n* junction (solar cell) gets modified due to photon or solar generated current (I_{sc}) flowing through the *p-n* junction as this (I_{sc}) is added with the reverse leakage current (I_0). The diode current equation is now modified as

$$I = -I_{sc} + I_0\,[e^{V/V_T} - 1]$$

and $$I = -I_{sc}$$

when $V = 0$; that is junction is short circuited.

Also, when $$I = 0,\ I_{sc} = I_0\,[e^{V/V_T} - 1]$$

or $$V = V_{sc} = V_T \log\left(\frac{I_{sc}}{I_0} + 1\right)$$

where V_{sc} is the open circuit voltage.

The above relation shows that when junction is radiated with sun's ray and it is short circuited at its terminals, there is a finite current called short circuit current (I_{sc}) that flows through the external circuit made with the short circuiting of the junction terminals. The magnitude of I_{sc} depends upon solar radiation. Figure 4.14 shows current–voltage characteristics at different isolations which include (i) dark, (ii) lesser amount of radiation, and (iii) larger amount of radiation. Hence, *p-n* junction can be considered an energy source or e.m.f having open circuit voltage as V_{oc} and short circuit current as I_{sc}.

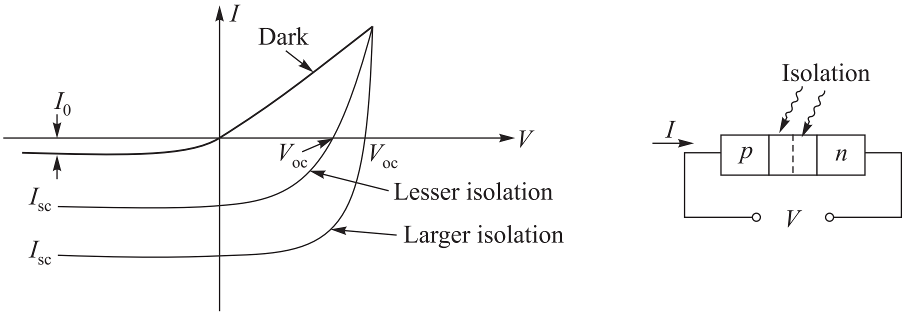


Figure 4.14 Current–voltage characteristics at different isolation levels.

In case we use standard convention in which current flowing out from a positive terminal of any energy source is always taken as positive and apply the same convention on a solar cell, the current and voltage characteristic can be redrawn with suitable modification as shown in Figure 4.15, and mathematically the current–voltage relationship can be written as follows:

$$I = I_{sc} - I_0 \times [e^{V/V_T} - 1]$$

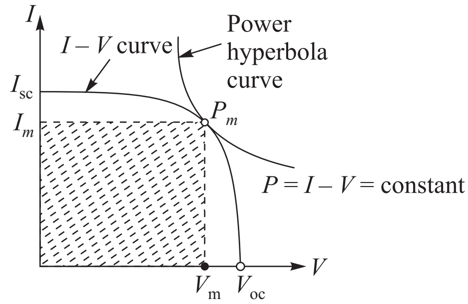


Figure 4.15 Current–voltage characteristics of solar cell and maximum power point (P_m).

The output power from solar cell is the product of voltage and current ($P = I \times V$). It is desirable to operate the solar cell to produce maximum power. The power is product of voltage and current and power curve is hyperbola. In case hyperbola ($P = I \times V$) of power is drawn on *I–V* characteristic curve, the hyperbola of power curve is tangential to *I–V* characteristic at the point of maximum power as shown by point P_m in Figure 4.15. The voltage and current corresponding to P_m are V_m and I_m respectively. Hence, there is only one point on the voltage–current characteristic curve of *p-n* junction at which the *p-n* junction produces maximum power for a given isolation or illumination level. In case we operate the *p-n* junction at any other point on *I–V* characteristic curve, power produced will be lesser than the maximum power, resulting in certain amount of solar radiation energy being wasted out as thermal power. The maximum power output can be determined when the value of the product of voltage and current is maximum. The product of voltage and current has the greatest value when the rectangle having sides equal to these voltage and current, as well as incribed within the characteristic curve, has the largest area. The rectangle having the largest area with sides V_m and I_m and depicting maximum solar power output (shown with hatched lines) is shown in Figure 4.15.

Fill factor (FF)

The maximum power output from a solar cell is possible when the output power from rectangle can fill up or utilise as much area as possible of the characteristic curve. The fill factor indicates the quality of solar cell, that is, how much power or area of the characteristic curve is being used. In ideal case, the fill factor should be unity when the complete area between the characteristic curve and axes has been utilised that is, the product of V_{oc} and I_{sc}.

The fill factor is defined as the ratio of peak power to the product of V_{oc} and I_{sc}.

Hence,

$$\text{FF} = \frac{V_m \times I_m}{V_{oc} \times I_{sc}}$$

The typical value of fill factor is in the range of 0.5–0.83. The fill factor can be improved by the following ways:

(i) Increasing the photocurrent and decreasing the reverse saturation current of a solar cell.
(ii) Minimising the internal series resistance
(iii) Maximising the shunt resistance.

Solar efficiency

It is the ratio of maximum possible solar cell power output $V_m \times I_m$ which is converted to the solar energy supplied to the cell.

$$\text{Efficiency} = \frac{V_m \times I_m}{\text{Solar power}}$$

Fill factor is given by the following equation:

$$\text{FF} = \frac{V_m \times I_m}{V_{oc} \times I_{sc}}$$

Hence, efficiency can also be given as

$$\eta = \frac{V_m \times I_m}{\text{Solar power}}$$

$$= \frac{\text{FF} \times V_{oc} \times I_{sc}}{\text{Solar power}}$$

4.4.2 Energy Losses of Solar Cell

- **Explain various factors contributing to losses in solar cell. How is the efficiency reduced due to these factors?**

or

- **What are the parameters limiting the performance of a cell?**

The highest conversion efficiency of a solar cell is about 24%. There are many factors which lead to energy losses and limit the conversion efficiency of the cell. The factors are as follow:

Reflection losses

Some of the incident radiation is lost due to reflection from the cell surface.

Incomplete absorption

The cell should be made of a material which can absorb the energy associated with the photons of solar radiation. The energy of a photon is related to its wavelength (λ) by the following relation:

$$E = \frac{h \times c}{\lambda}$$

where

h = Planck's constant ($= 3 \times 10^{-27}$ ergs)

c = Velocity of light ($= 3 \times 10^{8}$ m/s)

If we put these values in the equation we get energy as

$$E = \frac{1.24}{\lambda}$$

The materials suitable for absorbing the energy of photons of sunlight are silicon, cadmium sulphide and gallium arsenide. The difference between conduction and valence band is called band gap energy. Hence, photons having energy (E) larger than band gap energy (1.1 eV for silicon) will be absorbed in the cell material and will excite some of the electrons, thereby creating electron–hole pairs. Other photons of lower energy are wasted in generation of thermal energy. The higher is the band gap of the material, the greater is the wastage.

Partial utilisation of photon energy

Many photons in solar radiation generate electron and hole pairs which have more energy than that is needed for proper functioning of *p*-*n* junction, that is making the current flow through external circuit. The excess energy is dissipated as heat. The higher is the energy gap, the smaller is the wastage. The semiconductors with the energy gap of 0.9–1.1 eV would be best suited and thickness required to absorb is about 300 µm.

Collection losses

The electron–hole pair carriers formed due to solar radiation must be collected so as to contribute to the output current instead of recombining to generate heat. The collection efficiency is the ratio of the actual short circuit current density to the short circuit current density which would be obtainable when no recombining takes place. The collection efficiency depends upon (i) the absorption characteristics of semiconductors which determine the generation of electron and hole pairs (ii) the junction depth, (iii) the width of depletion layer, (iv) the recombining rate of electrons and holes, (v) the distance which carriers have to move for recombining, (vi) the thickness of *p* and *n* regions and (vii) the existence and strength of any built-in electric field which help to accelerate carriers.

Open circuit voltage

The open circuit voltage is always less than the band gap energy due to lower level of illumination and doping of semiconductor which lowers the potential difference at *p*-*n* junction.

The increase in barrier potential increases V_{oc} but reduces I_{sc}. There is an optimum value of V_{oc} and I_{sc} for generation of the maximum power output.

Curve factor

The maximum power output is always less than the product of V_{oc} and I_{sc}. The characteristic curve does not have a rectangular shape. Hence, the area of the characteristic curve is always less than the product of V_{oc} and I_{sc}.

Series resistance losses

The voltage and current characteristic curves are flattened due to power loss resulting from series resistance. The output power decreases as the area under the characteristic curve reduces.

Thickness of cell

Photons of high energy can pass through the cell material without any absorption if thickness is inadequate. *A* reflecting back ohmic contact is generally provided to enhance the absorption of high-energy photons.

4.4.3 Maximising the Performance

- **How can the performance of a solar cell be maximised?**

The performance of a solar cell can be increased by taking the following steps:

(i) **Maximising V_{oc} and I_{sc}.** The efficiency of solar energy conversion depends upon V_{oc} and I_{sc} same time I_{sc} depends upon photocurrent and V_{oc} depends upon the ratio of I_{sc} to I_0.

(ii) **Low series resistance.** It will give high fill factor, that is more output power possible as the area of characteristic curve increases. Reduction of resistance requires high doping of semiconductor.

(iii) **High shunt resistance.** Shunt resistance can be increased by preventing any leakage occurring at the perimeter of the cell. This is achieved by passivating the surface of the solar cell.

(iv) **Optimum solar cell size.** As the area of solar cell increases, it becomes difficult to maintain homogeneity of the material in solar cell and performance of the cell reduces.

- **Calculate the range of wavelength of solar radiation capable of creating electron–hole pair in silicon having energy gap of 1.12 eV.**

$$E = \frac{hc}{\lambda} = \frac{1.24}{\lambda} \quad \text{or} \quad \lambda = \frac{1.24}{E} = \frac{1.24}{1.12} = 1.11\ \mu\text{m}$$

- **Considering solar radiation of 200 J/m^2 and per unit time during daylight, find the area of PV cells needed to generate enough electric power to run**
  (i) a desktop computer using 400 W,
  (ii) an electric geyser using 1 kW and
  (iii) a toaster using 500 W.

Assume the efficiency of *PV* to be 25%

The photovoltaic cell power output is given by following equation:

$$\eta = \frac{\text{Power output}}{\text{Solar power}} = 0.25$$

$$\therefore \quad \text{Power output} = 0.25 \times 200 = 50 \text{ W}$$

Case 1: Desk type computer

$$\text{Power of appliance required} = 400 \text{ W}$$

$$\text{Area of PV cells} = \frac{400}{50} = 8 \text{ m}^2$$

Case 2: Electric geyser

$$\text{Power required} = 1000 \text{ W}$$

$$\text{Area of cells} = \frac{1000}{50} = 20 \text{ m}^2$$

Case 3: Toaster

$$\text{Power required} = 500 \text{ W}$$

$$\text{Area required} = \frac{500}{50} = 10 \text{ m}^2.$$

$$\text{Total load} = 400 + 1000 + 500 = 1900 \text{ W}$$

$$\text{Total area} = 8 + 20 + 10 = 38 \text{ m}^2$$

4.5 MATERIALS FOR SOLAR CELLS

- **What are different materials used for fabrication of solar cells?**

or

- **Explain the main features of different types of solar cells on the basis of materials used in fabrication.**

or

- **What are the steps involved in formation of silicon cells?**

or

- **What do you understand by thin film solar cells?**

The solar cells depending on the type of material used can be classified as single crystal silicon solar cell, polycrystalline and amorphous silicon cell, cadmium sulphide-cadmium telluride cell, copper indium diselenide cell and gallium arsenide cell.

Single crystal silicon

It is produced from silicon dioxide which is reduced to silica with 1% impurities. It is first purified to polycrystalline form and then further converted into the single crystal state. The conversion process into single crystal state is very expensive. The single crystal *p*-type silicon is obtained in the form of a long cylindrical block (diameter of about 6–15 cm). The block is sawed using diamond cutter to obtain a number of silicon slices or wafers having thickness of about 300 μm. The *p*-type silicon wafers are then exposed to phosphorous vapour (doping material) in a furnace so that phosphorous can diffuse into the silicon wafer for a short depth, thereby forming *n*-silicon region over the *p*-silicon bulk material. The efficiency of single crystal silicon is about 22%. It is most efficient and robust. It has two main drawbacks:

(i) it needs high energy to produce and hence is costly and
(ii) it requires high intensity of radiation to produce solar electricity.

Polycrystalline and amorphous silicon

The cells made of these materials are cost-effective but these have lower efficiency compared to a single crystal silicon cell. The process to produce polycrystalline silicon cells is similar to that of single crystal silicon except that the costly step of converting polycrystalline state to the single crystal is not required. The polycrystalline silicon is directly melted, doped with phosphorous and cooked to the desired shape and size. This helps in economy of materials and energy consumption for the production of cells.

Amorphous silicon cells are produced using thin film technology. These cells are a cheaper alternative to single crystal or multicrystallinc cells. The main drawbacks are that they have low efficiency (4–8%) and they degrade easily when used in outdoor applications. These cells are useful for indoor lights, pocket calculator, electronic watches and electronic instruments.

Cadmium sulphide–cadmium telluride cells

These cells are also produced using thin film technology. The cells require very less material. In thin film technology, the semiconductor (cadmium telluride) is vapourised and its film (10 μm) is deposited on a thin layer (12 μm) of cadmium sulphide. A barrier layer of copper sulphide is then deposited on top of the CdS–CdTe cell. The cell consists of *n*-type CdS and *p*-type CdTe. The cell has efficiency of 10% and it has no deterioration during outside applications.

Copper indium diselenide

It is a thin film polycrystalline cell made from copper indium diselenide. It has an efficiency of about 14%. Its properties remain stable. It has an easier manufacturing process.

Gallium arsenide

The cell has thin film of *n*-type and *p*-type gallium arsenide (GaAs) grown on a suitable substrate. The efficiency of the cell is about 20%, but it has high cost of production. The cell has high performance in extraterrestrial applications.

4.6 SOLAR PV SYSTEMS

- **How can solar PV systems be classified?**

or

- **With the help of block diagrams, explain the operations of stand-alone and grid interactive solar PV systems.**

The classification of solar PV systems is shown in Figure 4.16

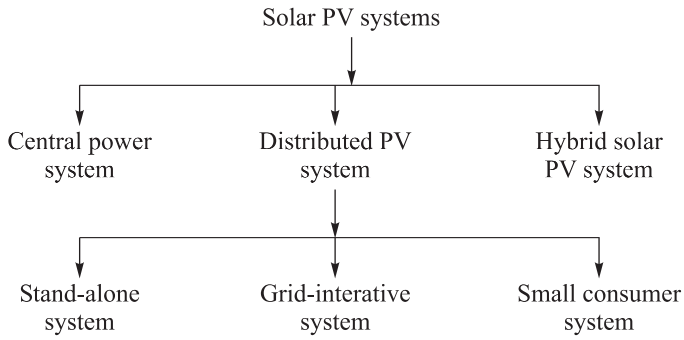


Figure 4.16 Classification of solar PV systems.

4.6.1 Central Power Station System

- **Explain central power station system.**

This type of solar power station is similar to other conventional power stations which are required to feed generated power into some national grid. This type of solar power stations are designed to meet high peak daytime load only and these have large generation capacity in megawatt (up to 6 MW). Only few such power stations have been installed worldwide as the capital cost of these plants is high.

4.6.2 Stand-Alone System

- **Write briefly about stand-alone system.**

Solar PV power station is planned and located at the load centre. Its complete electricity generation is meant to meet the electrical load of any remote area, village or installation. Energy storage is essential to meet the requirement during non-sunshine hours. A typical stand-alone solar PV system is shown in Figure 4.17. The maximum power point tracker (MPPT) senses the voltage and current outputs from the solar array and then suitably adjusts the operating point to obtain maximum power output from the solar array as possible from the climatic conditions. The solar electric output in direct current is converted into alternating current and it is fed into the load. The excess power is preferably stored by charging the battery and otherwise excess is dumped in the electric heaters. When the sun radiation is unavailable, the batteries supply the electricity through the converter.

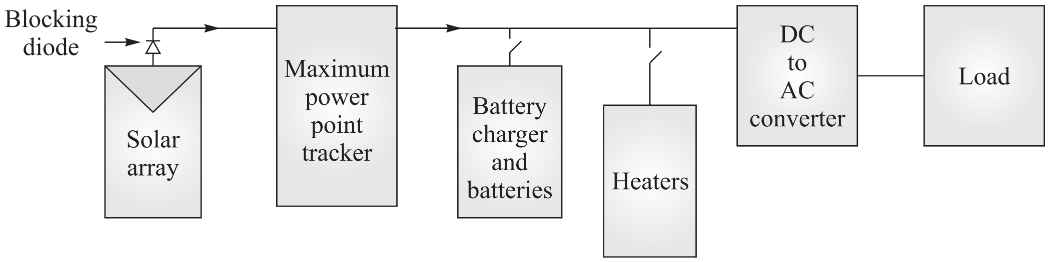


Figure 4.17 A schematic layout of a stand-alone solar PV system.

4.6.3 Grid Interactive Solar PV System

- **Write briefly about grid interactive solar PV system.**

In grid interactive solar PV system, the system first meets the requirement of house, village or installation and then all excess power is fed to an electric grid during sunshine hours (Figure 4.18). This arrangement helps in preventing any dumping of electricity as required in the stand-alone solar PV system. The second advantage of this system is that during absence of insufficient sunshine, the supply of electricity is maintained from the electric grid, thereby eliminating any need of battery. This system is very popular in the United Kingdom, where two-way electric meters provided to record (i) the electricity generated and supplied by rooftop PV system of various houses to the electric grid system during non-peak sunshine hours and (ii) electricity supplied to the houses from the electric grid during non-sunshine hours. The difference of two is paid to consumers or vice versa.

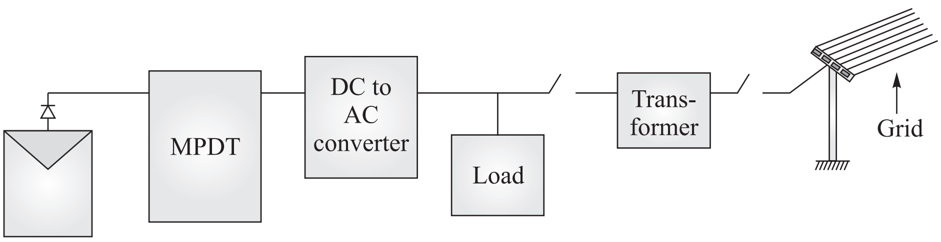


Figure 4.18 Grid interactive solar PV system.

4.6.4 Small Consumer Systems

- **Write briefly about small consumer systems.**

These systems are designed to meet the power requirement of low energy devices which are generally used for indoor applications, such calculators, watches and electric devices.

4.6.5 Hybrid Solar PV System

- **What do you understand by hybrid solar PV system?**

The hybrid solar PV system is designed to provide electric power by some other means besides solar electricity. It is difficult and uneconomical to provide all of the power from only solar PV system. It may be more economical to meet the power requirement by some other means, such as windmills, fuel cells and diesel or petrol generators. The best hybrid solar PV system is the one in which no amount of solar PV generated power is wasted.

4.6.6 Advantages and Disadvantages of PV System

- **What are the advantages and disadvantages of PV system over conventional power system?**

Advantages are as follows:

(i) It directly converts solar energy to electric power without any use of moving parts.
(ii) It is more reliable, durable and maintenance free.
(iii) It works without any noise.
(iv) It is non-polluting.
(v) It has long lifespan.
(vi) It can be located near the point of load and requires no distribution system.

Disadvantages are as follows:

(i) It has high cost of installation.
(ii) It has low efficiency.
(iii) It requires a large area for installation to produce sufficient power.
(iv) Its output is intermittent, thereby requiring some means to store energy to use during non-sunshine hours.

4.6.7 Solar PV System and Cost

- **Write down your comments on cost reduction of solar cells.**

There is gradual reduction in the cost of solar PV system due to (i) development of new improved techniques to produce solar cells and (ii) increase in the production volume. Cost reduction has been achieved by innovative manufacturing techniques used in thin film solar cells. These techniques have speeded up manufacturing process, reduced material wastage and helped to produce large size cells. Cost reduction has also been effected by the development of thin film devices, thereby requiring much less quantity of materials and less costly materials. The use of solar concentrators to focus the sun's rays in solar PV system has also helped in the cost reduction. The cost of solar power generation is reduced from the earlier cost of several thousand dollars per peak watt to the present cost of about one dollar per watt.

- **"Sunshine is free but solar energy is not." Comment.**

The solar power or energy is not free compared to sunshine due to the following reasons:

(i) Solar PV cells are costly.
(ii) Installation of solar PV cells is costly as a large number of solar cells are required to produce worthwhile power.
(iii) Solar power is available intermittently and storage devices like batteries are required which have to be replaced periodically.
(iv) Solar cells produce DC power output which has to be converted into AC power using inverter.

4.6.8 Solar PV Programme in India

- **What are the features of the solar PV programme in India?**

Ministry of Non-conventional Energy Sources (MNES) have started a countrywide solar PV programme for the past two decades to develop cost-effective solar PV technology and to ensure its application in large scale in rural and remote areas. In India, there are about 300 clear sunny days in a year when solar energy is abundantly available in most parts of the country. The programme started by MNES involves the implementation of the following solar PV systems and devices:

(i) Solar street lighting system
(ii) Solar water-heating system
(iii) Solar space heating system
(iv) Solar lanterns consisting of CFL and solar chargable battery
(v) Stand-alone-type Solar PV system
(vi) Solar PV water pumping system
(vii) Hybrid solar PV system.

4.6.9 Energy Payback Period of a Solar Cell

- **Explain briefly energy payback period of a solar cell.**

Energy payback period of a solar cell is defined as the length of time required for the solar cell to generate the same amount of energy which had been consumed during its production. The solar cell requires a very high amount of energy during its production while its power output is very small due to its low efficiency. Hence, energy payback period of a solar cell is very long, which is of the order of 5 years. The solar cell starts providing energy in excess to what it had consumed during its production after energy payback period.

CHAPTER 5

Biogas

5.1 INTRODUCTION

Plants grow through photosynthesis process which takes place primarily in their green leaves. Biomass is mainly in the form of wood and it is the source of energy. Biomass is used both in domestic and in industrial activities by way of direct combustion. Hence, we use solar energy in the form of biomass for cooking and heating purpose. The dominant use of biomass or fuel wood in the world is made for cooking and heating primarily in rural areas. Biomass accounts for about 15% of the energy used in the world. Biogas is the gaseous fuel which is obtained from biomass by means of anaerobic fermentation. The raw materials for biogas include waste from agriculture, waste from forest, rural animal waste, urban waste (left over food and other rubbish) and aqua waste (fishery, algae and hyacinth).

5.2 PHOTOSYNTHESIS

- **Explain the process of photosynthesis. What are the conditions necessary for it?**

or

- **What is biomass production efficiency?**

Photosynthesis is the process by which plants use their chlorophyll in green leaves to convert solar energy into carbohydrates in the presence of carbon dioxide from the atmosphere and water. The carbohydrates are used by plants for their growth. The plants absorb red and blue light but they do not absorb green light. This is the reason why leaves of plant or chlorophyll look green. The overall chemical reaction involved in photosynthesis is as follows:

$$6CO_2 + 6H_2O + \text{light energy} = C_6H_{12}O_6 + 6O_2$$

In respiration process, energy is released which is used by plant for growth and other activities.

$$\text{Carbohydrate} + O_2 = CO_2 + \text{energy} + \text{water}$$

Biomass production efficiency

It is the efficiency of converting incident solar energy into the chemical energy, that is, carbohydrates in plants. Plants use visible light with wavelengths between 0.4 and 0.7 μm, which is called photosynthetically active radiation (PAR). To understand biomass production efficiency, consider that (i) intercepted PAR is 50% of the total radiation, (ii) 80% of intercepted PAR is used by photosynthetically active compounds and rest is lost, (iii) 28% of used energy is converted into carbohydrates and (iv) 40% carbohydrates energy is used in respiration. Then biomass production efficiency is given by:

$$\eta = 100 \times 0.50 \times 0.86 \times 0.28 \times 0.60$$
$$= 6.7\%$$

Condition for photosynthesis

The photosynthesis depends on the following factors:

(i) Temperature should be between 20 and 30°C to have photosynthesis at the maximum rate.
(ii) Concentration of carbon dioxide in atmosphere as it increases the photosynthesis.
(iii) Concentration of oxygen as it reduces the photosynthesis
(iv) Water as its use efficiency increases with photosynthesis
(v) Intensity and proper wave distribution of solar radiation as PAR increases the photosynthesis.

5.3 BIOMASS

- **What is biomass? In what form, biomass can be used?**

Biomass is organic or carbon-based material that can either react with oxygen for combustion or undergo metabolic process to release heat.

Biomass can be used as such in its original form. More often, it is transformed to more convenient and useful form, thereby forming solid, liquid and gaseous fuels.

5.3.1 Biofuels

- **What are the different forms of biomass available as biofuels?**

The biofuels can be fuelwood, charcoal, fuel pellets, bioethanol, biogas, producer gas and biodiesel.

Fuel wood

It is the most common source of biomass energy. Direct combustion is the simplest way to obtain heat energy. It has energy density of about 16–20 MJ/kg.

Charcoal

It is obtained by carbonization of woody biomass. This helps in providing higher energy density per unit mass of about 30 MJ/kg. Charcoal can burn without generating smoke.

Fuel pellets

Fuel pellets are formed from crop residues such as straw or rice husk which are pressed into solid mass.

Bioethanol

It is derived from wet biomass containing sugars from sugarcane, starches from grains and potatoes or cellulose from woody matters. Ethanol (C_2H_5OH) is a colourless liquid biofuel with boiling point of 78°C and energy density of 26.9 MJ/kg.

Biogas

Biogas is the gaseous fuel obtained from biomass (organic waste from plants, animals and humans) by means of anaerobic digestion or fermentation. The anaerobic digestion process can be profitably applied to any wet organic matters. Anaerobes are microorganisms or bacteria found to live and grow in organic matter at the temperature of less than 60° in presence of moisture but in the absence of air or oxygen. The anaerobic organism consumes oxygen which it obtains from decomposition of organic matters. Decomposition of the organic matters by anaerobic microorganism is called digestion or fermentation. The biogas is liberated from the organic matters during digestion or fermentation. The biogas produced by digestion contains (i) methane gas (CH_4) 65–75%, (ii) carbon dioxide gas (CO_2) 25–35% and (iii) small traces of nitrogen, ammonia, hydrogen sulphide and other gases. The biogas has energy density of about 23 MJ/m^3. It can be used for cooking, lighting, heating and operating small IC engines.

Producer gas

It is obtained by gasification of solid fuels. In this, woody matter (crop residue, wood chips, rice husk, coconut shell and sugarcane residue) is converted into producer gas by thermochemical method which is infact the partial combustion and reduction operation of biomass. The producer gas has 19% carbon monoxide, 18% hydrogen, 1% methane, 11% carbon dioxide and the rest remaining nitrogen. The producer gas is used for IC engines for running pumps, motor vehicles, heating and generation of steam in a small-scale power plant.

Biodiesel

It is produced by blending of vegetable oils, with normal diesel to obtain cheaper version of diesel engine fuel. Besides vegetable oils, certain hydrocarbons having molecular weight equal to that of petroleum and that are obtainable as by-products from certain plants can also be used for blending purpose.

5.3.2 Biomass Resources

• **What are the biomass resources for the production of biomass energy?**

The biomass resources include organic materials obtainable from forest, agriculture, aqua culture and organic waste residue from industrial and social activities.

Forests

Forests (natural or cultivated) are source of fuel wood, charcoal and producer gas. Forest waste and residues from forest processing plants can be used as biomass. Certain plants produce seeds to yield vegetable oils which can also be used in biofuels.

Agriculture residues

Straw, rice husk, groundnut shell, coconut shell and sugarcane bagasse are crop residues which are the main biomass resources. The crop residues are generally gasified to obtain producer gas. The crop residues are also converted into fuel pellets to be used as solid fuels.

Energy crops

Energy crops are those cultivations which provide raw materials for biofuels. These include (i) sugar plants to provide bioethanol, (ii) starch plants (tubular plants and grains) to produce bioethanol and (iii) oil producing plants (sunflower, palm oil, groundnut and cottonseeds) to produce biodiesel.

Urban waste

Urban waste can be garbage or municipal solid waste (MSW) and sewage or liquid waste. Garbage can be burnt to obtain biomass energy while sewage has to be processed to obtain biogass.

Aquatic plants

Certain aquatic or water plants are capable of growing extremely fast and supply organic raw materials for producing biogas. The fast growing water plants include water hyacinth, seaweed, algae and kelp.

5.3.3 Advantages and Disadvantages of Biomass Energy

• **What are advantages and disadvantages of biomass energy?**

Advantages

(i) It is a renewable source.
(ii) It can be stored and used as per the requirement.
(iii) It helps in waste management.
(iv) It is an indigenous source of energy.
(v) It helps in economic development of rural areas.
(vi) It helps in improving sanitation in rural areas and towns.

(vii) It helps in providing fertilisers.
(viii) It provides economical use of various types of wastes and residues.

Disadvantages

(i) It has low energy density.
(ii) It is a labour intensive energy source.
(iii) Its production requires large land area.

5.4 BIOGAS

- **What is biogas?**

Biogas is the gaseous fuel which is obtained from biomass by means of an anaerobic digestion or fermentation of wet organic matters. The biogas is a flammable gas. The composition of biogas includes 50–60% methane gas, 35–40% carbon dioxide, 5% hydrogen and a small amount of hydrogen sulphide and other gases. Methane and hydrogen gases form the combustible portion of biogas. The biogas has energy density of about 23 MJ/m^3. It can be used for cookings, heating, lighting and running small IC engine.

5.4.1 Aerobic and Anaerobic Processes

- **Explain aerobic an anaerobic processes?**

The literary meaning of aerobic is any process taking place in the presence of air, while anaerobic means any process taking place in the absence of air or oxygen. It is the anaerobic process or digestion in biomass slurry which helps in converting biomass into biogas. The anaerobic digestion or fermentation in biomass slurry is started by a microorganism called anaerobe. The anaerobe microorganism grows on biomass at a temperature lower than 65°C in the presence of moisture but in the absence of air or oxygen. The microorganism anaerobe consumes oxygen for survival and growth which is obtained from the digestion or fermentation of the wet organic matter. During anaerobic digestion of wet biomass slurry, the biogas is liberated. Anaerobic bacteria are also called methane formers.

5.4.2 Anaerobic Digestion

- **Explain anaerobic digestion.**

or

- **Draw the schematic diagram of anaerobic digestion showing input materials and effluents.**

or

- **Write the basic chemical reaction, process and energetics involved in generation of biogas from biomass.**

or

- **Explain the process of production of biogas from biomass. What are the main advantages of anaerobic digestion of biomass?**

or

- **What are the factors affecting the performance of biogas digester?**

or

- **What raw materials can be used for the production of biogas?**

or

- **How biomass conversion takes place?**

Biogas is produced from biomass slurry having 90–95% water content by the bacterial action of microorganism called anaerobe. The carbon part of biomass is oxidized and the remaining is reduced to produce mainly methane gas (65–75%) and carbon dioxide (25–35%). These bacteria are found to live and grow without atmospheric oxygen as they produce themselves the needed oxygen by decomposing the biomass. The digestion or fermentation process of wet biomass by these bacteria is favoured by the factors such as wetness, warmness and darkness conditions.

The general equation for anaerobic digestion is as follows:

$$C_xH_yO_2 + \left(x - \frac{y}{4} - \frac{z}{2}\right) H_2O \rightarrow \left(\frac{x}{2} - \frac{y}{8} + \frac{z}{4}\right) CO_2 + \left(\frac{x}{2} + \frac{y}{8} - \frac{z}{4}\right) CH_4$$

In case of cellulose, the equation is given by:

$$(C_6H_{10}O_5)_n + n\ H_2O \rightarrow 3n\ CO_2 + 3m\ CH_4$$

The airtight equipment used to convert the wet biomass into biogas by digestion or fermentation process is called biogas digester or plant which is properly constructed and controlled to favour biogas or methane production. The conversion process is called biodigestion or anaerobic fermentation and the output is methane or biogas. The residuals or nutrients such as soluble nitrogen compounds remaining in the wet biomass slurry provide or produce excellent natural fertilizers and humus. The biogas can provide 60–75% of the energy of the dry converted biomass during combustion.

The biochemical process of converse in from biomass to biogas takes place in the following three stages:

(i) **Hydrolysis of organic matter.** The biomass (complex compounds of carbohydrate, protein and fats) is broken due to the action of water (hydrolysis) into simpler soluble compounds. Similarly, large molecules (polymers) are reduced to basic molecules (monomers). The process is completed in a day at a temperature of about 25°C.

(ii) **Anaerobic and faculative microorganisms.** These bacteria start growing to produce acetic and propionic acids. The process is completed in a day at the temperature of 25°C. The output of the process is the production of carbon dioxide.

(iii) **Digestion.** Anaerobic bacteria slowly digest the biomass slurry to produce biogas. The process is completed in 2 weeks at the temperature of about 25°C.

Digester

The anaerobic digester or plant is shown in Figure 5.1. Feed consists of organic material slurry prepared in mixing tank. Feed supply per day to the digester is called the loading rate.

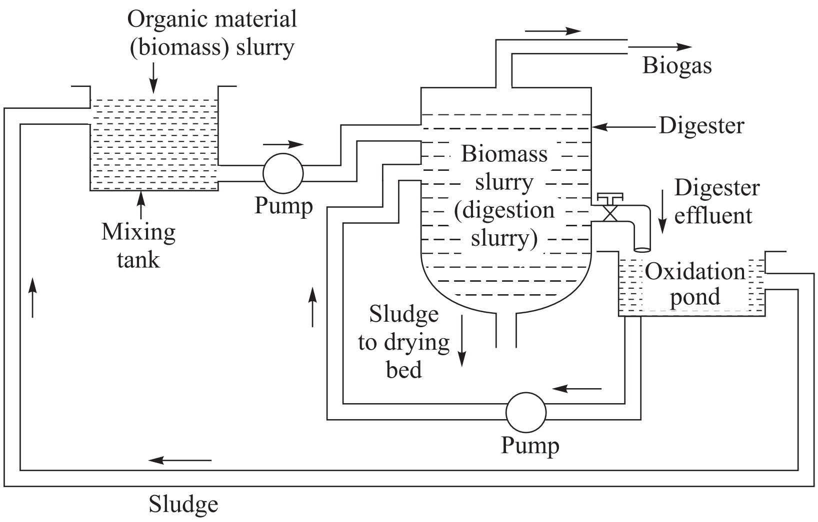


Figure 5.1 Biogas digester or plant.

Neither overloading nor underloading of the digester is desirable as it reduces biogas production. The acid forming bacteria grows rapidly, whereas methane forming bacteria (anaerobe) grows slowly. To obtain maximum biogas generation rate, seeding of digestion slurry with methane forming bacteria is done. This is achieved by adding certain portion of digested slurry to the fresh slurry. It is also possible to add nutrients containing nitrogen, hydrogen, oxygen, phosphorous, sulphur and carbon, which can also increase the anaerobic digestion rate. The recommended pH value for the digestion of biomass slurry is about to 7–8.

Advantages of anaerobic digestion

(i) It helps to obtain energy from discarded or waste matter. Otherwise, waste matter has to be disposed off with some additional cost.

(ii) It helps to provide two main benefits which include fuel by biogas and fertilizer in the form of sludge.

(iii) The process helps in conserving complete nitrogen content of the biomas. Hence, fertilizer produced as sludge is better in terms of both quantity and quality.

(iv) It helps in the waste management of an industry such as dairy or milk processing plant with simultaneously meeting the energy requirement of the same industry.

(v) It helps in the urban waste management such as municipal solid waste or garbage and sewage or liquid waste. The better management of urban waste improves the sanitation and hygiene in villages and towns.

(vi) Anaerobic digestion is carried out in the airtight enclosures, which helps in containing and controlling the odours of solid and liquid wastes. Digested slurry is completely odourless.

Raw material for biogas

The raw materials for biogas can be waste, cultivated material and harvested material. The waste includes industrial waste, agricultural crop residues and waste, animal waste, urban waste, aqua waste and forest waste. Agricultural crops include rice, wheat and cereals while agricultural wastes include wheat straw, sugarcane biogasses, groundnut shell, coconut shell and rich husk. Animal wastes include cow dung, horse manure, sheep manure and poultry waste. Urban wastes include paper, leftover food, plastic, rubber, wood and textile. Aqua wastes include water plants (hyacinth), algae and waste from fishery. Forest wastes include waste from sugar mill, tannery, fruit processing industry and paper mill.

Factors affecting the performance of a digester

The factors affecting the performance of a digester are as follow:

(i) **Temperature.** Anaerobic bacteria grow and work best in the temperature range of 20–65°C.

(ii) **Pressure.** A pressure of 6–10 cm of water column is considered ideal for proper functioning of the digester.

(iii) **Water.** The presence of water helps in better mixing of various constituents of the biomass, hydrolysis of biomass, movement of bacteria and faster digestion process. The optimum solid content of biomass is 9–10%.

(iv) **pH value.** The pH value in the acid forming stage of digestion process should be about 6 (acidic). During methane forming stage, the pH value should be about 6.5–7.5 as anaerobic bacteria do not grow in acidic solution.

(v) **Feeding rate.** A uniform feeding rate should be maintained. In case of faster feed, acids will accumulate to stop digestion process. In case of slow feed, the digestion progresses slowly due to non-availability of sufficient biomass.

(vi) **Presence of nutrients.** Carbon, nitrogen and other nutrients are essential for digestion. Carbon and nitrogen are main nutrients for anaerobic bacteria and their presence in proper ratio is essential to ensure the maximum microbiological activity. Selected raw materials should added to maintain the proper concentration of nutrients in digestion solution of bacteria.

(vii) **Seeding.** To start or accelerate the digestion process, it is customary to add a small amount of digested slurry containing methane forming bacteria to the freshly charged digester. This process is called seeding of bacteria.

(viii) **Mixing and stirring.** Mixing and stirring of digester slurry helps to mix the floating masses of biomass in the slurry for bacterial action so as to speed up the methane forming process in the slurry.

(ix) **Retention time.** It is the duration for which the biomass slurry remains in the digester. The digesters are designed to keep biomass for the retention period ranging from 30 to 50 days depending on the region (climatic temperature) and type of biomass. Retention time is optimised to get atleast 70–80% of digestion of the slurry.

(x) **Toxic substances.** The presence of pesticides, detergents and ammonia in the biomass affects the digestion process.

(xi) **Type of biomass.** The digestion process also depends on the type of biomass. The biomass can be cow dung, poultry manure, sheep manure, night soil, rice husk, algae and water hyacinth and these have a different rate of biogas yield per unit mass.

5.4.3 Classification of Biogas Plants

- **How are biogas plants classified? Explain them briefly.**

or

- **Name various models of biogas plants and describe any one of them.**

or

- **Write note on dome type biogas plant.**

or

- **Explain the availability and conversion theory of a biogas plant.**

or

- **Describe the factors that affect the size of a biogas plant.**

or

- **Explain the differences between fixed dome type and floating drum type biogas plants.**

or

- **Write the advantages and disadvantages of floating drum type and fixed dome type biogas plants.**

Biogas plants can be classified as batch type and continuous type. The continuous type biogas plants can be further classified as (i) floating drum or constant pressure type plant and (ii) fixed dome or constant volume type plant.

Batch type plant

A batch type plant consists of a number of digesters which are charged, used and emptied one by one in a synchronous manner to maintain regular supply to gas holder or storage tank. Each digester is charged with fresh biomass and it starts supplying biogas after 8–10 days. The digester is now capable of supplying biogas for about 40–50 days till its biomass is completely digested. Afterwards, this digester is emptied and recharged with fresh biomass. Hence, each digester should be charged in about at the interval of 50–60 days. Digesters in a batch biogas plant is shown in the Figure 5.2. The installation and operation of batch type plant is both capital and labour intensive.

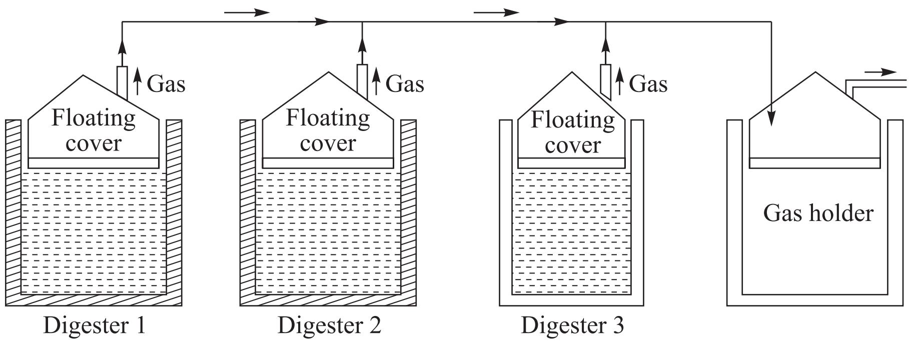


Figure 5.2 Biogas batch type plant with a number of digesters and a gas holder.

Continuous type biogas plant

In continuous type biogas plant, a certain quantity of biomass slurry is fed daily into the digester. This is made possible by the removal of digested slurry through an outlet so that the digester can have space to intake fresh biomass slurry. The biogas produced is either stored in the digester or removed to be stored in a gas holder. The plant operates continuously and it is stopped only for the removal of sludge. The layer of scum at the top of the biomass slurry is periodically broken with the help of the stirrer as shown in Figure 5.3. The stirring also helps in better mixing of biomass slurry to speed up the digestion process. This type of plant is most suitable for individual house owners as the daily wastage can meet the biomass feed requirement of the digester.

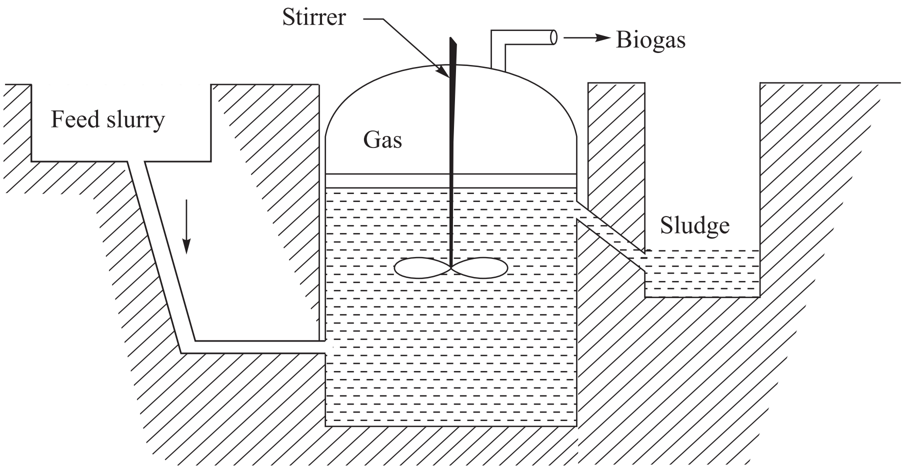


Figure 5.3 Continuous type biogas plant.

Floating drum type biogas plant

The plant consists of an inverted metallic drum to function as gas holder and an underground digester constructed from masonry with a partition wall as shown in Figure 5.4.

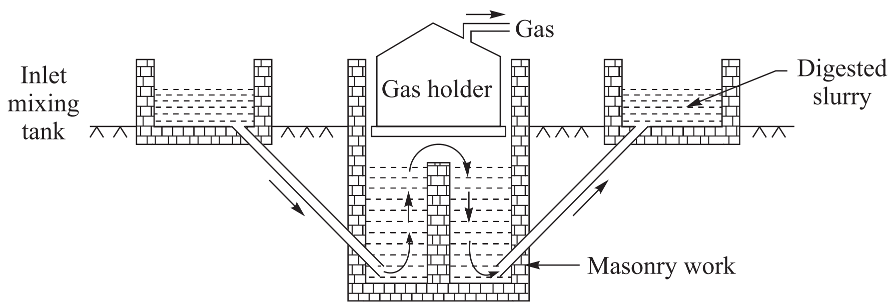


Figure 5.4 Floating drum type biogas plant.

The digester chamber is provided with a partition wall at the centre so that optimum conditions for growth of acid forming bacteria and methane forming bacteria can be provided in the partitioned portions as biomass slurry should be acidic and basic for acid forming and methane forming bacteria, respectively. The pipe arrangements are provided to the digester for the supply of fresh feed of biomass slurry and the removal of digested slurry. As the digester has floating gas holder, the pressure inside the digester remains constant. There is no risk of explosion due to prevailing low pressure of gas.

Fixed dome type biogas plant

It has constant volume but varying pressure inside the digester as it has no movable type gas holder but a fixed dome at the upper portion of the digester as shown in Figure 5.5. The biomass and water are mixed into slurry in inlet mixing tank, which is fed into the digester through the inlet pipe. A stirrer is provided in the digester tank to mix the slurry inside the digester, which also helps in mixing of scum floating on the slurry. The generated biogas accumulates in the fixed dome of the digester and it is taken out by an outlet pipe. The residual digested slurry is taken out from an opening in the digester. In the modified fixed dome type biogas plant, a displacement tank is also provided which is connected to the digester. As the pressure of gas in the fixed dome increases, the level of the slurry inside the digester goes down and it forces the slurry to rise in the displacement tank. This arrangement helps in maintaining a constant pressure inside the digester about 1 m of water column and the removal of digested slurry from the displacement tank.

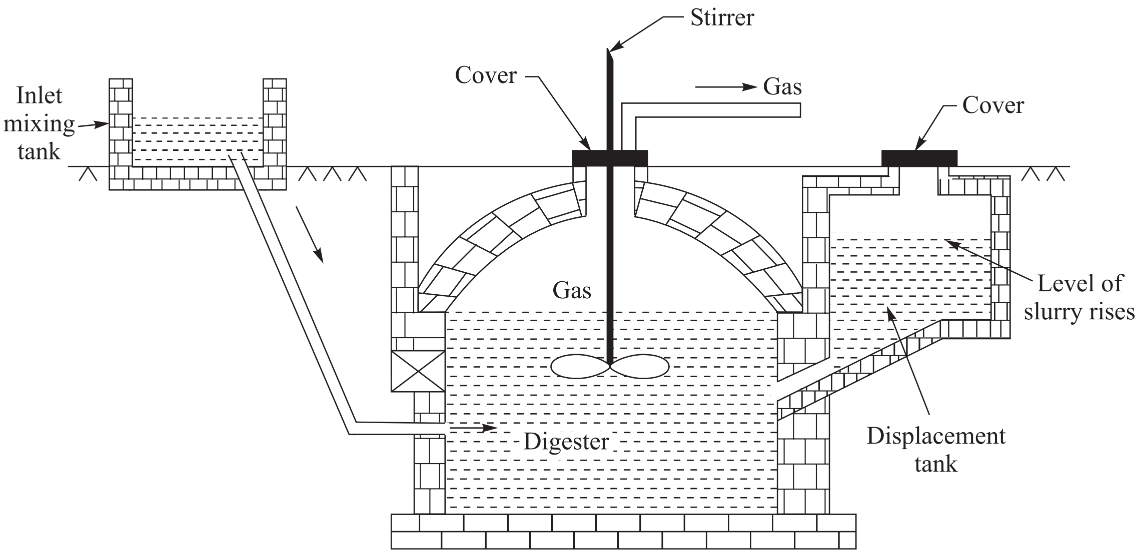


Figure 5.5 Fixed dome type biogas plant.

Comparison of floating drum and fixed dome types of plants

The comparison of floating drum and fixed dome biogas plants is given in Table 5.1.

TABLE 5.1 Comparison of floating drum and fixed dome plants

Floating drum	*Fixed dome*
It has constant pressure in the digester	It has constant volume in the digester
The pressure in the digester is slightly more than the atmospheric pressure	The pressure inside the digester can be as high as 1 m of water column
No danger of explosion of gas as pressure in the digester is low	Danger of explosion exists as pressure is high
No danger of leakage of gas	Due to high pressure there is danger of leakage of gas
Cost is more due to floating steel drum provision	Less costly
Corrosion of steel floating drum is likely	No such danger
More maintenance needed due to sliding metallic drum	Less maintenance needed
Gas production is high due to lower pressure in the digester	Low production of gas
Installation is simple	Installation is difficult.

Advantages and disadvantages of floating drum type biogas plant

The advantages are as follow:

(i) Higher gas production per cubic meter of digester volume.
(ii) No gas leakage problem.
(iii) Constant gas pressure.
(iv) No danger of gas explosion.
(v) No separate pressure equalising device is needed when fresh feed is added or digested slurry is removed from the digester.
(vi) Simple installation.

The disadvantages are as follows:

(i) It has higher cost due to movable metallic drum.
(ii) It has corrosion problem in the metallic movable drum provided.
(iii) It requires more maintenance.

Advantages and disadvantages of fixed drum type biogas plant

The advantages are as follows:

(i) It has lower cost.
(ii) It has no corrossion problem.
(iii) It has better heat insulation.
(iv) It requires no maintenance.

The disadvantages are as follows:

(i) Gas production per cubic meter of the digester is less.
(ii) It has variable pressure of biogas.

(iii) It has more risk of leakage due to higher pressure of gas.
(iv) It has more risk of explosion.
(v) It involves complex installation.

5.4.4 Application of Biogas in IC Engine

- **How biogas can be utilised in IC engines?**

The properties of biogas are as follows:

(i) **Composition.** Methane 60%, carbon dioxide 40% and traces of hydrogen, hydrogen sulphide and other gases
(ii) **Calorific value.** Calorific value 5160 kcal/m^3 or 4250 kcal/kg
(iii) **Stoichiometric air fuel ratio.** The stoichiometric A/F ratio is 5.27 by volume
(iv) **Calorific value of mixture.** It is equal to 767 kcal/m^3, that is, 85% of gasoline

The biogas alone cannot be used in IC engine unless some modification is carried out in the IC engine. However, with blending of biogas in small amount with both petrol and diesel, it is possible to run IC engine by it with small modification (providing gas kit and supply system). It is found that a mixture of biogas and gasoline containing 5–10% biogas can be successfully used as IC engine fuel, thereby reducing the limited and costly gasoline consumption by 5–10% and at the same time reducing the cost of fuel.

5.4.5 Models of Biogas Plants

- **Name the various models of biogas plants.**

Different models of biogas plants are as follows:

(i) Common circular digester with floating gas holder without water seal (KVIC design, India)
(ii) Common circular fixed dome digester (China)
(iii) Flexible gas type combined digester and gas holder
(iv) Taper digester with floating gas holder (Nepal)
(v) Two-chamber rectangular digester with floating gas holder and water seal (Philippines)
(vi) Jet digester with separate gas holder (Thailand)
(vii) Khadi and Village Industries Commission (KVIC) model
(viii) Planning Research and Action Division (PRAD) model
(ix) ASTRA (Application of Science and Technology to Rural Areas) model
(x) Ganesh model.

5.4.6 Biogas Plant in Hilly Area

- **In a hilly geographical region in India, a huge quantity of biomass is available round the year, but this area is highly deficient in electricity supply. Suggest the ways in which the biomass energy can be converted into electrical energy and substantiate your answer with a suitable diagram.**

In hilly regions, the average temperature remains below 15°C. The anaerobic bacteria grow and digest biomass in the temperature range of 25–75°C. Owing to low temperature of biomass, it is impossible to convert biomass into biogas in hilly regions. However, this problem can be overcome by following methods:

(i) **Hot water circulation.** This method is reported to be efficient for maintaining the biomass slurry at a high temperature in the digester, but the cost of circulation of hot water is high.
(ii) **Use of chemicals.** Urea and urine have been reported to increase the temperature of biomass slurry in the digester.
(iii) **Solar energy system.** Solar collector can be used to increase the temperature of biomass in the digester.

A way to obtain electrical energy in hilly region is shown in Figure 5.6. Solar collector is used to heat water, which is circulated in the digester to heat biomass slurry. The biogas is used to generate steam to run turbine. The generator coupled with turbine generates electricity.

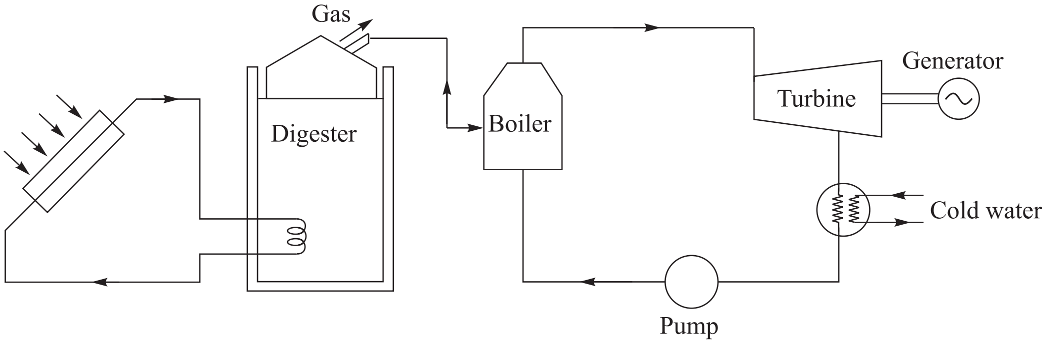


Figure 5.6 Biogas generating electricity in the hilly region.

5.4.7 By-Product of Digestion

• **Explain by-product of digestion with the help of a schematic diagram.**

The by-products of digestion are shown in Figure 5.7.

Properties		Uses
Gas	Biogas	Combustible gas
Fiberous	Scum	Insulator
Liquid	Supernatant	Biologically active
Solid/liquid	Effluent	Fertiliser
Solid	Inorganic solids	Waste

Figure 5.7 By-products of digestion of biomass.

5.4.8 Location of Biogas Plant

- **What are the factors considered while locating a biogas plant?**

The considerations for locating a biogas plant are as follow:

(i) Do not locate the plant within 13 m of a well or spring used for drinking water purposes.
(ii) Locate the plant near to area where biomass is generated.
(iii) Water source should be available near the site to meet the need of digester.
(iv) The site should be open and exposed to the sun as digester gives better performance at the temperature between 25 and 75°C.
(v) The site should be as close as possible to the point of gas consumption to avoid pressure losses in the pipe system.

5.4.9 Size of Biogass Plant

- **What are the considerations made to fix the size of biogas plant?**

The considerations made to decide the size of the plant are as follows:

(i) How much waste is generated with the number of animals and people?
(ii) How much gas the owners requires?
(iii) What will be the volume of the digester tank needed to handle the mixture of biomass and water?
(iv) What is the size and shape of digestion tank required?
(v) What should be the size of the floating drum of the digester?
(vi) What are the requirements of various items for the installation of the digester?

- **Calculate the volume of cow dung-based biogas plant to meet cooking requirement of five persons (230 l/day), and lighting of three 100 CP mantle lamps consuming 120 l/h for 3 h. Also, calculate the required number of cows to run the plant in case cow dung produced is 1 kg/day and collection efficiency is 70%, percentage of solid is 16% and production of gas from solid is 340 l/kg.**

Gas requirement

$$\text{Gas for cooking} = 5 \times 0.230 = 1.15 \text{ m}^3\text{/day}$$

$$\text{Gas for lighting} = 3 \times 0.120 \times 3 = 1.08 \text{ m}^3\text{/day}$$

$$\therefore \quad \text{Total gas requirement} = 1.15 + 1.08 = 2.23 \text{ m}^3\text{/day}$$

Cow requirement

$$\text{Cow dung per cow} = 10 \text{ kg/day}$$

$$\text{Collection efficiency} = 70\%$$

$$\text{Collected cow dung per day} = 10 \times 0.7 = 7 \text{ kg/day}$$

Weight of dry cow dung (18%) = 0.18×7 kg/day

Gas production (340 l/kg) = $0.34 \times 0.18 \times 7$ m^3/day

Gas produced by n number of cows = $n \times 0.34 \times 0.18 \times 7$

Equating this with the requirement, we obtain

$$0.34 \times 0.18 \times 7 \times n = 2.23$$

or

$$n = \frac{2.23}{0.34 \times 0.18 \times 7}$$

$$= 5.2 = 6 \text{ cows}$$

Size of digester

Cow dung daily = $6 \times 7 = 42$ kg

Water to mix equally = 42 kg

Slurry = $42 + 42 = 84$ kg

$$= \frac{84}{1090} = 0.077 \text{ m}^3 \text{ (density} = 1090 \text{ kg/m}^3\text{)}$$

In case the retention of biomass is 50 days

Volume of biomass = 50×0.77

$= 3.85$ m^3

Digester's volume (10% extra) = $3.85 \times \frac{110}{100}$ m^3

$= 4.24$ m^3

5.4.10 Problems and Constraints in the Use of Biogas

- **Why biogas plants are not successful in India even after the subsidies provided by the Government of India?**

Many problems associated with the biogas programme are putting hinderance to its success. The problems are as follows:

(i) **Technical problems**

- Problems caused due to modifications in the design and specification at local level
- Lack of temperature control due to poor insulation and seasonal variations
- Improper designing and development of gas appliances
- Unsuitability of biogas digester to meet different climatic conditions

(ii) **Socio-economic problems**

- Wood fuel is available free of cost in most rural areas and necessity of biogas plant is not realized villages
- Lack of awareness of benefits of biogas plants
- Lack of awareness of technology about biogas plants

(iii) **Installation problems**

- Defective construction due to untrained man power
- Lack of techincal knowledge about biogas plants
- Unavailability of plant components
- Delay in sanction and disbursement of bank loans.
- Lack of coordination among government and other agencies involved in biogas programme.

In spite of the government providing financial assistance in the form of subsidy, incentives training, technical assistance and repairing cost, biogas plants are not becoming popular.

5.4.11 Community Biogas Plants

- **Write briefly about community biogas plants.**

The community biogas plants can help in transforming village life by providing not only efficient cooking fuel but also electricity for (i) lighting, (ii) operating cottage industries, (iii) irrigation, (iv) supplying drinking water, (v) maintaining sanitation and (vi) fertillisers for improved agriculture. To improve the productivity and efficiency biogas plants, following suggestions are being considered:

(i) Biogas is to be used in dual fuel engine to generate power which can be sold to the state electricity boards

(ii) The hot exhaust of power generating system should be used to operate biogas plants at higher temperature, thereby increasing biogas production from a biogas plant

(iii) The use of additional materials such as water plants with animal waste to generate biogas

(iv) The new methods of biogas generation using bacterial support structures and recycling of spent slurry help in reducing cost of biogas generation.

5.5 BIOMASS CONVERSION TECHNOLOGIES

- **Explain how biomass conversion takes place.**

There are basic technologies or procedures to convert the biomass into (i) direct energy or (ii) more valuable or convenient products. These technologies or procedures are incineration, thermochemical and biochemical.

Incineration

It is the burning or combustion of the biomass to obtain useful heat. The heat can be used for space heating and cooking or it can be used to generate steam in boiler to run turbine with electric generater, thereby producing electricity. Furnaces and boilers have been designed to burn various types of biomass such as wood waste wood, agricultural waste products, food industry waste, urban waste and forest industry waste.

Thermochemical

The biomass can be converted into more valuable and convenient fuels by the use of the thermochemical process called pyrolysis. Pyrolysis can process all forms of biomass (organic materials), including rubber and plastic which cannot be converted by any other methods. The pyrolysis process is carried out by heating the biomass in absence of air (or oxygen) or by partial combustion of some portion of the biomass in restricted presence of air (or oxygen).

Three types of biofuels are obtained by pyrolysis depending upon feedstock, temperature and pressure:

(i) A gaseous mixture of gases such as H_2, CO, CO_2, CH_4 and N_2
(ii) A liquid in the form of oil such as acetic acid, acetone, methanol, oil and tar
(iii) A pure carbon char

If pyrolysis is carried out at higher temperature (above 1000°C), maximum amount of gaseous product is formed. This high temperature pyrolysis is called gasification. This process is generally used to produce charcoal and it is also called carbonization.

Liquid product from biomass is obtained by catalytic liquefaction process at low temperature (250–450°C) and high pressure (270 atm).

Biochemical

The conversion of biomass is carried out using metabolic action of microorganism or bacteria. The process produces liquid and gaseous fuel. The major biochemical processes for the conversion of biomass are as follows:

(i) **Anaerobic digestion or fermentation.** The biomass in the presence of water is converted into biogas by the action of anaerobic bacteria. The methane and carbon dioxide are the two main components of biogas.

$$\text{Biomass + water} \xrightarrow[\text{anaerobic digestion}]{25\text{–}75°\text{C}} \text{Biogas } (CH_4\ 50\text{–}60\% + CO_2\ 35\text{–}40\%)$$

The biomass used includes animal manure, algae, kelp, hyacinth, urbane waste (garbage + sewage) and industrial waste.

(ii) **Ethanol fermentation.** It is formed due to the alcoholic fermentation of simple hexose sugars (six carbon atoms per molecule such as $C_6H_{12}O_6$) in aqueous solution by the action of a enzyme present in yeast (act as catalyst) in the acidic conditions (pH value between 4 and 5). The chemical reaction can be given as:

$$C_{16}H_{12}O_6 \xrightarrow[\text{fermentation}]{32°\text{C}} \underset{\text{(ethanol)}}{2C_2H_5OH} + \underset{\text{(carbon dioxide)}}{2CO_2}$$

5.5.1 Biomass Gasification

- **What do you understand by biomass gasification? How are gasifiers classified?**

Biomass gasification is used to convert solid biomass such as wood and its waste or agriculture waste into a combustible gas mixture of carbon monoxide and hydrogen. This combustible gas mixture is called producer gas. The gas is produced by partial combuston of biomass in the absence of sufficient air. It has a great potential for the gasification process as it can simultaneously produce charcoal which is a biofuel and producer gas which can be used as fuel for power generation, irrigation pumping and village electrification. It has been reported that producer gas can be used to replace up to 75% diesel in a diesel engine.

The gasifiers can be classified into (i) fixed bed updraft gasifier, (ii) fixed bed down draft gasifier, (iii) cross draft gasifier and (iv) fluidized bed gasifier, depending on the direction of airflow. A typical fixed bed updraft gasification is shown in Figure 5.8.

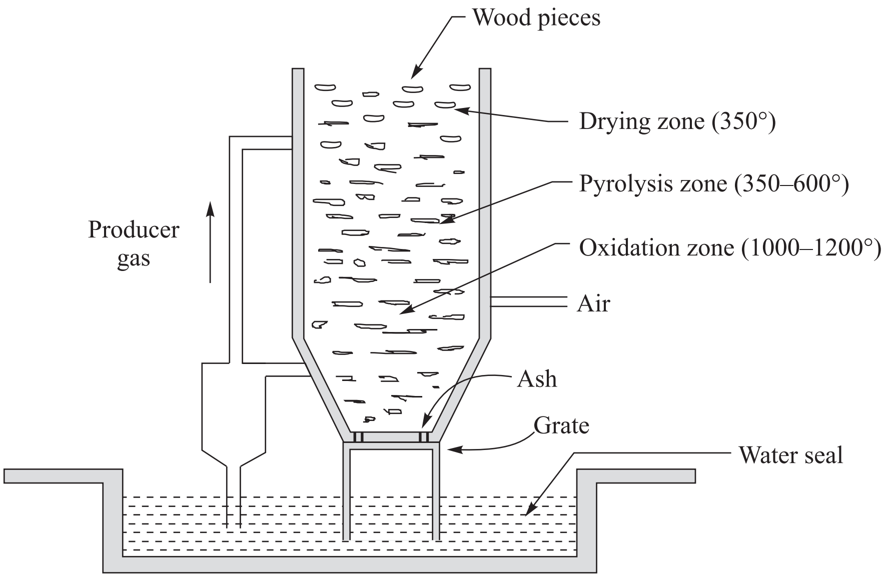


Figure 5.8 An updraft gasification.

5.5.2 Energy Recovery from Urban Waste by Landfill Reactors

- **Explain in detail a landfill reactor. What is the optimal moisture content in the MSW and what is the percentage (dry basis) of biodigradable part of the MSW? What is the gas production rate in a landfill?**

Municipal solid waste (MSW) is disposed off by the controlled method of sanitary landfilling. Biodegradable urban wastes are segregated and compacted so that these waste can be used to generate biogas. The ground selected for landfilling has to be prepared in such a way that groundwater is not contaminated due to any leaching of garbage. The landfilling site should be first lined with layers of plastic liner and clay to stop any leaching of garbage to the underground water at the site. A leachate collection system is also provided at the landfilling site to collect and recycle leachate either to speed up the decomposition process of biomass or to dispose it at sewage treatment facility. When a landfill is completed, a plastic liner is placed at the top, covering the landfilling before closing it with soil. The optimum moisture content of the garbage is about 60%, which should be ensured before covering the garbage. Less or more moisture content hinders the biogas production. The landfills use a system of water and oxygen circulation to speed up decomposition of waste and produce biogas (mainly methane) much faster than that by natural process. The biodegradable part of garbage (about 70% of MSW) is slowly digested by the anaerobic bacteria to produce biogas. The temperature rises to 60°C during digestion of biomass. The gas collection system consists of cylindrical pipes of diameter 80–120 mm having holes on their periphery. These perforated GI or plastic pipes are laid as shown in Figure 5.9.

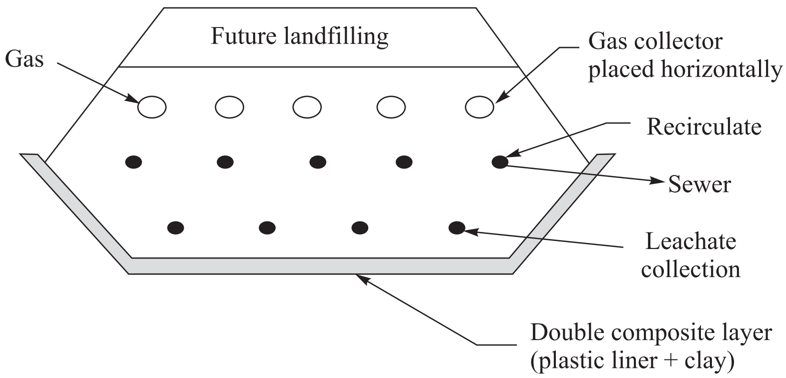


Figure 5.9 Landfill reactor.

It has been reported that 1 ton of refuse can generate about 225 m^3 of biogas. A landfill of 40 hectare area with waste fill height of 100–125 m can yield gas quantity of about 135 m^3 per minute continuously for a period of about 15–20 years.

About 90% landfills in India are merely serving as dumpsites rather than landfill reactors without providing provisions for extracting biogas.

5.5.3 Power Generation from Liquid Waste

- **We want to reduce the cost of waste water treatment, increase energy generation and eliminate greenhouse gas emission. For long, we have thought of treatment plants as places where we remove the organic matter and waste nitrogen. We need to view these wastes as resources, not simply something to dispose of. Comment on this statement.**

Sewage treatment is a facility designed to receive the waste from domestic, commercial and industrial sources. It is also meant to remove materials that damage water quality and compromise public health and safety when discharged into water receiving systems, such as rivers and streams.

Conventional wastewater treatment consists of a combination of physical, chemical and biological processes and operations to remove solid, organic matter and nutrients from wastewater. The treatment is carried out in two stages. Primary treatment is the removal of organic and inorganic solids by sedimentation and the removal of scum (floating materials) by skimming. The secondary treatment is performed to remove the residual organics and suspended solids. The aerobic biological treatment is applied at this stage to remove biodegradable, dissolved and colloidal organic matters, which is performed in the presence of oxygen. Aerobic bacteria are grown to metabolize the organic matter in the water waste and produce more microorganisms (bacteria) and inorganic end gaseous products such as CO_2 and NH_3. The rate of aerobic digestion depends upon aeration or supply of air to the waste which is generally carried in the controlled conditions. Trickling filters, oxidation ditches, rotating biological contractor (RBC) and activated sludge processes are used to control the rate at which bacteria metabolize the organic matter.

The most common methods of treating industrial and urban liquid wastes are as follow:

(i) Man-made ponds or lagoons are made to hold waste water for the settlement of coarse solids and other large materials. The waste water is further biologically improved by its retention. Ponds or lagoons for retention of waste water are constructed and lined with clay and plastic liners to prevent any leakage into the groundwater at the site. The treatment method relies more on sunlight, algae, bacteria and oxygen for the treatment of water.

(ii) Man-made ponds or lagoons with air pumps are developed to aerate the waste water to achieve bacterial treatment through aerobic digestion of waste. The aerobic treatment system can achieve 80–90% removal of biodegradable waste with retention time of 1–10 days.

(iii) Modern method of treating waste water is carried out by using advanced anaerobic digestion plants which run and generate electricity with production of methane gas. The "Okhla sewage treatment" plant in India was recently started which generates power using biogas based power engines. The biogas is generated from treatment of sludge. The plant has the capacity produce 1105 kWh and 30 M6D of sewage as manure.

5.5.4 Biomass Resource Development and Energy Plantation

- **What do you understand by energy plantation?**

or

- **Energy plantation can be considered as long-term alternatives to fossil and nuclear energy resources. Comment on the statement.**

When land plants are grown purposefully to capture and store solar radiation so that it can be used for their fuel values, such plantation is called energy plantation. Such plants serve as a convenient means to store solar energy as it is done by other storage devices and accumulated energy can be released or taken whenever it is required. It is found that more heat or thermal energy is derived from materials of forest origin than from other thermal sources. Hence, more consideration should be given to planting and harvesting plants to serve as fuels. It is more worthwhile to think energy plantation in terms of heat content or calorie instead of trees, grasses or farm crops. Energy plantation should be designed, managed and operated to produce a substantial amount of usable fuel continuously throughout the year and at competitive rate in comparison to other available fuels. Normal plants and agricultural crops are unsuitable for providing a year-round supply of fuel. These normal plants and agriculture crops grow too slowly to provide sufficient yield of fuel. Hence, special biomass plantation for energy should be adopted. Such energy plantation can be done by short-rotation intensive culture (SRIC) plantation or by plantation of herbaceous plants which can be harvested periodically without replanting (only once in a decade). A large number of potentially fast growing plant species are known which could be taken up for plantation on wasteland. Growth of plants for their fuel value can offer a renewable and profitable source of liquid fuel and organic chemicals. The energy plantation can also help in improvement of the environment besides providing biomass fuels.

5.5.5 Biomass Energy Programme in India

- **What is the present status of development of biomass energy resources in India?**

It has been estimated that 40 million tons of solid waste and 5000 million tons of liquid wastes are generated in India every year in the urban areas over and above the wastes generated in industrial sector. Owing to lack of stringent provision against pollution and lack of awareness, most of the waste generated is discharged into rivers, ponds and low-lying land without any treatment or utilisation. Such disposal of waste without treatment or utilisation results in creating odour, pollution of water and air, and emission of greenhouse gases such as methane and carbon dioxide. Biomass conversion technology can help in generation of biomass energy, reduction in the quantity of waste and improvement in quality of waste water to meet the pollution control standards before discharging into rivers and streams. It is estimated that there is a potential of generating about 1700 MW power from urban and industrial wastes in India. Currently nearly 415 MW power is being generated from industrial wastes in India. MNES is promoting the setting up of more waste energy projects in India.

India is in fact a predominantly agricultural country and it is reported to have the potential to generate nearly 19,500 MW power from agricultural wastes. It is reported that a total of 613 MW power is being generated from these wastes in India. India has also launched a scheme to blend 5% ethanol in petrol, which has helped to considerably reduce the import of crude oil. Ethanol is produced from sugarcane and this blending has encouraged greater cultivation of sugarcane crop in India.

Biomass fuels such as firewood are used by villages for cooking and heating purposes. The present chulhas are incapable of burning such fuels efficiently, thereby causing serious health problems besides economic loss. Technologies and devices are being developed to produce more efficient and clean fuels from the rural biomass. More efficient chulhas are also developed. India has presently installed 58 MW power plant running on biogasifiers. About 120 lakh biogas plants have been installed which are running on cow dung, family waste and agro waste.

CHAPTER 6

Wind Energy

6.1 INTRODUCTION

Wind is essentially air in motion. Hence, air has wind energy because air is in motion. The amount of energy available in the wind at any instant is proportional to cube power of the wind speed. Wind energy is in fact an indirect form of solar energy. A small part of solar radiation reaching the earth is converted into wind energy. Air motion or wind is generated owing to the differential heating of earth (and its atmosphere) by the sun. Wind energy is harnessed as mechanical energy with the help of windmill or turbine. The mechanical energy obtained from wind can be used to operate either mechanical devices such as water pumps and farm appliances or electric generators to generate electricity. Slow and strong winds cannot be utilized. Moderate to high speed winds having speed about 5–25 m/s are suitable to operate wind turbines. Hence, some storage device of wind energy is needed to meet the power requirement when wind turbine cannot operate during unfavourable wind conditions. The idea of harnessing wind energy is not new. It was one of the first natural energy sources to be used by mankind. Wind energy was even used to run water pumps, grind grains and sail ships about 5000 years ago.

6.2 ORIGIN OF WINDS

The winds can be classified as:

- Global winds
- Local winds

6.2.1 Global Winds

- **With the helps of a diagram, indicate the circulation of global winds. What are forces responsible for determining the speed and direction of global winds?**

The primary force for global winds is produced due to differential heating of the earth surface at equator (0° longitudes) and polar regions (about ± 90° longitude). More heating takes place near the regions of equator and less heating occurs at polar regions, and so cold winds move from polar to equatorial regions. The air in touch with ocean water is much colder than air in the plain areas, and so cold winds generated from ocean areas move towards plain areas.

The rotation of the earth on its axis produces Coriolis force and this force is responsible for forcing the global winds towards westernly direction. These air currents are also called trade winds as sailing ships in the past used these air currents for ship movement and trading. The global winds and circulations are shown in Figure 6.1.

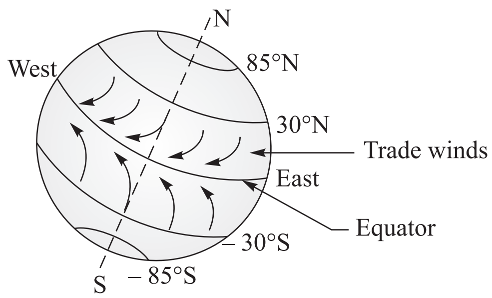


Figure 6.1 Global winds and their circulations.

6.2.2 Local Winds

- **Explain the mechanism of production of local winds.**

Local winds are generated due to uneven heating. Uneven heating occurs on land surface and water bodies due to solar radiation. As a result, cool and heavy air currents move from water bodies to land surface. At night, the direction of wind is reversed as land surface cools more rapidly than water bodies. The same conditions also prevail in hilly areas where hill slope heats up during the day and cools down during the night more rapidly than the low land. This temperature difference causes air currents to move to the hill slope during the day and to the low-lying land during night.

6.2.3 Distribution of Wind Energy

- **What are the factors responsible for distribution of wind energy on the surface of earth?**

The factors affecting the distribution of wind energy are as follows:

(i) The chain of mountains channelise the air currents
(ii) The hills, trees and building act as obstructions and change the direction of airflow

(iii) The frictional effect of the surface determines the wind speed. This is the reason why wind speed is quite high at seashore as frictional effect is less on smooth surface or sea surface.

(iv) Climatic disturbances resulting from rains affect wind speed.

(v) Topography of an area also affects wind speed, for example, wind can speed up when passing through narrow gap such as mountains gaps.

6.2.4 Nature of Wind

- **What do you understand by the behaviour and structure of wind?**

or

- **What are Beaufort numbers?**

Before installation of a wind turbine, it is essential to have full knowledge of the behaviour and structure of wind. The winds vary from place to place. The nature of wind at a site depends upon general climate of the region, physical geometry of the locality and terrain around the site. The wind intensity can be described by Beaufort number as per wind speed as given in Table 6.1.

TABLE 6.1 Wind description and Beaufort number

Beaufort number	*Wind description*	*Characteristics*	*Wind speed* (m/s)
1	More light	Smoke drifts	0.4–1.8
2	Less light	Slight movement of leaves	1.6–3.6
3	Light	Flag starts fluttering	3.6–5
4	Moderate	Moving of small branches of tree	5.8–6.5
6	Strong	Large branches sway	11–14
8	Gale	Twigs breaking off from trees	17–21
10	Strong gale	Trees are uprooted	25–29
12	Hurricane	Extensive damage to all structures	> 34

6.2.5 Meterological Data about Wind Speed

- **What do you understand by meteorological data on wind speed?**

or

- **What principles are used for measurement of wind speed?**

or

- **What is the standard height for the measurement of wind speed?**

or

- **What are the advantages of presenting wind data in the form of a wind rose?**

Every country has its meteorological department to record and publish weather data along with wind speed and direction prevalent at all places in the country. The wind speeds are recorded at three heights which are 10, 50 and 150 m during strong winds. These records are used to specify the nature of winds in these regions. The wind speed are measured using an instrument called anemometer and wind direction is measured using a wind vane or cock.

A typical anemograph consisting of wind speeds recorded at three heights during strong winds is shown in Figure 6.2. Following are the conclusions which can be drawn from this anemograph:

- Wind speeds are more at greater heights
- Wind speeds at all heights fluctuate or change with time
- The fluctuation of wind speeds can be high.

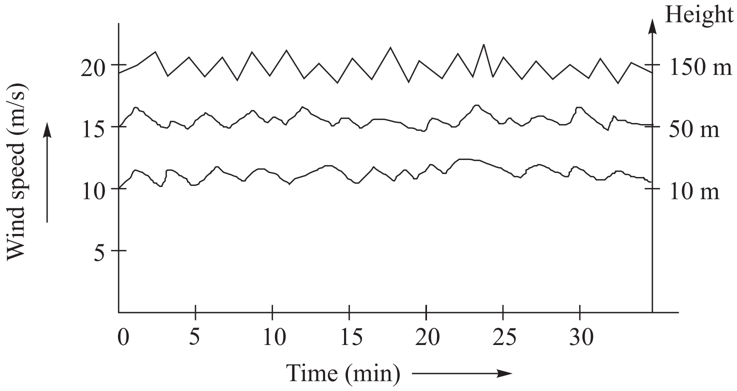


Figure 6.2 Anemograph of wind speeds at three heights.

Anemometer

It is a device to measure wind speeds. It can work using any of the following principles:

(i) When a swinging plate hinges along its top edge is hung vertically, the angle of deflection of the plate with respect to vertical axis is an indicator of wind speed.

(ii) When three or four cups are mounted symmetrically about a vertical axis, the speed of rotation of these cups is an indicator of wind speed.

(iii) When flat plate stops the wind, the wind pressure at the plate increases. The measured wind pressure is an indicator of wind speed.

(iv) When wind passes on a hot wire, the wire gets cooled depending upon the wind speed. By recording the cooling effect of the wind on hot wire, the wind speed can be determined.

(v) It is observed that wind with different speeds can create different sonic effects which can be recorded to determine wind speeds.

(vi) Use of laser technique with Doppler effect can help in determining wind speed.

Wind rose

The wind speed is measured and recorded at an effective height of 10 m from the ground. Wind rose is drawn showing mean wind speeds based on averaging period which may vary from 10 min to 1 h. The mean wind speed, its duration and its direction are depicted on a single graph as shown in Figure 6.3. The wind rose shows compass bearing from which the wind arrives (from all 6 directions) along with mean wind speed and duration in a year. The lengths of bars are drawn suitably to represent the percentage of duration of wind.

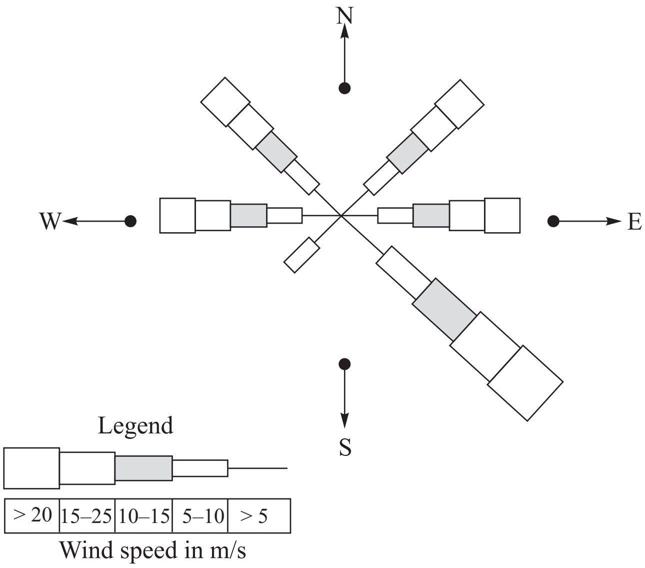


Figure 6.3 Wind rose describing mean wind speeds.

6.2.6 Wind Speed Variations with Height

- **With the help of a diagram, explain the variation of wind speed with height from the ground.**

or

- **Explain the terms (i) wind shear, (ii) gradient height, (iii) free atmosphere, (iv) planetary boundary, (v) surface layer and (vi) Ekman layer.**

Wind speed falls almost to zero at earth's surface and it increases as its height increases from the ground.

Wind shear

The rate of change of wind speed with height is called wind shear. The lower air layers moving slowly tends to retard air layer above them, resulting in the change in mean wind speed with height.

Gradient height

The wind speed increases as height increases because shear force reduces with height. At a certain height, the shear force reduces to zero and wind speed does not change above this height. This height is called the gradient height.

Free atmosphere

The gradient height is generally about 2000 m from the ground. Above this gradient height, any change in the ground conditions does not affect the wind speed; that is, wind speed is uniform above the gradient height. This atmosphere with uniform wind speed is called the free atmosphere.

Planetary boundary layer

The layer of air from ground to the gradient height is called the planetary boundary layer.

Surface layer

It is the air layer considered from the height of local obstruction to a height of about 100 m.

Ekman layer

It is the air layer from surface layer (100 m) that extends up to the gradient height. The variation of shear stress can be neglected in this layer, and the mean wind speed with height can be given by Prandtl logarithmic law:

$$u_z = V \log_e \frac{z-d}{z}$$

where u_z is the mean wind speed, V is the characteristic speed, z_0 is the roughness height of surface and d is the zero plane displacement.

The variation of mean wind speed with height is as shown in Figure 6.4.

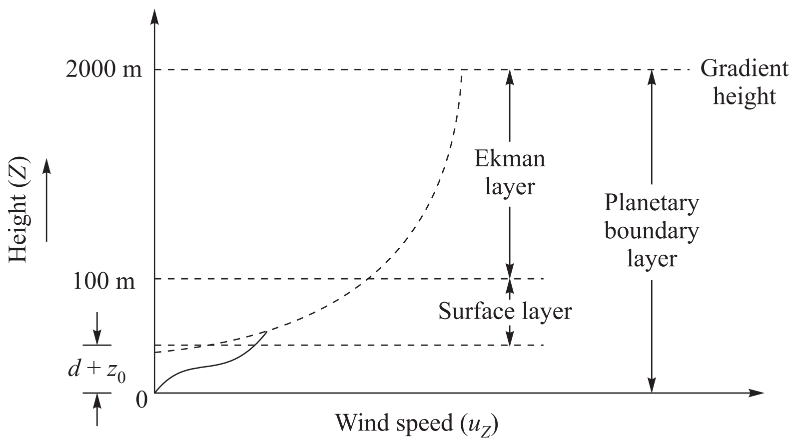


Figure 6.4 Logarithmic variation of wind speed with height.

As the wind speed is measured at a height of 10 m from the ground and also wind turbines are operated at a height of more than 10 m, a simpler empirical relation can be used to determine mean wind velocity at other heights, which is as follows:

$$u_z = u_H \left(\frac{z}{H}\right)^{\alpha}$$

where u_H is the wind velocity at the reference height H or 10 m,
α is the parameter that depends upon roughness and range of height (z) and
z is the height of the wind turbine.

6.3 WIND TURBINE SITING

- **What are the most favourable sites for installing wind turbines?**

or

- **Write criteria for site selection for setting up a wind farm.**

or

- **Describe the main consideration for selecting a site for wind generator.**

or

- **What are the criteria for site selection of a windmill?**

The main considerations for selecting a site for wind generator are as follows:

(i) **High annual mean wind speed.** A basic requirement for a successful use of a windmill or farm is an adequate supply of wind and good wind speeds. The wind power is proportional to the cubic power of wind speed.

(ii) **No obstruction.** There should not be any high structure to obstruct wind for a distance of 3 km to the windmilll.

(iii) **Open plain.** The site should be the open plain such as open sea shoreline where strong winds prevail.

(iv) **Height.** The wind speed increases with height, which can be obtained when the windmill is located on a hill or a ridge with gentle slope.

(v) **Near lake or ocean.** Differential heating of water and land generates wind of sufficient speeds.

(vi) **Topography.** Topography such as mountain gap helps to channelise and speed up winds.

(vii) **Favourable land cost.** It helps in restriction or reducing the cost of project.

(viii) **Nearness to load centre.** It reduces the cost of transmission of the generated power.

(ix) **Nearness to road or rail link.** It helps in installation of windmill.

(x) **Availability of wind rose.** It helps in designing of windmill as wind data of the site can be determined.

6.4 WIND TURBINE AERODYNAMICS

Wind carries with it kinetic energy. This wind energy is extracted when the direction of motion of wind is changed in accordance with the Newton's second law of motion; that is, the change of momentum of any body is equal to the force acting on it. The amount of energy extracted depends the amount of energy available in the wind on account of its speed.

6.4.1 Energy Available in Wind

- **Derive an expression for the total power of a wind stream.**

The wind has kinetic on account of its motion. This kinetic energy can be given by the following equation:

$$KE = P_0 = \frac{1}{2} \times \dot{m}u_0^2 \quad (6.1)$$

where $\dot{m}$ is the mass of air passing through an area A per unit time and
u_0 is the speed of free wind.

The mass of wind can be given as:

$$\dot{m} = \rho\, A\, u_0 \quad (6.2)$$

where ρ is the density of air. From Eqs. (6.1) and (6.2), we have

$$P_0 = \frac{1}{2}(\rho A u_0)\, u_0^2$$

$$= \frac{1}{2}\rho A u_0^3$$

or

$$\frac{P_0}{A} = \frac{1}{2}\rho u_0^3$$

The above relation indicates that the power available in wind per unit area is proportional to the cubic power of its speed.

6.4.2 Terms and Definitions of Fluid Mechanics

- **Discuss the following parameters used in rotor design: (i) rotor, (ii) solidity and (iii) tip speed ratio.**

or

- **With the help of a diagram, explain the terms free and relative wind velocities, drag and lift forces, solidity, pitch angle and chord.**

Rotor

The wind turbine extracts energy from the wind streams by transforming the kinetic energy of the wind into the rotational motion of the rotor of the wind turbine. The wind energy is extracted by the rotor of wind turbine as it has one, two or three blades having aerofoil shape and these blades are attached to hub. The wind moving over the surface of blades (aerofoils) attached to the rotor generates the requisite forces to turn the rotor.

Solidity

It is defined as the ratio of the projected area of the rotor blades on the rotor plane to the swept area of the rotor. High-solidity rotors use drag force for rotation and these rotors turn slower. Low-solidity rotors have slender aerofoil blades and these rotors use lift force for rotation. They turn faster.

Chord

It is the width of the blade which is across distance from one edge of the blade to the other edge as shown in Figure 6.5.

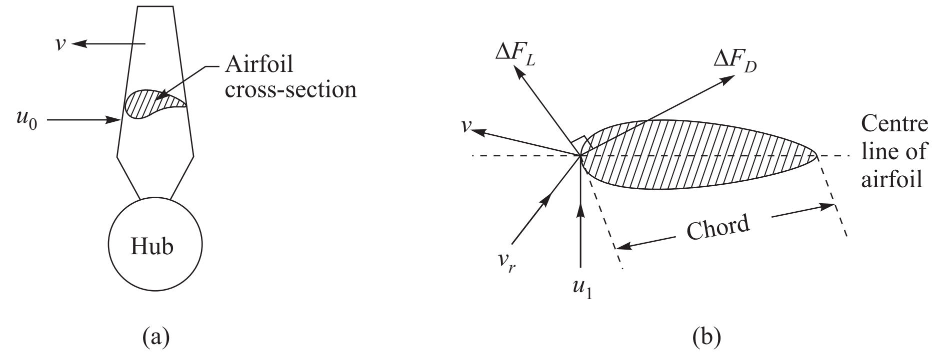


Figure 6.5 Rotor blade and its cross-section. (a) Rotor blade and (b) Aerofoil shape of blade's cross-section.

Different velocities

Various velocities are as follows:

(i) **Wind velocity (u_0).** The velocity of free air stream at sufficient distance away from wind turbine where there is no disturbance due to rotation of the wind turbine.

(ii) **Incident wind velocity (u_0).** It is the velocity at which the wind strikes the blade. This velocity is always slightly lower than the free air stream velocity (u_0).

(iii) **Blade linear velocity (v).** It is the tangential velocity of the blade due to the rotation of blade. If ω is the angular velocity of the blade and R is the length of the blade, then blade linear velocity $v = \omega \times R$.

(iv) **Relative velocity (v_r).** It is the relative velocity of wind with respect to the moving blade. It is the vector sum of incident wind velocity (u_1) and blade linear velocity (v). Mathematically, it can be given as:

$$\vec{v_r} = \vec{u_1} + \vec{v}$$

Angle of attack or angle of incidence (α)

It is the angle between the centreline of the aerofoil (blade cross-section and the relative wind velocity v_r) as shown in Figure 6.6. The airflow remains attached to the aerofoil for small angle of attack. The airflow is separated from the aerofoil for large angles of attack.

Pitch angle or blade setting angle (γ)

It is the angle between the centreline of the aerofoil and the direction of linear motion of the blade. The output of a turbine is greatly influenced by blade pitch angle. The blade pitch control is a very effective way to control. The output power, speed or torque of the turbine.

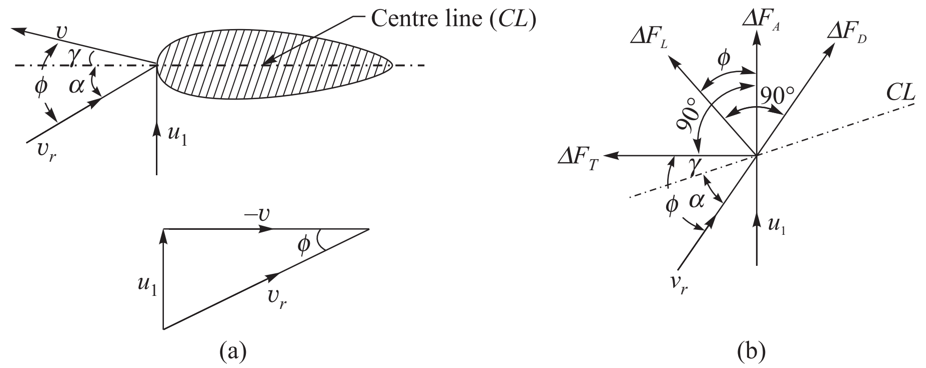


Figure 6.6 Velocities and forces acting on aerofoil (a) Various velocities and angles of aerofoils, (b) Various forces on aerofoil.

Drag force (ΔF_D)

When a body (aerofoil) is placed in uniform airflow, there are two forces acting on the body, namely, pressure force acting normally to the surface of the body, and shear force acting along the surface of the body. The pressure force and shear force can be combined to give the total force exerted by the wind on the body. This total force can be now resolved in the direction parallel to airflow and perpendicular to the airflow. The component of total force parallel to the direction of airflow is called drag force. The drag force always opposes the relative motion between the body and the air. It is given by the following equation:

$$\text{Drag} = \Delta F_D = C_D \times \frac{1}{2}\rho u_1^2 \cdot A$$

where C_D is the drag coefficient and

A is the projected area of the body aerofoil perpendicular the direction of airflow.

Lift force (ΔF_L)

The component of the total force (pressure force and shear force) on the body in the direction perpendicular to airflow is called lift force. As the name suggests, this force tries to lift the body. It is given by the following equation:

$$\text{Lift} = \Delta F_L = C_L \times \frac{1}{2}\rho \cdot u_1^2 \cdot A$$

where C_L is the lift coefficient.

Axial force (ΔF_A)

The total force (pressure force and shear force) can also be resolved along the axis of rotation of blade and perpendicular to it (tangential force on the blade). The component of total force acting on the blade along the axis of rotation of the blade is called the axial force. The axial force does not contribute to the rotation of the blade. It is also called thrust force and has to be balanced by a suitable reaction force generated by any thrust bearing provided on a rotor. The axial force contributes to waste energy which cannot be extracted from wind energy. Hence, axial force should be as less as possible. The axial force can be given as follows:

$$\Delta F_A = \Delta F_L \cos \phi + \Delta F_D \sin \phi$$

where $$\phi = \alpha + \gamma .$$

Tangential force (ΔF_T)

It is the component of total force on the blade acting tangential to its circular path of rotation. This is the force which contributes mainly to the useful energy extracted from the wind energy. It should be as high as possible. It is given by:

$$\Delta F_T = \Delta F_L \sin \phi - \Delta F_D \cos \phi$$

Tip speed ratio (λ)

The tip speed ratio is defined as the ratio of the speed of tip of the rotor blade to the speed of on coming air. Hence, tip speed ratio is:

$$\lambda = \frac{\omega \times R}{u_0}$$

For a particular wind speed, there exists an optimum turbine tip speed to produce the maximum output. It is important to match the rotation of wind turbine to the corresponding wind speed.

- **A windmill has rotor of 6 m with 30 blades. Each blade has width of 0.30 m, find the solidity. What is the implication of solidity?**

$$\text{Solidity} = \frac{\text{Projected area of blades}}{\text{Swept area}}$$

$$\text{Solidity} = \frac{30 \times 0.30}{\pi \times 6^2} \times 100\%$$

$$= 7.96\%$$

The greater is the solidity of a rotor, the slower it needs to turn to intercept the wind. When windwill has a lesser number of blades, it needs to rotate fast to intercept the wind so that wind should not be lost through the large gap existing between two blades without importing a part of wind power.

- **Find the tip-speed ratio if a 6 m diameter rotor has rotation of 20 rpm and the wind speed is 4 m/s. What is the implication of tip speed ratio?**

$$\text{Tip speed ratio} = \frac{W.R}{u_0}$$

$$\text{Tip speed ratio} = \frac{\frac{\pi R N}{60}}{4}$$

$$= \frac{\pi \times 6 \times 20}{60 \times 4} = 1.6$$

The windmill rotating fast has tip speed ratio greater than 1. Two or three-bladed rotors rotate faster, thereby having tip speed ratio ranging from 3 to 10. More bladed rotors rotate move slowly, thereby having tip speed ratio between 1 and 2.

6.4.3 Principle of Power Generation

- **How energy from wind can be extracted? Explain the process by using suitable diagram.**

or

- **Explain the principle of wind energy conversion.**

or

- **Explain Betz model of expanding airstream tube to determine extraction of wind energy by windmill.**

Wind turbine is used to extract useful energy from wind. The energy can be extracted by partially decelerating and expanding the airstream (reduction of pressure) using wind turbine. The rotor of the wind turbine collects wind from the whole area swept by the rotor. The area swept can be considered as airstream tube which is continuously expanding as shown in Figure 6.7. This airstream tube model is also called Betz model of expanding air. As air mass flow rate should be the same everywhere within the stream tube according to the Law of Continuity, the wind speed must decrease as air expands. As shown, airstream tube has area of A_0 at upstream, area of A_1 while passing through rotor blade (aerofoil) and area A_2 downstream.

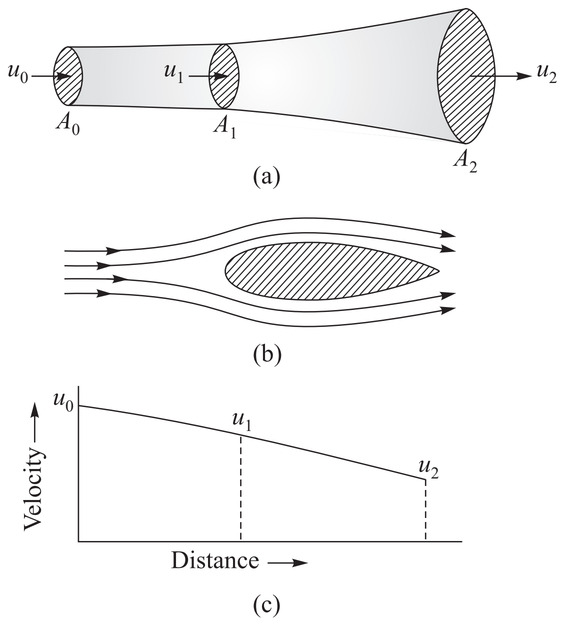


Figure 6.7 Extraction of wind energy and Betz model of expanding air. (a) Airstream tube, (b) Airstream on aerofoil, (c) Variation of wind velocity.

Consider that u_0 and u_2 are wind velocities at upstream and downstream. The velocity reduction from u_0 to u_2 means that there is a reduction in momentum of the wind as it passes through the wind turbine, resulting in a force being exerted on the blade of rotor, which is given by the following equation:

$$\text{Force} = F = \dot{m} \times u_0 - \dot{m} \times u_2 = \dot{m}\,(u_0 - u_2)$$

where $\dot{m}$ is the air mass flow per unit time through stream tube.

The above force is exerted at a uniform rate when airflow moves over the rotor blade with velocity of u_1. Therefore, the power extracted is equal to the work done by the airstream in moving for a distance of u_1 against force of F, which is given by:

Power of turbine $= P_T = F \times u_1$

or

$$P_T = \dot{m}\ (u_0 - u_2) \times u_1 \qquad (6.3)$$

The power extracted by the wind turbine from the wind is also equal to the change or loss of kinetic energy of the wind.

$$\Delta KE = P_W = \frac{1}{2}\dot{m}\ (u_0^2 - u_2^2) \qquad (6.4)$$

Now the energy extracted is equal to the energy lost by wind:

$$P_T = P_W$$

$$m\ (u_0 - u_2) \times u_1 = \frac{1}{2}\dot{m}\ (u_0^2 - u_2^2)$$

or

$$u_1 = \frac{u_0 + u_2}{2}$$

The above relation indicates that turbine velocity u_1 is the average of the entrance and exit velocities of stream tube. Putting the value of u_1 in Eq. (6.3), we get

$$P_T = \dot{m}\ (u_0 - u_2)\frac{(u_0 + u_2)}{2}$$

$$= \frac{1}{2} \times \dot{m} \times (u_0^2 - u_2^2) \qquad (6.5)$$

The mass flow ($\dot{m}$) can be given as the product of area, velocity and density. Hence,

$$\dot{m} = A_1 \times u_1 \times \rho$$

$$= A_1 \times \frac{(u_0 + u_2)}{2} \times \rho \qquad (6.6)$$

From Eqs. (6.5) and (6.6), we have

$$P_T = \frac{1}{4} \times A_1 \times \rho \times (u_0^2 - u_2^2)(u_0 + u_2)$$

Now suppose we have interference factor a, which is given by:

$$a = \frac{u_0 - u_1}{u_0}$$

Then $$u_1 = (1 - a) \times u_0$$

Also, $$a = 1 - \frac{u_1}{u_0} = 1 - \frac{u_0 + u_2}{2 \times u_0}$$

$$= \frac{u_0 - u_2}{2 \times u_0}$$

And $$u_2 = (1 - 2a) \times u_0$$

Then we have extracted turbine power as:

$$P_T = \frac{1}{4} \times A_1 \times \rho \times (2 \times a \times u_0)\ [u_0 + (1 - 2a)\ u_0]^2$$

$$= \frac{1}{2} \times A_1\rho \times a \times u_0 \times u_0^2 \times 4\ (1 - a)^2$$

$$= 2\times A_1\rho \times a\ (1 - a)^2 \times u_0^3$$

$$= 4 \times a \times (1 - a)^2 \left[\frac{1}{2}\rho \times A_1 \times u_0^3\right] \qquad (6.7)$$

But wind power is given by:

$$P_W = \frac{1}{2} \times \rho \times A_1 \times u_0^3 \qquad (6.8)$$

From Eqs. (6.7) and (6.8), we have

$$P_T = 4a\ (1 - a)^2 \times P_W$$

$$= C_P \times P_W$$

where C_P is the power coefficient and it is given by

$$C_P = 4a\ (1 - a)^2$$

The power coefficient C_P indicates the portion or fraction of wind power which can be extracted by the wind turbine. Following conditions may result:

(i) When $a = 0$, then $u_1 = u_0$, $u_2 = u_0$ and no power generation takes place.

(ii) When $a = \frac{1}{3}$, then $u_1 = \frac{2}{3} u_0$, $u_2 = \frac{1}{3} u_0$ and maximum power generation takes place.

(iii) When $a = \frac{1}{2}$, then $u_1 = \frac{1}{2} \times u_0$, $u_2 = 0$ and only turbulence occurs at downstream.

(iv) When $a = 1$, then $u_1 = 0$ and it results in the stalling of turbine.

- **What is the condition of maximum output power from a wind turbine? Find its value.**

or

- **Show that a wind turbine cannot extract more than 59.3% wind energy.**

The power output from wind turbine is given as follows:

$$P_T = \frac{1}{4} \times A \times \rho \times (u_0^2 - u_2^2)(u_0 + u_2) \tag{6.9}$$

The power output depends on outlet velocity u_2. Hence, for the maximum power output

$$\frac{dP_T}{du_2} = 0$$

$$-2 \times u_2 (u_0 + u_2) + (u_0^2 - u_2^2) \times 1 = 0$$

$$-2\, u_2 u_0 - 2u_2^2 + u_0^2 - u_2^2 = 0$$

$$3u_2^2 + 2u_2 u_0 - u_0^2 = 0$$

$$3u_2^2 + (3u_2 u_0 - u_2 u_0) - u_0^2 = 0$$

$$3u_2 (u_2 + u_0) - u_0 (u_2 + u_0) = 0$$

$$(u_2 + u_0) + (3u_2 - u_0) = 0$$

$\therefore$ $u_2 = -u_0$, which is impossible

or $$u_2 = \frac{u_0}{3}$$

Hence, putting the value of u_2 in Eq. (6.9), we have

$$P_T = \frac{1}{4}\rho A \times \left[u_0^2 - \left(\frac{u_0}{3}\right)^2\right]\left[u_0 + \frac{u_0}{3}\right]$$

$$= \frac{1}{4}\rho A \times \left(u_0^2 \times \frac{8}{9}\right)\left(\frac{4}{3} \times u_0\right)$$

$$= \frac{8}{27}\rho A u_0^3$$

$$= \frac{16}{27}\left(\frac{1}{2}\rho A u_0^3\right)$$

$$= \frac{16}{27} \times P_W$$

$$= 59.3\% \times P_W$$

The power output of a wind turbine cannot be more than 59.3% of wind energy.

- **Find the maximum power output of a turbine if wind speed u_0 = 8 m/s, air density ρ = 1.2 kg/m^3 and rotor diameter = 60 m.**

$$A = \frac{\pi d^2}{4} = \frac{\pi \times 60^2}{4}$$

$$= 2826 \text{ m}^2$$

$$P_W = \frac{1}{2}\rho A \times u_0^2$$

$$= \frac{1}{2} \times 1.2 \times 2826 \times 8^2$$

$$= 108.52 \text{ kW}$$

$$P_T = \frac{16}{27} \times P_W$$

$$= \frac{16}{27} \times 108.52$$

$$= 64.31 \text{ kW}$$

6.4.4 Axial Thrust on Turbine

- **Derive the expression for maximum axial thrust experienced by a wind turbine and also find the condition for such operation.**

The Betz model of expanding airstream tube is shown in Figure 6.8. In case of no energy extraction and on applying the Bernoulli equation at upstream and downstream of the tube, we have

$$\frac{P_0}{\rho} + g \times z_0 + \frac{u_0^2}{2} = \frac{P_2}{\rho} + gz_2 + \frac{u_2^2}{2}$$

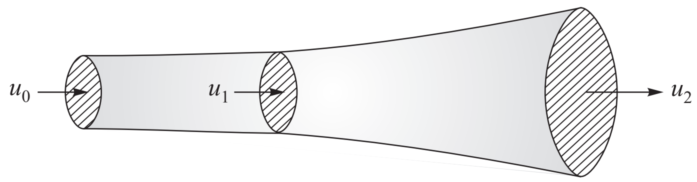


Figure 6.8 Betz model of expanding airstream tube.

Taking $z_0 = z_2$, we have

$$P_0 - P_2 = \Delta P = \frac{(u_0^2 - u_2^2) \times \rho}{2}$$

If $u_2 = 0$, we have

$$\Delta P = \frac{1}{2} \rho \times u_0^2$$

The maximum thrust on the blade is:

$$(F_A)_{max} = \Delta P \times A_1$$

$$= \frac{1}{2} \times A_1 \rho u_0^2$$

When wind turbine is extracting power, the axial thrust is equal to the loss of momentum of the airstream, which is given by:

$$F_A = m \times u_0 - \dot{m} \times u_2 = \dot{m}\,(u_0 - u_2)$$

and

$$\dot{m} = A_1 \times u_1 \times \rho$$

$$= A_1 \times \frac{u_0 + u_2}{2} \times \rho$$

$$\therefore \quad = A_1 \times \rho \times \frac{u_0 + u_2}{2} \times (u_0 - u_2) \quad (6.10)$$

Putting $u_2 = (1 - 2a)\, u_0$ in Eq. (6.10), we get

$$F_A = 4a(1 - a) \left(\frac{1}{2} \times A_1 \, \rho \, u_0^2 \right)$$

$$= C_F \times (F_A)_{max}$$

$$\therefore \quad C_F = 4a(1 - a) = \text{Coefficient of axial thrust}$$

When $a = 0.5$, $C_F = 1$ and the maximum axial thrust occurs. When $a = \frac{1}{3}$ (condition for maximum power output), the axial thrust coefficient $= C_F = 8/9$.

6.4.5 Torque Generated by Wind Turbine

- **What do you understand by torque coefficient? How is it related to power coefficient?**

The maximum energy of wind is given by P_0 and it exerts torque at the blade of wind turbine. If T_{max} is the maximum torque exerted on turbine rotor at the tip of the blade having radius R, we have

$$T_{max} = F_{max} \times R$$

But wind maximum energy $$P_0 = F_{max} \times u_0$$

$$\therefore \quad T_{max} = \frac{P_0}{u_0} \times R \tag{6.11}$$

Now tip speed ratio is

$$\lambda = \frac{\omega \times R}{u_0} \tag{6.12}$$

where ω is the angular velocity of the rotor.

From Eqs. (6.8) and (6.9), we have

$$T_{max} = \frac{P_0 \times \lambda}{\omega} \tag{6.13}$$

For a wind turbine which is producing torque T, less than T_{max} we have

$$T = C_T \times T_{max} \tag{6.14}$$

where C_T is the torque coefficient.

In case wind turbine is producing power P_T, we have

$$P_T = C_P \times P_0 \tag{6.15}$$

From Eqs. (6.13) and (6.14), we have

$$P_T = C_P \times \frac{\omega \times T_{max}}{\lambda} \tag{6.16}$$

From Eqs. (6.14) and (6.16), we have

$$P_T = \frac{C_P \times \omega}{\lambda} \times \frac{T}{C_T}$$

But $$P_T = \omega \times T$$

∴ $$\omega \times T = (\omega \times T) \times \frac{C_P}{C_T} \times \frac{1}{\lambda}$$

or $$C_T = \frac{C_P}{\lambda}$$

The above relation indicates that both C_T and C_P are functions of λ. The wind turbines havings high tip speed ratios will require low starting torque.

6.4.6 Tip Speed Ratio for Maximum Output

- **Explain the variation of output of a wind turbine with tip speed ratio of the rotor.**

A turbine should be designed in such a way that neither of the following conditions is met:

(i) If the blades are provided in excess or blades are rotated fast, this results in a blade moving in the air turbulence created by a proceeding blade.

(ii) If the blades are provided in less numbers or blades are rotated slowly, this results in a large amount of wind passing through the space between two blades without interacting with the blades.

If a wind turbine has "n" numbers of blades and it is rotating with angular velocity ω, the time (t_1) taken for a blade to move into the previously occupied blade's position is given by

$$t_1 = \frac{2}{n \times \omega} \tag{6.17}$$

If x is the length of the wind stream's disturbance created by a blade, the time (t_2) taken for this disturbance to move out is given by

$$t_2 = \frac{x}{u_0} \tag{6.18}$$

The maximum power output by the wind turbine will take place at the blade when we have

$$t_1 = t_2$$

or $$\frac{2}{n \times \omega} = \frac{x}{u_0}$$

or $$\frac{\omega}{u_0} = \frac{2}{n \times x}$$

Multiply with R, that is length of blade, we obtain

$$\frac{\omega \times R}{u_0} = \frac{2R}{n \times x}$$

$$\lambda_0 = \frac{2R}{n \times x}$$

where λ_0 is the tip speed ratio for the maximum output.

In case $x = \frac{R}{2\pi}$, we have

$$\lambda_0 = \frac{4\pi}{n}$$

The maximum power extraction will occur when tip speed ratios are:

(i) $\lambda_0 = \frac{4\pi}{2} = 2\pi$, where $n = 2$

(ii) $\lambda_0 = \frac{4\pi}{4} = \pi$, where $n = 4$

The maximum output is possible when power coefficient $C_P = 0.59$. The relationship between C_P and λ for ideal propeller type rotor and other wind turbines are as shown in the Figure 6.9.

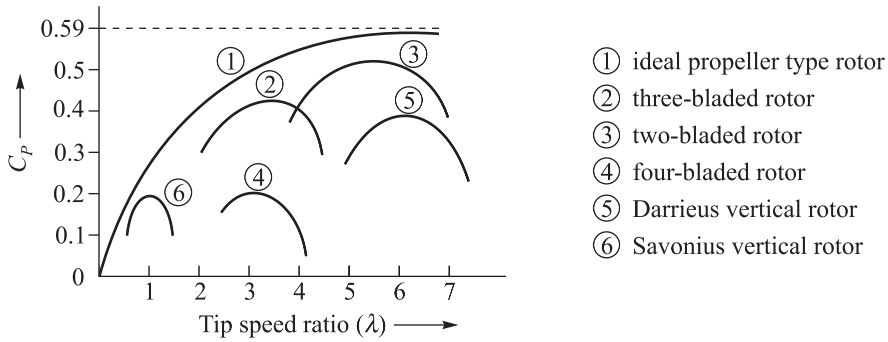


Figure 6.9 Variation of power coefficient with tip speed ratio.

6.4.7 Aerodynamic Considerations

- **Discuss the aerodynamic considerations in windmill design.**

or

- **What parameters should be considered while selecting a windmill?**

When wind moves on an aerofoil, it exerts two types of forces (i) lift force and (ii) drag force. The drag force acts in the direction of wind while lift force acts perpendicular to the direction of wind, trying to lift the aerofoil as shown in Figure 6.10. The relative magnitude of lift and drag forces depends upon the shape of the aerofoil. A streamlined aerofoil has a small drag force and a large lift force. Lift devices are more efficient as they have lower drag forces. The lift forces are created due to higher speed of airstreams moving at the top surface of the airfoils compared to lower speed of airstreams moving at the lower surface of the aerofoils, and so higher static pressure is created at the lower surface of the aerofoils to act upwards.

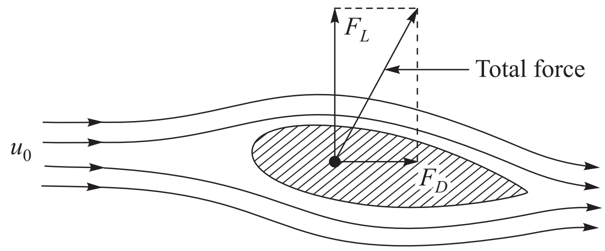


Figure 6.10 Lift and drag forces on an aerofoil.

The design parameters or aerodynamic considerations while designing a windmill are discussed next.

Pitch

The blades of a rotor are curved so that they can deflect the wind to create lift. The created lift force causes the rotor to rotate. To generate the maximum amount of lift, the blades are to be set at an appropriate angle to the wind direction, which is called pitch. The tips of the blades move faster than other points near the axis. Hence, pitch angle (γ) varies along the length of blade. The pitch angle should be large without taking any risk of stalling the rotor. To make the pitch angle large all the way along the blade, it has to be twisted. For rotor rotating fast as in two- or three-bladed windmills, the blades are to be given smaller pitch. Certain rotors are provided a mechanism to control the pitch depending upon the wind conditions. The effect of blade pitch on performance coefficient and tip speed ratio characteristics is as shown in Figure 6.11.

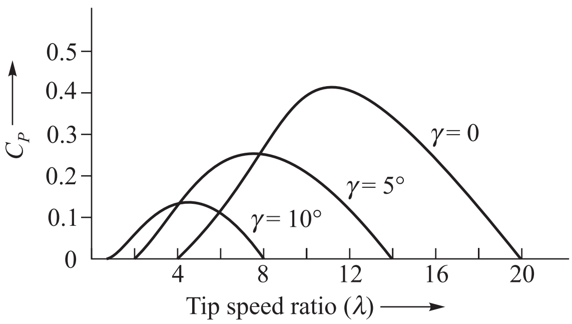


Figure 6.11 Effect of pitch angle on performance coefficient.

Solidity

The greater the solidity of a rotor due to the presence of multiple blades, the slower it needs to intercept the wind with the help of rotation. The windmills with low solidity such as two- or three-bladed rotors have to run rapidly to intercept the wind and to avoid any loss of wind energy through the large gaps existing between the blades.

Tip speed ratio (λ)

Faster rotating windmills have tip speed ratios of more than 1, while slower rotating windmills have tip speed ratios of less than 1. Rotors rotating with the help of drag force have lesser tip speed ratios (tip speed is less than wind speeds). Savonius and Darrieus rotors have low tip speed ratios. On the other hand, two- or three-bladed wind turbines rotate very fast and these have high tip speed ratios ranging from 3 to 10. Multibladed rotors have tip speed ratios between 1 and 2 and these are suitable for only wind pump applications. Each rotor has a certain optimum tip speed ratio at which it can give maximum output.

Performance coefficient

The performance coefficient indicates what fraction of wind energy passing through the rotor is converted into the output power. It depends upon the tip speed ratio and solidity. The range of tip speed ratios for optimum output or performance coefficient with rotors having different solidities is shown in Figure 6.12.

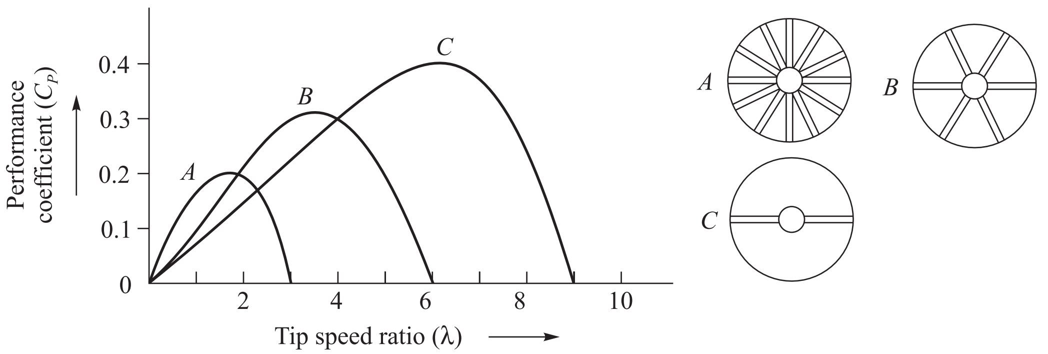


Figure 6.12 Variation of performance with solidity and tip speed ratios.

Torque

Torque is generated by tangential or turning force acting on the blades of a rotor. It depends on solidity and tip ratio of the rotor. High-solidity rotors with low tip speed ratios (as in multibladed rotors) produce much more torque compared to low-solidity rotors as shown in Figure 6.13. The high-speed wind turbines has higher performance coefficient (C_P) but has a low starting torque coefficient (C_T). On other words, high-solidity rotors produce high starting torque, but these have low performance coefficients.

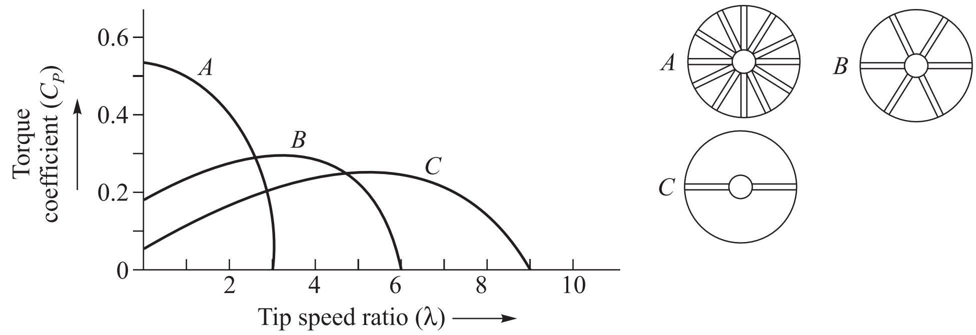


Figure 6.13 Variance of torque coefficient with solidity and tip speed ratios.

Load characteristics

The choice of rotor depends on the load characteristics. The loads requiring high torque (such as for piston pumps) have to be provided with rotors with either high solidity or some arrangement to detach the rotors from the load so that low starting torque windmills can be used. However, windmills used to generate electricity need low torque and high speed, which are met with wind rotors of low solidity and high tip speed ratios. In case of wind pumps, these require three times more torques than what are required for normal working. Hence, these windmills require low wind speeds for running but a gust of higher wind speeds to start them initially. High-speed windmills are unsuitable for running directly any reciprocating pump unless these produce electricity by generators.

6.5 TYPES OF WINDMILLS

- **How can windmills be classified?**

or

- **How wind energy conversion system is classified? Discuss in brief.**

The windmills can be mainly classified as horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). When the axis of rotation is parallel to the airstream, the turbine is called HAWT and when it is perpendicular to the airstream, it is called VAWT. Horizontal axis windmills are the most commonly used machines and these have rotors similar to aircraft rotors. Vertical axis windmills have eggbeater type of rotors.

6.5.1 Horizontal Axis Wind Turbine

- **Describe the working of a wind power system with a neat sketch, including its various components.**

or

- **Describe the working of wind energy conversion system (WECS) with main components.**

or

- **Describe horizontal axis type aerogenerator.**

The constructional details of a three-bladed, horizontal axis wind turbine are shown in Figure 6.14. The components or main subsystems include turbine blades, hub, nacelle, yaw control mechanism, generator and tower.

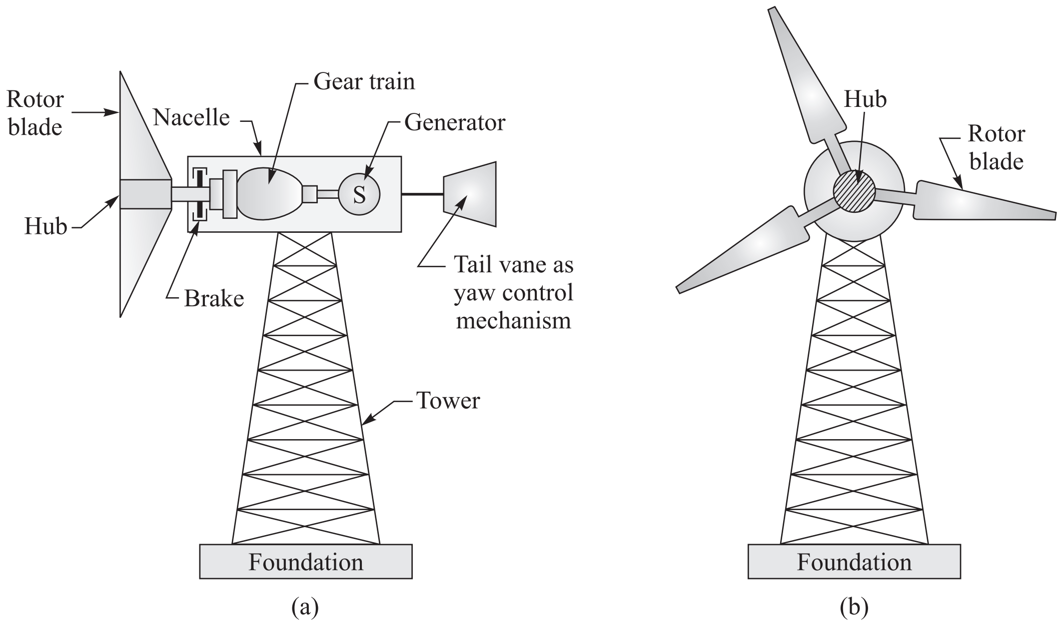


Figure 6.14 Wind turbine (a) Side view of the wind turbine, (b) Front view of the wind turbine.

Turbine blades

Turbine blades have aerofoil type cross section to extract energy from wind. These blades are made of high-density materials such as wood, glass fibre and epoxy composites. The blades are twisted from tip to root to maintain pitch angle. Most of wind turbines have two- or three-blades similar to the propeller of an old aeroplane, but blades of a wind turbine rotates very slowly compared to that of an aeroplane. A two-bladed rotors give much smoother power output compared to three-bladed rotors. A three-bladed rotor generates little more power output (more than 5%), but additional blade incorporation adds to substantial additional weight to the windmill (about 50% extra). A two-bladed rotor is also simpler to be constructed and erected on the ground.

Hub

The central solid portion of a rotor is called hub. It helps in the attachment of all blades and the incorporation of pitch angle control mechanism.

Nacelle

The rotor is attached to nacelle which is mounted at the top of a tower. It houses gearbox, generator, controls and brakes. The purpose of gearbox is to regulate the output rotation from the rotor with the speed of the generator. Electromagnetic brakes are provided for automatic application of brakes if the wind speeds exceed the designed speed.

Yaw control system

The yaw control system is provided to adjust the nacelle around the vertical axis so that rotor blades are always facing the wind stream. In small wind turbine, a tail vane is used as passive yaw control.

Tower

Tower is provided to support nacelle and rotor. The tower height should be sufficient so that enough wind speed can be intercepted by the rotor. For medium- and large-sized wind turbines, the tower is slightly taller than the rotor diameter, while in small sized wind turbines, the tower is much larger than the rotor diameter. There should not be any obstruction in the way of windstream in its approach to the rotor. Tower can be made of materials such as steel or concrete.

Electrical systems

The wind turbines are provided with induction generators to convert mechanical energy into electrical energy. Induction generation has brushless and rugged construction. It is also available at economical cost.

6.5.2 Rotors of HAWT

- **Discuss various designs of rotor and their relative merits and demerits.**

The rotors of HAWT can be (i) single blade rotor, (ii) two blades rotors, (iii) three blades rotors, (iv) Chalk multiblades rotor, (v) multibladed rotor and (vi) Dutch-type rotor as shown in Figure 6.15. The single, two-bladed, three-bladed and chalk multibladed rotors are relatively

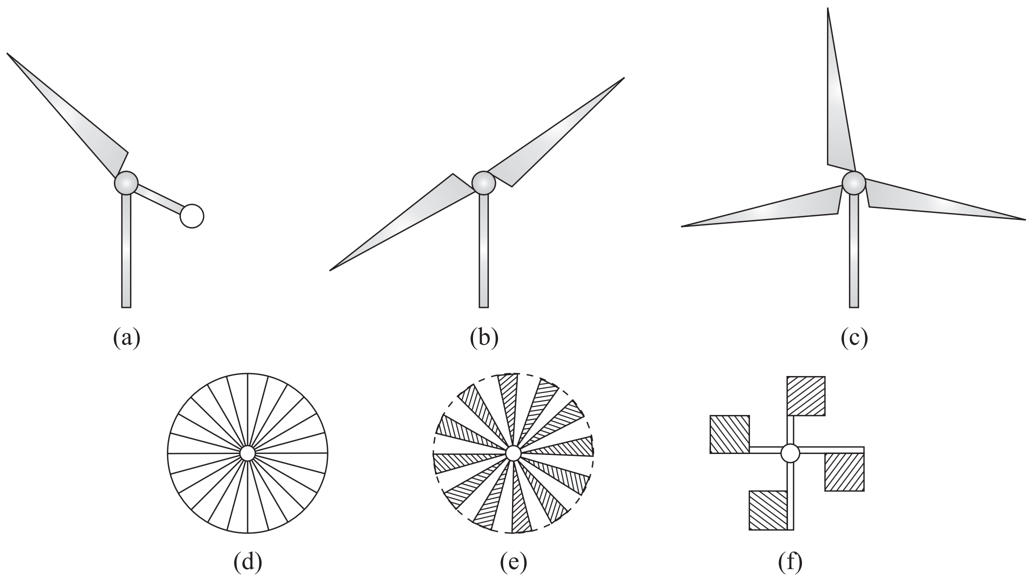


Figure 6.15 Different rotors used for HAWT. (a) Single-bladed rotor, (b) Two-bladed rotor, (c) Three-bladed rotor, (d) Chalk multi-blade rotor, (e) Multi-bladed rotor, (f) Dotch-type rotor.

high-speed machines and these machines are, therefore, suitable for applications such as electric power generation. HAWTs are commonly produced with two- and three-bladed rotors. A single-bladed rotor with balancing counterweight has simple construction and less cost, but it makes more noise during operation. It is used where small power is required. The multibladed and Dutch-type rotors are used where low speeds are required. Hence, these rotors are suitable for applications such as piston pumps where high starting torque is needed. As these rotors have high solidity, these can operate even when slow winds are present.

6.5.3 Vertical Axis Wind Turbine

- **Sketch the diagram of a VAWT and explain the functions of its main components.**

Vertical axis wind turbine has the axis of rotation of its rotor perpendicular to the wind stream. Vertical axis wind turbine is advantageous as (i) it can accept wind from any direction, thereby eliminating the necessity of any yaw control system and (ii) it can have its gearbox and generator system (nacelle) at the ground level, thereby eliminating the necessity of mounting the heavy nacelle (with gearbox and generator) at the top of the tower. These features of VAWT also help in the simpler design and installation of the wind turbine, the easier inspection and maintenance of the wind turbine and reducing the overall cost of the wind turbine.

A VAWT (Darrieus) with all its components is shown in Figure 6.16. The components and subsystems include tower blades and support structure.

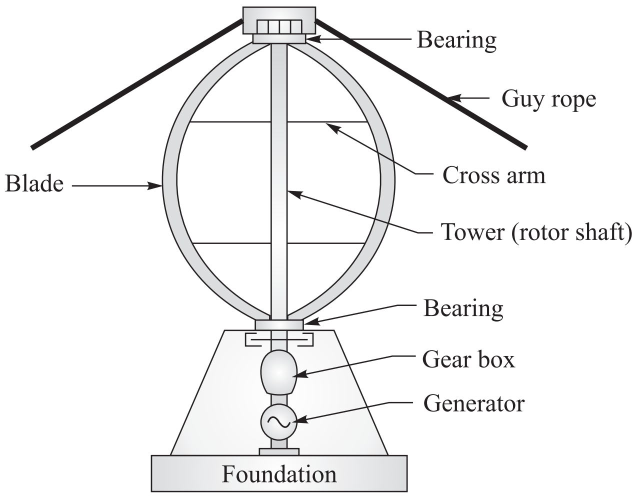


Figure 6.16 Vertical axis wind turbine.

Tower (rotor shaft)

The tower consists of a hollow vertical shaft which can rotate about its vertical axis between its bearings at top and bottom. It is provided with a support structure at the bottom and at the upper end, it is supported by guy ropes. The height of the tower is about 100 m.

Blades

The wind turbine has two or three blades which are thin and curved shaped similar to an "eggbeater". The blades are curved in such a way that minimum bending stresses are produced on rotation due to the centrifugal forces. The blades are designed in such a way that they offer aerofoil type cross section to wind stream. The height of blade is kept 94 m, diameter about 65 m and chord length about 2.4 m.

Support structure

It is provided with blades, gearbox and generator to support the weight of tower.

6.5.4 Rotor of VAWT

- **Explain various designs of blades of VAWTs and their relative features.**

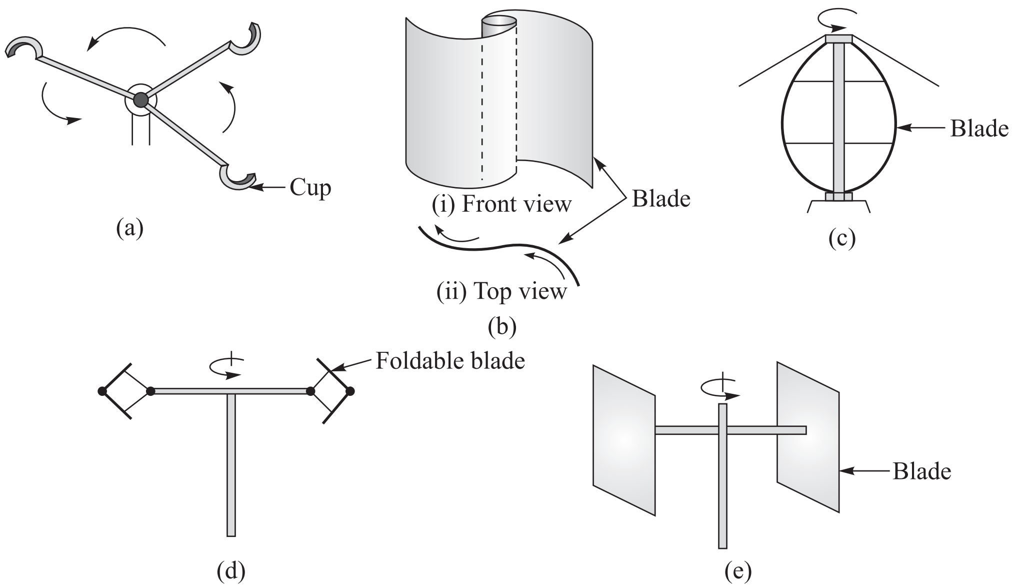


Figure 6.17 Various rotors of VAWT, (a) Cup type rotor, (b) Savonious rotor, (c) Darrieus rotor, (d) Musgrove (H-shaped) rotor, (e) Evans rotor (gryromill).

The VAWTs can have various types of rotors which include Cup type rotor, Savonious rotor, Darrieus rotor, Musgrove rotor and Evans rotor as shown in Figure 6.17. The simplest of all rotors is cup type rotor, which consists of three or four cup type structures attached symmetrically to a vertical shaft. It works on the principle that drag force on a large concave surface is more than that on a convex surface of the cup when wind stream strikes these surfaces, and so the rotor consisting of cups starts rotating. However, such rotors cannot extract enough energy from winds and therefore are not used for power generation. These devices are mainly used for wind speed measuring instruments such as the cup anemometer. The Savonius rotor (S-rotor) is formed with two half-cylinders attached to a vertical axis, but facing in opposite directions. S-rotor can produce high starting torque at low wind speed. It has also low efficiency of conversion of wind energy. As it can extract power even from low-speed winds, it can operate and deliver power throughout the day. Hence, such rotor is used for applications where low power is required, such as in wind pumping. Darrieus rotor consists of two or three curved blades attached to a rotor shaft similar to an eggbeater. It has good power coefficient and is used for large power generation. It also has a large tip speed ratio, thereby developing large bending stresses in the blades due to centrifugal forces formed. The main drawback of this rotor is that it is not self-starting due to lower starting torque developed by it. It has to be run generally by using its electrical generator as motor. The blades also have fixed pitch which cannot be changed. This results in unmanageable output at high wind speeds. Musgrove (H-shaped) rotor has fixed pitch on blades attached to rotor shaft, but the blades are foldable to control power. The Evans rotor has blades which are hinged on a vertical rotor shaft and the blade pitch is varied cyclically during rotation to regulate the power output. It is a self-starting rotor.

6.5.5 Comparison of HAWT and VAWT

- **Compare horizontal and vertical axis windmills.**

or

- **What are the relative features of drag and lift type machines?**

or

- **Discuss advantages of vertical axis windmill over horizontal type.**

The comparison of HAWT and VAWT is shown in Table 6.2.

TABLE 6.2 Comparison of HAWT and VAWT

HAWT	*VAWT*
Axis of rotation is parallel to the airstream	Axis of rotation is perpendicular to the airstream
These are commonly used and almost fully developed	These are under development stage
The rotor has to face wind stream. It is provided with yaw mechanism to keep it facing wind stream	The rotor can accept wind stream from any direction. There is no need of yaw mechanism
Nacelle carrying gear train, controls and generator has to be mounted on top of the tower	Gear train, controls and generator can be located at ground level
Tower has to be strong and designed properly	Tower is simple in construction and installation
Inspection and maintenance of windmill is difficult	Inspection and maintenance of windmill is easy
Costly	Less costly
Less noisy	More noisy
Extract more power from wind	Extract less power from wind
Technology is fully developed	Technology is under development
Less fatigue to parts due to wind action	More fatigue to parts due to wind action
Designed to use lift force	Designed to use drag force
More efficient	Less efficient
Smooth output	Fluctuating output
Produces lower starting torque	Produces high starting torque
Operates properly in moderate wind speeds	Can operate even in low wind speeds
Pitch of blade can be controlled	Pitch of blade cannot be controlled

6.5.6 Savonius Rotor

- **Write the advantages and disadvantages of Savonius rotor.**

Advantages

(i) It has vertical rotating rotor shaft which eliminates the need of any expensive transmission system from the rotor to generator.
(ii) It produces power effectively in slow wind speeds (as low as 8 km/h).
(iii) The generator can be located at ground level which helps in easy maintenance.
(iv) The tower is simple in construction and installation due to lower loads.
(v) The cost of construction and installation is low.
(vi) Yaw and pitch control mechanisms are not required.

Disadvantages

(i) It utilises drag force which results in its lower efficiency.
(ii) Power output is very low.
(iii) The power output is low as the pitch control of the blade is impossible.
(iv) It is unsuitable where tall installation is necessary due to wind conditions.
(v) It has low power to weight ratio.

6.5.7 Darrieus Rotor

- **What are the advantages and disadvantages of Darrieus rotor?**

or

- **What are the arrangements required for starting a Darrieus wind turbine?**

Advantages

(i) The rotor blade can accept the wind from any direction.
(ii) It does not require any yaw control mechanism.
(iii) The blades have constant pitch. There is no need of pitch control mechanism.
(iv) The gear train and generator are mounted at the ground level.
(v) The tower is simple in construction.
(vi) The cost of construction and installation is low.
(vii) It has higher power coefficient and tip speed ratio compared to S-rotor.

Disadvantages

(i) It is not self-starting machine.
(ii) It works on drag force and its efficiency to convert wind energy is low compared to horizontal axis rotors.
(iii) It can have limited height. It cannot utilize high wind speeds available at higher level.
(iv) It cannot be yawed out of the wind; special high torque braking system is required during the occurrence of high wind speeds.

Darrieus wind turbine operates on drag force created on it by wind stream. It also has full directional symmetry to capture wind energy, thereby resulting in presence of zero starting torque. Hence, Darrieus rotor requires some external arrangements for starting. Following are the arrangements for its starting:

(i) S-rotors have directional unsymmetry. Hence, these rotors can be attached at the top and bottom of the shaft of Darrieus rotor to help it start up. However, this method is successful only for small Darrieus rotors.
(ii) The generator can be designed to run as motor so as to start up the wind turbine initially and it can act as generator when the wind turbine picks up speed.
(iii) Its rotor is partly shielded from the windstream in the beginning to behave as unsymmetrical rotor so as to develop starting torque.

6.6 WIND ENERGY STORAGE

- **Explain how the energy produced by a wind turbine can be stored for reuse.**

or

- **Write a short note on wind energy storage.**

Wind energy is an intermittent source of power. There are variations in wind speeds on hourly, daily, monthly, yearly and seasonal basis. Therefore, the output of wind turbine varies according to wind speeds. Wind turbine is also non-operational during the periods of very high and low wind speeds. Hence, wind turbine needs some form of energy storage to meet the varying loads of its customers. The energy can be stored by following storage means:

(i) **Chemical energy.** The power output of wind turbines can be used to charge batteries which can store energy as chemical energy. The stored chemical energy can be converted into electrical energy to serve the varying loads of customers.
(ii) **Thermal energy.** The energy output from wind turbines can be stored by heating water. The water heating can be done either by passing power through a resistance or churning water. The heated water can be used for various purposes.
(iii) **Compressed air.** The energy can be stored as compressed air in a suitable storage tank. The stored compressed air can be utilised when required to drive an air turbine to generate electricity through a directly coupled generator.
(iv) **Electrolysis of water.** The output as electricity is used for electrolysis of water, which produces hydrogen and oxygen gases. These gases can be easily stored and converted into electric energy using fuel cells.
(v) **Pumping water.** The output can be used to pump water which can be stored in a high tank. The water can be used when it is needed for various purposes.
(vi) **Integration to electric grid.** The output of wind turbine is fed into any existing electric grid to store or meet peak demands.

6.7 ENVIRONMENTAL IMPACTS OF WIND TURBINES

- **Comment on the environmental impacts of wind energy.**

or

- **What are the demerits of wind farms?**

The environmental impacts of wind turbines are as follows:

(i) **Emission.** There is no pollution or emission of carbon dioxide during operation of wind turbine. Carbon dioxide emission only takes place during manufacturing and installation of wind turbine, which is also very low. Even energy used to construct and install wind turbine is low, which is also paid back by generating same amount of energy in a period of few months.

(ii) **Bird's life.** The rotating rotors pose a threat to bird's life. It has been reported that a large number of birds are killed every year when they fly into the fast rotating blades unknowningly.

(iii) **Noise.** The rotating blades create noise of high sound level due to movement of blades and churning of air (aerodynamic noise). The noise disturbances caused by a wind turbine are very high and unbearable. This is the reason why the wind turbine is not located close to any inhabited areas.

(iv) **Interference to transmission.** Wind turbine with high tower can interfere with the microwave signals of TV and communication, thereby adversely affecting the quality of radio and TV reception at nearby areas.

(v) **Visual intrusion.** Wind turbines with their high towers are visible over a wide area, thereby disturbing the natural beauty of a site.

(vi) **Safety.** The rotating blades may cause harm and injury when any of these blades may break or get damaged, specially during high wind conditions.

(vii) **Impact on ecosystem.** The wind is produced due to differential heating of the earth surface so that ecosystem is maintained. Hence, large-scale interception and use of wind energy can cause adverse impact on ecosystem.

6.8 RECENT DEVELOPMENT

- **What are the recent developments in the technology of large windmills?**

Large windmills use more sophisticated methods to speed control and provide safety measures specially during high wind speeds. These recently developed windmills have following features:

(i) **Yaw and tilt control.** The control is achieved by shifting the rotor axis out of wind direction by yaw control and by tilting the rotor plane with respect to normal plane when wind speeds are high enough to damage the machine.

(ii) **Pitch control.** The pitch of rotor blades can be regulated by a servo system to generate the maximum output. Large machines use pitch control to maintain constant turbine speed.

(iii) **Stall control.** The blades can be shifted to a position in which high winds cannot damage the machines.

(iv) **Fixed blades (constant pitch).** The twist and thickness of the blade are so designed and provided along blade length that the speed is maintained as constant as possible.

(v) **Eddy current braking system.** It is provided to control speeds so that wind mills can perform at high wind conditions.

(vi) **Variable speed drive system.** The system allows rotor speed to vary optimally with the wind speeds to capture maximum power. The variable speed drive helps in capturing more power compared to the fixed speed drive system.

- **What are the major factors that have led to the acceleration and development of the wind power?**

The major factors are as follows:

(i) **Improved materials.** Improved materials such as high-strength fibre composites are available that enable the production of large-sized rotor blades at low cost.
(ii) **Power electronics.** The power electronics to regulate and control the functioning of wind turbine are available at low cost.
(iii) **Variable speed drive system.** It helps wind turbines to capture maximum energy at various wind speeds.
(iv) **Bigger turbines.** Larger wind turbines are being produced to generate significant power output at an economical rate.
(v) **Short energy payback.** The wind turbine has shorter energy payback period of about 1 year.
(vi) **Improved plant.** Improved plant operations have ensured the supply of power from the wind turbine plant as high as 95%.
(vii) **More expertise.** The field trials and experiences have helped in the improved development, installation and operation of wind turbine plants.
(viii) **Renewable resource.** It is the fastest growing energy source among all renewable energy resources. It is now competing with conventional power sources.

- **How energy extracted from wind by turbine can be increased?**

The amount of energy extracted from wind power by a wind turbine can be increased by providing the following:

- Pitch control
- Yaw control
- Large size blades
- Variable speed drive
- Tilt control of blades
- Stall control by shifting of blades
- Eddy current bracking system to maintain speed
- Power electronics.

6.9 WIND ENERGY PROGRAMME IN INDIA

- **Discuss the prospects and status of wind energy in India.**

or

- **What do you know about Indian wind power programme?**

or

- **Write briefly about availability of wind energy in India.**

The wind energy potential in India is estimated to be about 2.5×10^4 MW. India is now the 5th country in the world having the largest wind power installed capacity. The installed capacity is now above 1870 MW.

Wind energy programme in India was started during 1983–1984 and has been implemented and managed by MNES. Many wind power projects are making their presence felt, with almost all new wind power projects coming up in the private sector. The role of government sector is that of a catalyst, providing technical and financial assistance. Nationwide wind mapping and wind monitoring activities are also undertaken to measure wind speeds at poteritial sites in various states. The assessment has enabled to identify about 53 sites suitable for wind power farming. The government has also started wind energy demonstration programme in which installation of wind pumps, wind battery chargers, stand-alone wind electric generators and wind farms has been undertaken to demonstrate the wind turbine technology. Over 3000 wind pumps have been installed. Over 120 wind battery chargers from 50 to 4000 W capacity and stand-alone generators of capacities ranging from 10 to 25 kW, with total capacity of 175 kW, have been installed. Wind farms of about 80 MW have been installed in various states. The government aims to generate about 7,000 MW from winds by 2012. A wind–diesel hybird project is under implementation at Sagar Island in West Bengal. Similar Projects are being prepared for islands of Lakshadweep and Andaman and Nicobar. About 21 Indian firms have tied up with foreign collaborators for joint venture to produce and install wind turbines. Several state governments have agreed to purchase power generated by the private sector. The central and state governments are offering a number of economic incentives such as subsides, land allotment, tax benefits and free imports to give a boost to the wind energy generation.

CHAPTER 7

Electrochemical Effects and Fuel Cells

7.1 INTRODUCTION

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

7.2 FUEL AND OXIDANT

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

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

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

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

The reduction reactions are as follows:

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

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

• Explain the combustion reaction process.

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

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

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

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

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

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

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

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

The reaction at anode electrode is as follows:

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

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

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

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

or

• List the fuels used in fuel cells.

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

TABLE 7.1 Fuel and oxidant

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

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

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

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

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

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

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

TABLE 7.3 Differences between fuel cell and primary battery

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

7.2.1 Primary and Secondary Fuel Cells

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

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

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

7.3 FUEL CELL

7.3.1 Principle of Fuel Cell

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

or

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

or

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

or

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

or

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

Principle of fuel cell

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

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

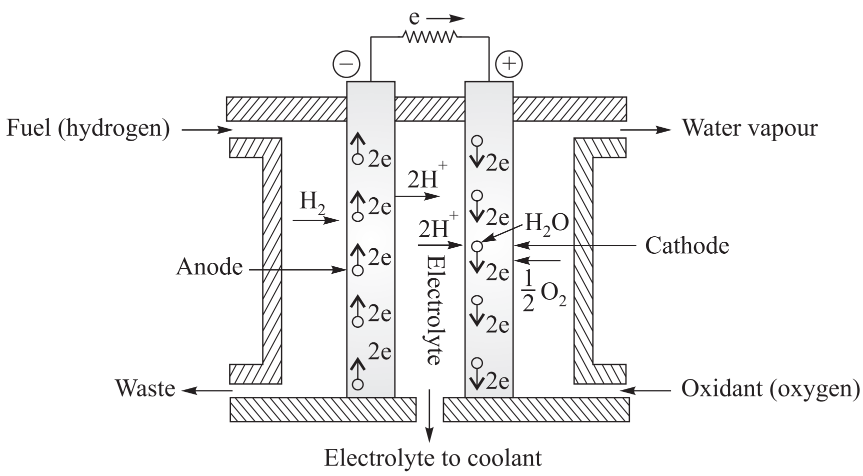


Figure 7.1 A hydrogen–oxygen or phosphoric acid and fuel cell.

(i) Anode

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

(ii) Cathode

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

(iii) Electrolyte

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

7.3.2 Efficiency of Fuel Cell

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

or

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

or

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

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

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

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

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

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

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

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

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

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

But Gibbs free energy is given by the following equation:

$$G = H - TS$$

On differentiation, we get

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

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

$\therefore$ $$\Delta G = \Delta H - T \cdot \Delta S \qquad (7.2)$$

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

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

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

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

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

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

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

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

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

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

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

In case of hydrogen–oxygen fuel cell we have

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

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

Putting these values in the efficiency relation, we obtain

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

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

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

The reaction in the fuel cell is as follows:

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

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

Now electromotive force of fuel cell is

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

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

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

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

  The cell operates at 25°C. Assume

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

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

The reaction is as follows:

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

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

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

$$= 83\%$$

Electrical work output per mole is given by

$$\Delta W = nFE$$

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

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

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

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

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

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

Heat transfer to surrounding is given by

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

7.3.3 Types of Fuel Cells

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

or

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

or

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

or

- **How are fuel cells classified?**

or

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

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

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

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

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

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

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

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

Phosphoric acid or hydrogen–oxygen fuel cell

It includes the following (Figure 7.2):

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

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

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

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

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

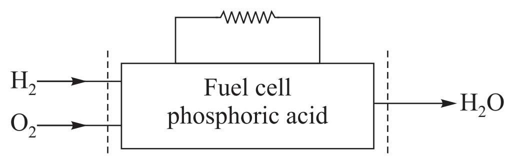


Figure 7.2 A hydrogen–oxygen or phosphoric acid fuel cell.

Alkaline fuel cell

It includes the following (Figure 7.3):

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

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

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

(vi) **Output:** 1.23 V at 90°C

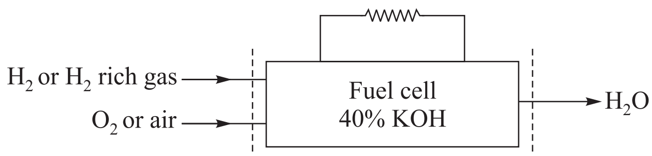


Figure 7.3 Alkaline fuel cell.

Polymer electrolyte or proton exchange membrane fuel cell

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

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

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

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

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

(vi) **Output:** 1.23 V at 25°C.

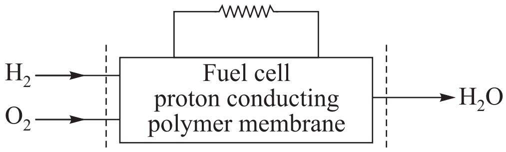


Figure 7.4 Polymer electrolyte membrance fuel cell or proton exchange membrane fuel cell.

Molten carbonate fuel cell

The cell includes the following (Figure 7.5):

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

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

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

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

(vi) **Output:** 1 V at 700°C

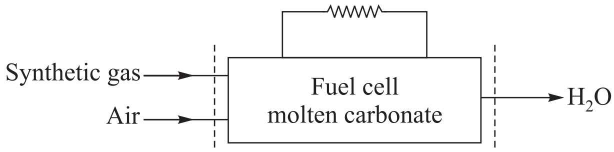


Figure 7.5 Molten carbonate fuel cell.

Solid oxide fuel cell

It includes the following (Figure 7.6):

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

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

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

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

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

(vi) **Output:** 1 V at 800–1000°C

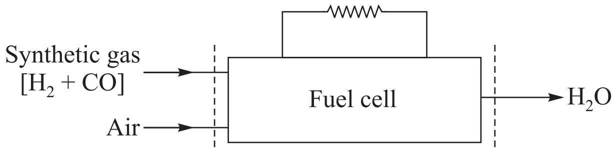


Figure 7.6 Solid oxide fuel cell.

Regenerative cell

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

7.3.4 Polymer Electrolyte Membrane Fuel Cell

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

or

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

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

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

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

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

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

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

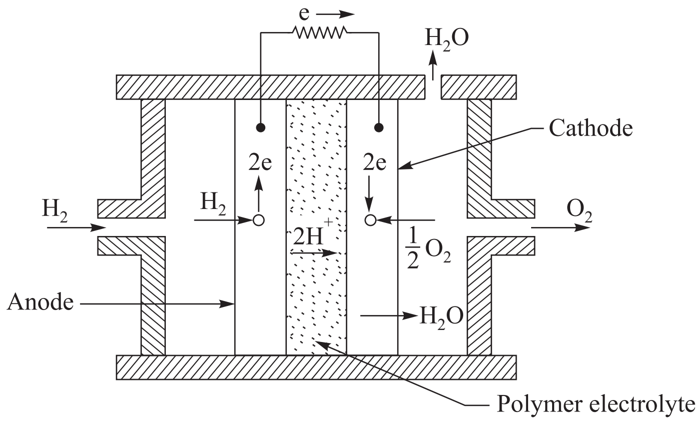


Figure 7.7 Polymer electrolyte or photon exchange membrane fuel cell.

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

7.3.5 Alkaline Fuel Cell

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

or

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

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

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

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

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

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

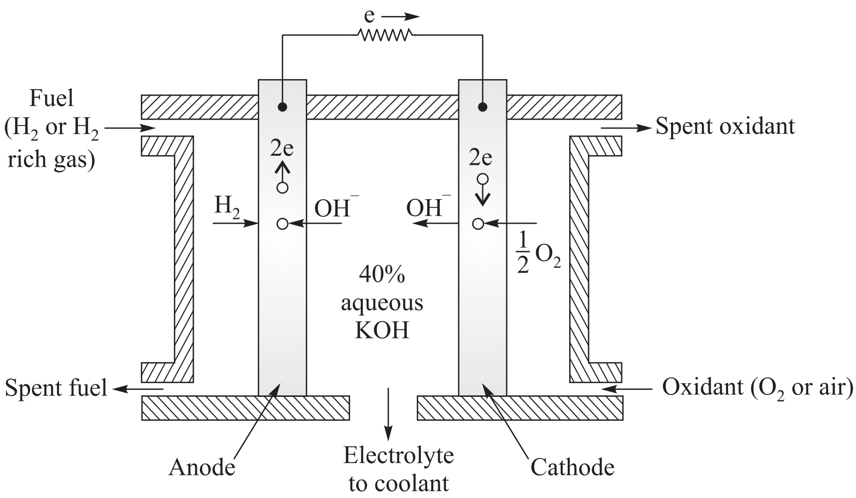


Figure 7.8 Alkaline fuel cell.

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

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

7.3.6 Molten Carbonate Fuel Cell

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

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

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

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

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

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

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

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

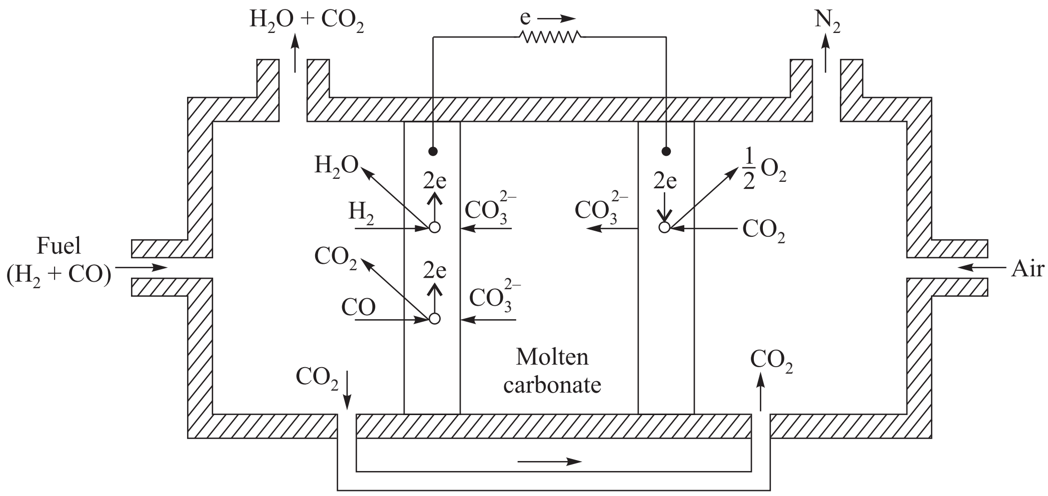


Figure 7.9 Molten carbonate fuel cell.

7.3.7 Solid Oxide or Ceramics Fuel Cell

- **Describe solid oxide fuel cell.**

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

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

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

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

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

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

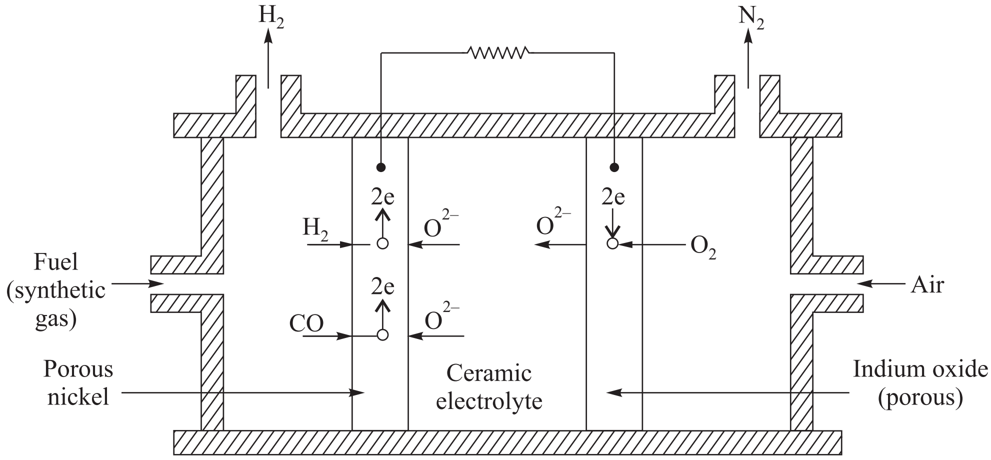


Figure 7.10 Sodium oxide fuel cell.

7.3.8 Regenerative Fuel Cell

- **Describe regenerative fuel cells.**

or

- **Write briefly on reversible cell.**

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

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

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

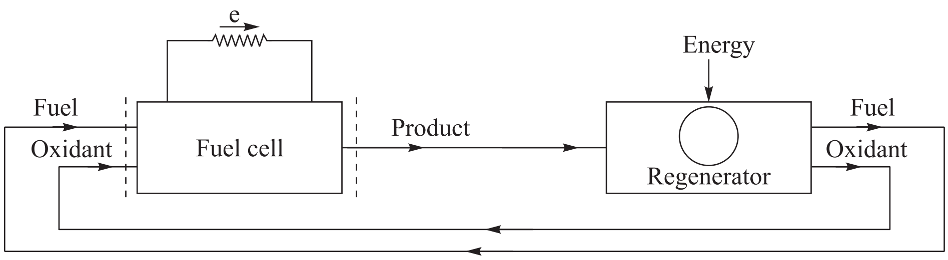


Figure 7.11 Regenerative fuel cell.

7.3.9 Performance Limiting Factors of Fuel Cell

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

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

(i) reactivity (ii) invariance

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

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

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

7.3.10 Losses of a Fuel Cell

• Explain briefly the losses of a fuel cell.

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

7.3.11 Advantages and Limitations of a Fuel Cell

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

or

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

The advantages of a fuel cell are as follows:

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

Limitations of a fuel cell are as follows:

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

7.3.12 Application of a Fuel Cell

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

The applications of a fuel cell are as follows:

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

CHAPTER 8

HYDROGEN ENERGY

8.1 INTRODUCTION

Hydrogen is a non-polluting and easily transportable fuel. Hydrogen does not produce pollutants on combustion unlike conventional fuels. The gas can be easily transported by rail or road to long distances without much loss or cost. It can be easily converted into power using IC engines or fuel cells at consuming points. It can be easily produced from fossil fuels or electrolysis of water. These are the reason why hydrogen gas is considered the ideal fuel for the future.

8.2 HYDROGEN AS A SOURCE OF RENEWABLE ENERGY

- **What are the properties of hydrogen?**

or

- **What are various basic factors considered in the introduction of hydrogen as an energy source?**

or

- **Why hydrogen is considered as a secondary energy source?**

Hydrogen is considered an ideal fuel for future as it has the potential to be used as fuel for running cars and rockets, in meeting the energy needs of buildings and generating the electricity to meet the needs of industry. A hydrogen economy is considered to solve some of the negative effects created while using hydrocarbon fuels owing to the release of carbon during their combustion. Hydrogen is an environmentally friendly source of energy, specially when used in transportation and other applications, because it does not release any pollutant. Free hydrogen does not occur naturally in nature. It has to be generated from some other energy sources. Hence, it cannot be classified as a primary source of energy. Hydrogen is always obtained using some primary source and it is, therefore a secondary source. Hydrogen is a secondary energy carrier just as electricity. As a secondary source of energy, hydrogen is used for the purpose of transportation and storage of primary energy when generated in excess. The primary energy can be a solar or nuclear source which may be harnessed at any remote location. This primary energy can be converted into secondary energy such as hydrogen and the hydrogen can be easily transported to load point where hydrogen can be converted into electricity by fuel cells or into heat by combustion in air.

Hydrogen has the following properties which make it an attractive alternative energy source:

(i) It is a light gas. It has a low density which is one-fourth of that of air and one-ninth of that of natural gas.
(ii) It liquefies at a very low temperature (–253°C).
(iii) The specific energy of hydrogen is superior to gasoline on mass basis, but it is inferior on volume basis. The heating value for hydrogen is 120 MJ/kg, while it is 44 MJ/kg for gasoline.
(iv) It has flame speed during burning which is faster than that of natural gas.
(v) It needs lower amount of heat energy to initiate combustion compared to that of natural gas.
(vi) If can form a combustible mixture with air, with the ratio of 18 to 59%. The mixture can be used for combustion in an IC engine. Hence, the adjustment of air–fuel ratio for IC engine is less critical in case of hydrogen compared to gasoline.
(vii) It produces water vapour on combustion. Hence, it is pollution free.

The other features which make hydrogen an ideal source of renewable energy are as follow:

(i) Primary energy resources can be easily stored after conversion as hydrogen.
(ii) It can be economically and technically stored so that it can be used when required.
(iii) It can be easily converted into heat on combustion or electricity by using fuel cell.
(iv) It can be easily transported to long distances through piping system or some other transportation means. Transportation cost of hydrogen is lesser than the cost of transmission of electricity.
(v) Its use is pollution free.

8.3 PRODUCTION OF HYDROGEN

- **Discuss the production of hydrogen.**

or

- **Discuss various methods of production of hydrogen for use as an energy carrier.**

The various methods of production of hydrogen include electrolysis of water, thermochemical or steam reforming of methane, thermal decomposition or thermolysis of water and biophotolysis.

Electrolysis of water

It is the simplest method of hydrogen production. The method uses an electrolytic which consist of two electrodes immersed in an aqueous conducting solution called electrolyte as shown in Figure 8.1. When a direct current is passed through the cell, it decomposes water

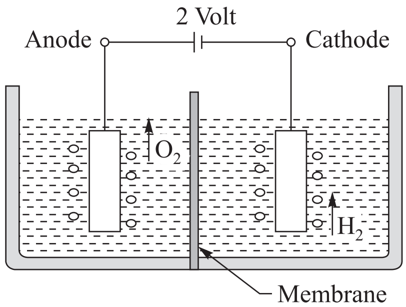


Figure 8.1 Electrolysis of water.

into hydrogen and oxygen. Oxygen is formed at anode while hydrogen is formed at cathode. Metal or carbon plates are used as electrodes. The aqueous KOH solution is used as the electrolyte. A decomposition voltage of 2 V is applied. The chemical reactions of decomposition of water are as follows:

$$4\ H_2O + 4\bar{e} \rightarrow 2H_2 \uparrow + 4OH\ \text{(cathode)}$$

$$4\ OH^- \rightarrow O_2 \uparrow + 2H_2O + 4\bar{e}\ \ \text{(anode)}$$

Thermochemical method

This method consists of steam reforming of natural gas to produce hydrogen. It is the most efficient, cost-effective and commercialised technology available. The natural gas consisting of methane and carbon monoxide is reformed with the help of steam at 900°C to produce a mixture of H_2 and CO_2. CO_2 is removed at the later stage by scrubbing process to get hydrogen. The cost of production of H_2 by this method is very much same to what it costs to produce electricity using natural gas. The reactions of reforming of natural gas with steam are as follows:

$$CH_4 + 2H_2O = CO_2 + H_2$$

$$CO + H_2O = CO_2 + H_2$$

Thermolysis of water

It is the process of producing hydrogen by splitting water directly using heat energy. The splitting of water is similar to electrolysis in which electricity is used for splitting and this is the reason why this splitting is called thermolysis. The thermolysis requires a high temperature of about 2500°C. To carry out thermolysis at the lower temperature of about 850°C, the process is carried out in different stages using chemical materials which are recovered on completion of the cycle.

Biophotolysis

The method uses the ability of plants such algae to generate hydrogen gas when these plants are exposed to water and sunlight. The hydrogen gas can be produced by this method at a low cost. Since this process is essentially a decomposition of water using photons of solar energy in the presence of biological catalysts of plants, the reaction is called biophotolysis of water.

8.4 STORAGE OF HYDROGEN

- **What are the various methods of hydrogen storage?**

Hydrogen can be stored in the following forms:

- Hydrogen gaseous form
- Hydrogen liquid form
- Metallic hydrides form
- Chemical hydrides form

Hydrogen gaseous form of storage

As hydrogen has lower density compared to natural gas, it requires 3.6 times the volume occupied by natural gas to store the same mass of gas at the same pressure. However, this drawback is compensated as hydrogen can be converted to other forms of energy at the desired location more efficiently compared to natural gas. The hydrogen can be stored in strong steel tanks or cylinders like natural gas, but storage pressure is kept high in the range of 350–750 atm so that sufficient mass of gas can be stored. This method is suitable where a small amount of hydrogen is required. Large amount of hydrogen is generally stored in the underground facilities.

Hydrogen liquid form of storage

Hydrogen can be stored in the liquid form as liquid takes less storage space. However, storage space in liquid form requires cryogenic or temperature lower than 20 K (–253°C). This low temperature has to be maintained for the complete storage duration, which makes this type of storage a costly preposition.

Metallic hydrides form of storage

Hydrogen chemically joins with certain metals and forms hydrides. When hydrides are heated, the hydrogen gas can be liberated. The pressure of gas released depends on temperature and it remains constant at a certain temperature. The metallic alloys used for forming hydrides are lanthanum nickel, iron titanium and magnesium nickel.

The reactions forming metallic hydrides with hydrogen are as follow:

$$La\ Ni_5 + 3H_2 \rightleftharpoons (La\ Ni_5)\ H_6 + heat$$

$$Fe\ Ti + H_2 \rightleftharpoons (Fe\ Ti)\ H_2 + heat$$

$$Mg_2\ Ne + 2H_2 \rightleftharpoons (Mg_2\ Ni)\ H_4 + heat$$

Owing to the heavy weight of all metallic alloys, hydrides storage is unsuitable to be used for running of vehicles. Metallic hydride storage is desirable when metal alloys forming hydrides is (i) inexpensive, (ii) hydrides is able to contain a large amount of hydrogen, (iii) storage of hydrogen in metallic alloy can be done at the room temperature and (iv) significant pressure of liberated gas is possible at the room temperature.

Chemical hydride form of storage

In chemical hydride method, chemical compounds are used to form hydrides in alkaline solution. Chemical hydride process is a safer method compared to metallic hydride from of storage. It is also a more volumetrically efficient storage method.

8.4.1 Advances in Storage of Hydrogen

- **Discuss the advances in the technology of hydrogen storage.**

Hydrogen is considered a promising alternative to fossil fuels as it has clean combustion and does not spew greenhouse gases and harmful pollutants like hydrocarbon-based fuels on combustion. Water is the product of hydrogen combustion. Compared to gasoline, hydrogen is lightweight. It can provide a higher energy density and is readily available. But hydrogen is unsafe and it cannot be stored at high densities. The hydrogen storage technology has lagged behind other clean energy fuels.

In recent years, hydrogen storage has improved by locking hydrogen into solids to achieve large packing of gas into a smaller volume. It has been found that most solids can absorb only a small amount of hydrogen and these solids requires extreme heating to liberate the gas. A new composite consisting of nanoparticles of magnesium metal sprinkled through a matrix of polymethyl methacrylate has been reported to be developed. This nanocomposite can readily absorb and release hydrogen gas at moderate temperature.

It is reported that aluminium hydride (AlH_3) has been developed which has a high capacity to store hydrogen. It is a cost-effective material for hydrogen storage which also allows repeated release and recharge of hydrogen gas.

It is reported that a structure of new material has been developed which can store a relatively large quantity of hydrogen gas within its crystal structure for later release. The material has improved ion mobility. The material consists of a mixture of lithium amide and lightweight metal hydride having calcium layer in between through which lithium ions can travel rapidly.

8.4.2 Hydrogen Powered Vehicles and Storage

- **How hydrogen energy can be used for air and surface transport?**

or

- **Write briefly about practical hydrogen powered vehicles.**

Hydrogen is an explosive gas and scientists are trying to develop a safe and practical way of storing it so that hydrogen powered vehicles may become an reality. Researches have developed ways to use “carbon nanotubes” (CNTs) to store hydrogen which can be liberated and used by fuel cells provided in the vehicles. The vehicles can run using electric power generated by fuel cells with the help of hydrogen. Scientists hope to use carbon nanotubes as miniature storage tanks to store hydrogen. The stored gas can be used for running the vehicles as fuel cells can convert hydrogen into electric power. The hydrogen storage system consists of parallel graphite sheets (one-atom-thick carbon layer) with added lithium ions to increase the storage capacity. The storage capacity is 41 g of H_2 per litre as against the specified target by Department of Energy (DOE) of 45 g per litre.

It is also reported that a sponge-like nanomaterial with a record high surface area for holding hydrogen gas has been developed. An ounce of this material has the approximate surface area of a football field and this large surface area helps in the storage of gas.

It is also reported that efforts are being made to use silicon nanotubes instead of carbon nanotubes which are more efficient in storing hydrogen gas.

It is also reported that ammonia borane as a chemical hydride for storing hydrogen has been developed. Ammonia borane storage is attractive as it can store hydrogen up to 20% of its weight, which can help hydrogen-fuelled vehicles to cover more than 300 miles on a single tank. The only drawback is that no efficient method to recycle ammonia borane has been developed.

Liquid hydrogen is used in air transportation as it is possible to provide certain arrangement in it to keep the gas in liquid form, that is, highly insulated storage cylinders with cooling devices.

8.4.3 Cost of Hydrogen Storage

- **Discuss the cost of hydrogen storage.**

The cost of hydrogen storage may include the following:

(i) The compression cost of hydrogen gas to high pressure
(ii) The compression and liquefaction cost of hydrogen
(iii) The cost of container to store the gas
(iv) The cost of maintaining low temperature in the storage of liquid hydrogen
(v) The cost of transportation of gas cylinders
(vi) The weight of hydrogen tank increase the weight of vehicle, thereby increasing specific fuel consumption when vehicle is running.

8.4.4 Transportation or Delivery of Hydrogen

- **How is hydrogen transported?**

The hydrogen gas can be transported or delivered by gas tanks and cylinders or by using pipeline. Gas cylinders and tanks can be loaded onto trucks or rail cars for transportation. When demand is more, pipeline is economical. When distance is short, that is, about 300 km, the gas is transported using high pressure cylinders. For very long transportation, the gas is transported in liquid form in superinsulated cryogenic tankers on road or rail. Hydrogen can also be transported as metal hydride. However, metal hydrides suffer from lower gas absorption in comparison to their weights.

8.4.5 Hydrogen as Fuel and Safety Issues

- **Discuss safety precaution of hydrogen as fuel.**

or

- **Discuss safety issues related to the use of hydrogen.**

As hydrogen is a highly inflammable gas, it should be handled carefully. Hydrogen can be dangerous if it leaks during storage or transportation. It may pose a risk of fire or explosion in case any leakage occurs. Hydrogen can escape and spread about three times faster than natural gas from a leak of a given size. Hence, the leaked gas can form rapidly a flammable mixture in the air in a closed space. Hydrogen can also disperse or spread faster in air owing its lower density and it needs lower heat or weak spark for ignition to take place. The risk of flammability of hydrogen is four times higher than that of natural gas. It is also difficult to detect hydrogen when it leaks as its flame is invisible. Any leakage from liquid hydrogen can also create another risk of cold burns. Liquid hydrogen cannot be filled in any cylinder unless air is completely removed from it. This is done to avoid the formation of any inflammable mixture of hydrogen and air in the cylinder.

When hydrogen is used as fuel for vehicles, safety has to be ensured when vehicles are inoperative or parked, in normal operation and in collision. In inoperative or parking state, the fuel tank carries major bulk of hydrogen and it is a source of explosion. Similarly, in collision, hydrogen fuel tank can pose greatest risk of explosion. Any leakage of hydrogen gas from pipeline connecting fuel tank to the engine may also cause fire or explosion when in operation.

The safety precautions to be taken while using hydrogen as fuel are as follow:

(i) Proper system design of fuel tank and pipeline to avoid any leakage
(ii) Ensuring leak detection by smell which can be made possible by adding an odorant to the hydrogen fuel
(iii) Ensuring prevention of ignition of escaped hydrogen gas. This is made possible by automatic disconnection of battery on collision so that no ignition spark can take place
(iv) Installing fire detection, alarming and fire extinguishing system.

8.4.6 Conversion of Hydrogen

- **Discuss various conversion technologies of hydrogen to useful application.**

Hydrogen can be converted into some useful form of energy in many ways. Hydrogen can be used (i) to fuel IC engine similarly to gasoline or natural gas to obtain mechanical or electrical energy, (ii) in fuel cells to obtain electrical energy, (iii) in gas turbines to obtain mechanical energy, (iv) in boilers for steam generation to run steam turbines or mechanical work, (v) in catalytic combustion and (vi) in running vehicle using metal hydride technology.

IC engine operating with hydrogen has high efficiency and it produces lesser pollutants compared to gasoline, diesel and natural gas. A hydrogen engine can also operate on a wide range of lean or high mixtures of fuel. However, hydrogen engine can give lesser power output compared to conventional fuel engines. In gas turbines, hydrogen can be used instead of conventional fuels. Hydrogen turbines do not have any problem of corrosion of blades. Hydrogen turbines have better efficiencies and lesser pollution problems. In space craft and rockets, hydrogen in liquid form mainly used as fuel as it is light. Steam generators using hydrogen can have high efficiency of about 100%. Combustion of hydrogen in oxygen produces pure steam with temperature of 3000°C. It is also possible to burn hydrogen in oxygen at lower temperatures up to 500°C using certain catalysts. This principle is used while designing catalytic burners and heaters for cooking appliances. Direct generation of electric power is possible using hydrogen as fuel in a fuel cell. Metallic hydrides are formed by hydrogen when it reacts with certain metal alloys. Metallic hydrides can be used as fuel tanks on transports to run vehicles. Metallic hydrides can also be used to supply pure hydrogen for hydrogenation of vegetable oils.

8.4.7 Applications of Hydrogen

- **What are the applications of hydrogen?**

The applications of hydrogen are as follows:

(i) Hydrogen is used as fuel in various types of fuel cells to generate electric power.
(ii) Hydrogen is used as aviation fuel as it has high energy density.
(iii) Hydrogen is used in catalytic combustion, thereby replacing LPG for domestic cooking.
(iv) Hydrogen can be used as fuel in running vehicles as it has lesser pollutants on combustion.
(v) Hydrogen can be used as steam generator as it gives pure water on combustion.
(vi) Hydrogen is used for cooling of large electrical generators and motors.
(vii) Hydrogen is used for hydrogenation of vegetable oils.
(viii) Hydrogen is used for manufacturing ammonia.
(ix) Hydrogen is also used for manufacturing synthetic methanol and urea (ammonium nitrate).
(x) Hydrogen is used for manufacturing tungsten filaments of lamps.
(xi) Hydrogen has a great potential to be used as intermediate means either to store energy or to transport energy to long distances.

CHAPTER 9

Thermoelectric Systems for Direct Energy Conversion

9.1 INTRODUCTION

Thermoelectric, magnetohydrodynamic and thermionic systems help in direct conversion of thermal energy into electrical energy without need of any mechanical device. These systems do not have any moving parts. At the atomic scale, an applied temperature gradient causes charge carriers in the material to diffuse from hot side to cold side, thereby inducing a thermal current.

9.2 IMPORTANT PHYSICAL EFFECTS

- **Explain Seeback, Peltier and Thomson effects in relation to thermoelectric conversion.**

or

- **Discuss Peltier effect, Seeback effect and Thomson effect.**

The term "thermoelectric effect" encompasses three separately identified effects, namely, Seeback effect, Peltier effect and Thomson effect.

Seeback effect

It is the basic principle behind thermoelectric power generation. It states that whenever there exists a temperature difference between two junctions in a loop made of two dissimilar conductors, the electromotive force (emf) is produced in the loop. This type of loop is called a thermocouple. A thermocouple formed with *p*-type and *n*-type semiconductors can produce a fairly large emf. A thermocouple formed with *p*-type and *n*-type semiconductors is shown in Figure 9.1. The current flow is always in the direction of heat flow in *n*-type semiconductor. The amount of emf produced is always proportional to the temperature difference between the two junctions of the thermocouple. The emf produced can be given as follows:

$$E = \alpha + \Delta T$$

where α is the Seeback coefficient and ΔT is the temperature difference between the two junctions.

By measuring E, it is possible to determine the unknown temperature of hot body in reference to known temperature of cold body. This phenomenon can also be used to produce electrical energy directly from the heat of combustion and such device is called thermoelectric generator. The electric power of thermoelectric generator is given by

$$P \propto Q_{\text{input}} - Q_{\text{rejected}} = i^2 \times R$$

The thermal efficiency of thermoelectric generator is very low.

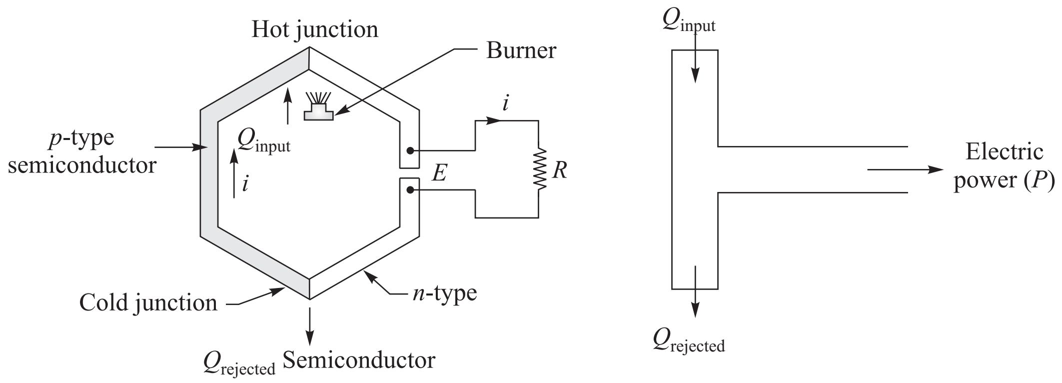


Figure 9.1 Seeback effect and the principle of thermoelectric.

Peltier effect

The Peltier effect is a temperature difference created by applying a voltage between two electrodes connected to *n*-type and *p*-type semiconductor materials. This phenomenon can be useful when it is necessary to transfer heat from one medium to another on a small scale. In a Peltier device, the electrodes are made of a metal having excellent conductivity. The semiconductor materials between the electrodes create two junctions with semiconductor materials having flow of electrons and holes with temperature gradient as shown in Figure 9.2. The movement of charge carriers creates a thermocouple voltage acting on the electrodes. This voltage difference drives current through the semiconductors, and so thermal energy starts flowing in the direction of the charge carriers. The Peltier devices can be used for thermoelectric cooling in electronic equipment and computers as other more conventional cooling methods are impractical in these devices.

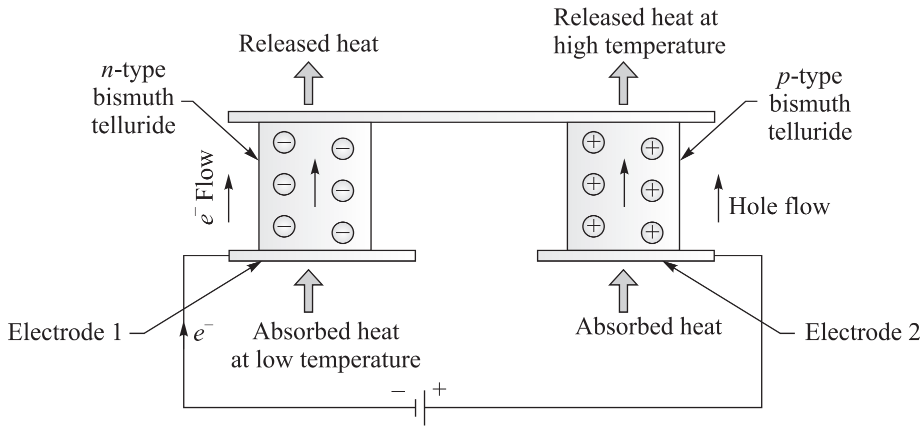


Figure 9.2 Peltier effect due to charge carriers transporting heat.

The Peltier effect can create heat flux at the junction between two different types of materials. A Peltier thermocooler or thermoheater (heat pump) is a solid–state active heat pump which transfers heat from one side of the device to the other side against the temperature gradient (from cold to hot side, that is, refrigeration effect) with consumption of electrical energy. Peltier device is a heat pump and it uses electric energy (direct current) to move heat from one side to the other. It can be used the purpose of heating or cooling. Solid-state Peltier refrigeration system based on the Peltier effect does not have any moving part.

The heat removed or absorbed at electrodes depends upon the magnitude of current and the direction of current. The heat is given by

$$Q = \alpha \times I$$

where α is the Peltier coefficient and I is the current.

Thomson effect

If a conductor has temperature gradient along its length and electric current flows through it, some heat will be absorbed or released due to the current flow. This phenomenon is called Thomson effect.

William Thomsom (Lord Kelvin) was led by thermodynamic reasoning to conclude that a source of emf exists in a thermoelectric circuit in addition to those located at the junctions. Therefore, he predicted, that an emf would also arise within a single conductor if a temperature gradient was maintained in it.

In Thomson effect, we deal only with metallic rod and not with thermocouples as in Peltier or Seeback effect. When a current flows through an unequally heated metal, an absorption or evolution of heat in the body of the metal takes place. The positive or negative Thomson effects are shown in Figure 9.3. When a rod is subjected to the steady current, heat is absorbed from the rod as current approaches the hot point and heat is evolved or transferred from the rod just beyond the hot point as shown in Figure 9.3(a). The Thomson effect is reversible as shown in Figure 9.3(b). The heat released or absorbed is given by the following relation:

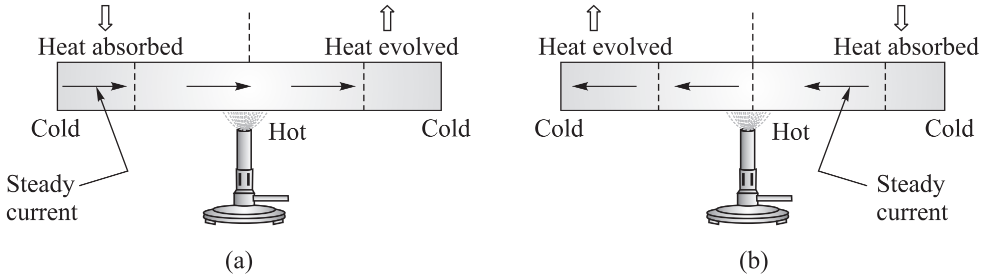


Figure 9.3 Thomson effect. (a) Positive Thomson effect and (b) Negative Thomson effect.

$$Q = I \times \int_{T_1}^{T_2} \sigma \times dT$$

where $\sigma \left(= \dfrac{dQ/dx}{dT/dx} \right)$ is the Thomson coefficient,

$\dfrac{dT}{dx}$ is the temperature gradient,

$\dfrac{dQ}{dx}$ is the heat flow per unit time and unit length and T_1 and T_2 are the temperatures at two points.

Thomson coefficient (σ) of a material is the amount of heat absorbed or released between two points of a rod having a unit temperature difference when a unit current is passed through the rod (Figure 9.4).

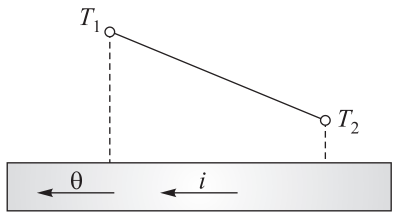


Figure 9.4 Thomson effect.

The Thomson effect can also be explained by the phenomenon in which a temperature gradient along a metallic wire or strip causes an electric potential gradient to form along its length. It is nothing but a thermoelectric conversion.

9.3 THERMOELECTRIC GENERATOR

- **Analyse the working of a thermoelectric generator. Derive an expression for its power output.**

Thermoelectric power generator consists of a number of thermocouples connected in series. The thermocouple has materials A and B which are joined to form a common hot junction while other ends are maintained at a cold temperature. According to Seeback effect, an electromotive force is generated between the cold ends. The current flow continues as long as heat is supplied to the hot junction. The power output can be measured by increasing the temperature difference between hot and cold ends. A typical thermocouple operating with hot and cold temperatures at junctions is shown in Figure 9.5 (about 800 and 200°C) and it can give output having 1 V and 2 amp (power = 0.1 × 2 = 05 W). To obtain higher output, a number of such thermocouples can be joined in series. A 1 kW device will require about 5000 such thermocouples in series (Figure 9.6).

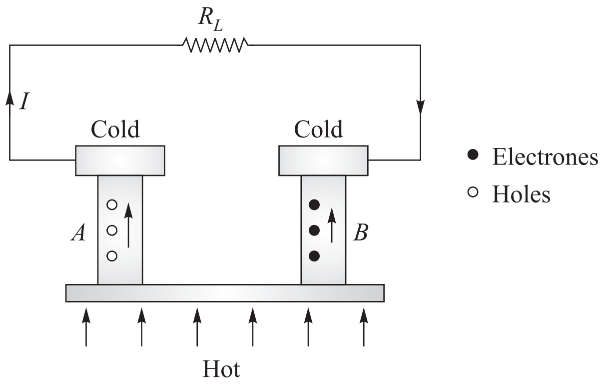


Figure 9.5 Thermocouple working.

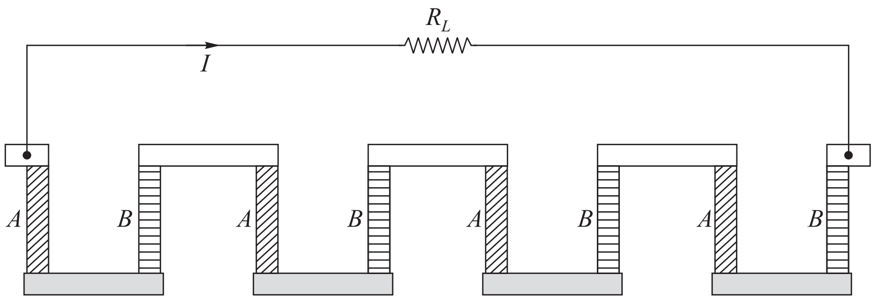


Figure 9.6 Thermocouples in series.

The open circuit emf (E) of a thermocouple consisting of A and B materials can be given by the following equation:

$$E = (\alpha_A - \alpha_B) \times \Delta T = \Delta\alpha \times \Delta T$$

where α_A is the absolute Seeback coefficient for material A,
α_B is the absolute Seeback coefficient for material B and
ΔT is the difference of temperatures at junctions.

If R_i and R_L are the internal and external resistances, power output (P) is given by

$$P = E \times I - I^2 \times R_i = I^2 \times R_L$$

$$= (\Delta\alpha \times \Delta T) \times I - I^2 R_i = I^2 R_L \quad \text{(i)}$$

For maximum power output,

$$R_i = R_L \text{ and putting in equation (i)}$$

$$\therefore \qquad (\Delta\alpha \times \Delta T) \times I - I^2 R_i = I^2 \times R_i$$

or

$$I = \frac{(\Delta\alpha \times \Delta T)}{2 \times R_i}$$

Maximum output power is given by

$$P_{max} = I^2 \times R_i$$

$$= \frac{(\Delta\alpha \times \Delta T)^2}{4R_i}$$

9.3.1 Materials for a Thermoelectric Generator

- **What are the properties of materials used in a thermoelectric generator?**

The properties required in a material used in the thermoelectric generator are as follows:

(i) It should be capable to withstand high temperatures.
(ii) Its thermal conductivity should be small.
(iii) It must have high mobility for charge carriers.
(iv) It can be a semiconductor of *n*-type and *p*-type.
(v) It should have low ionization energy.
(vi) It should have high corrosion resistance.

9.3.2 Characteristics of a Thermoelectric Generator

- **What are the characteristics of the thermoelectric generator?**

The characteristics of a thermoelectric generator are as follows:

(i) It has no moving parts.
(ii) It can be used in remote areas.
(iii) It can be used for aerospace applications.
(iv) It can be used as a system for waste heat recovery.
(v) It has low thermal efficiency.

9.3.3 Applications of a Thermoelectric Generator

- **Discuss the applications of a thermoelectric generator.**

The applications of a thermoelectric generator are as follows:

(i) Thermoelectric generator can be used with fuel elements of the nuclear reactor to obtain additional power.
(ii) Thermoelectric generator can also be used with steam power plant for obtaining higher efficiency.
(iii) Thermoelectric generator can be used to produce electricity using the waste heat from gas turbines, diesel engines and stack gases.

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

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

9.4 MAGNETOHYDRODYNAMIC POWER CONVERSION

- **Briefly explain magnetohydrodynamic power conversion.**

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

9.4.1 Principle of Operation of an MHD Generator

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

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

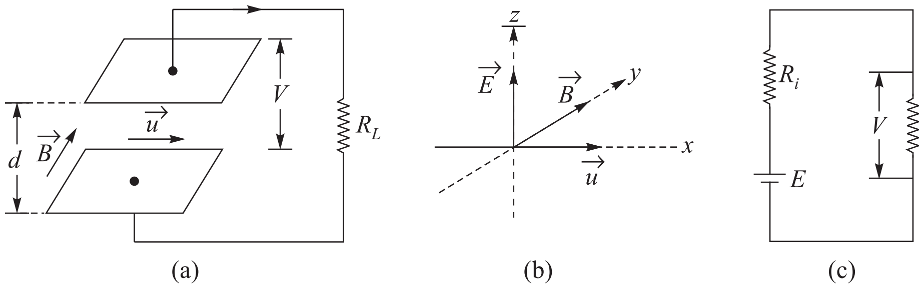


Figure 9.7 Principle of MHD generator. (a) Application of magnetic field $\vec{B}$ on moving gas $\vec{u}$. (b) Induced electric field. (c) Equivalent electric circuit.

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

$$F = qE + quB$$

$$= -q\frac{V}{d} + quB \qquad (9.1)$$

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

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

or $$V_0 = Bud$$

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

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

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

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

∴ $$P_{max} = i^2 R_i$$

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

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

But $$V_0 = Bud$$

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

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

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

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

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

But volume of gas = Ad

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

9.4.2 MHD Generator

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

or

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

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

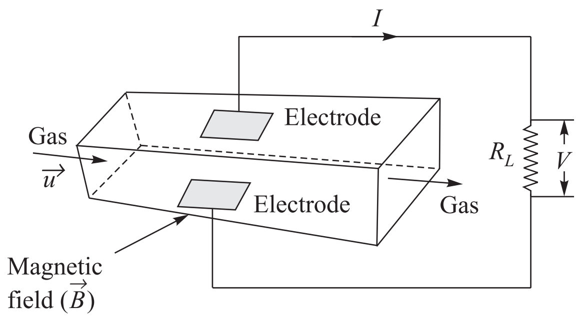


Figure 9.8 An MHD generator.

Advantages

The advantages of MHD generating system are as follow:

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

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

Limitations

The limitations of an MHD generating system are as follow:

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

9.4.3 Seeding of Carrier Gas in MHD Generator

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

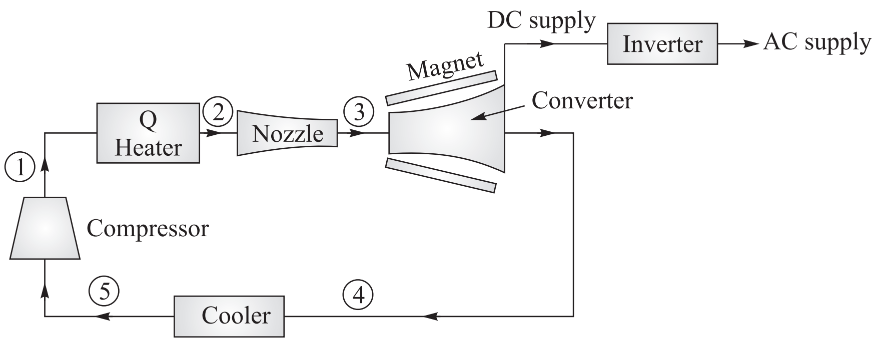
In the MHD generator, the solid conductor is replaced by a gaseous conductor; that is, ionized gas is employed as the conducting fluid. Ionization is produced by

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

9.4.4 Overall Power Cycle with MHD Converter

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

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



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

Figure 9.9 Overall power cycle with MHD convertor closed system.

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

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

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

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

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

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

9.4.5 MHD Systems

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

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

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

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

9.4.6 Open Cycle Systems

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

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

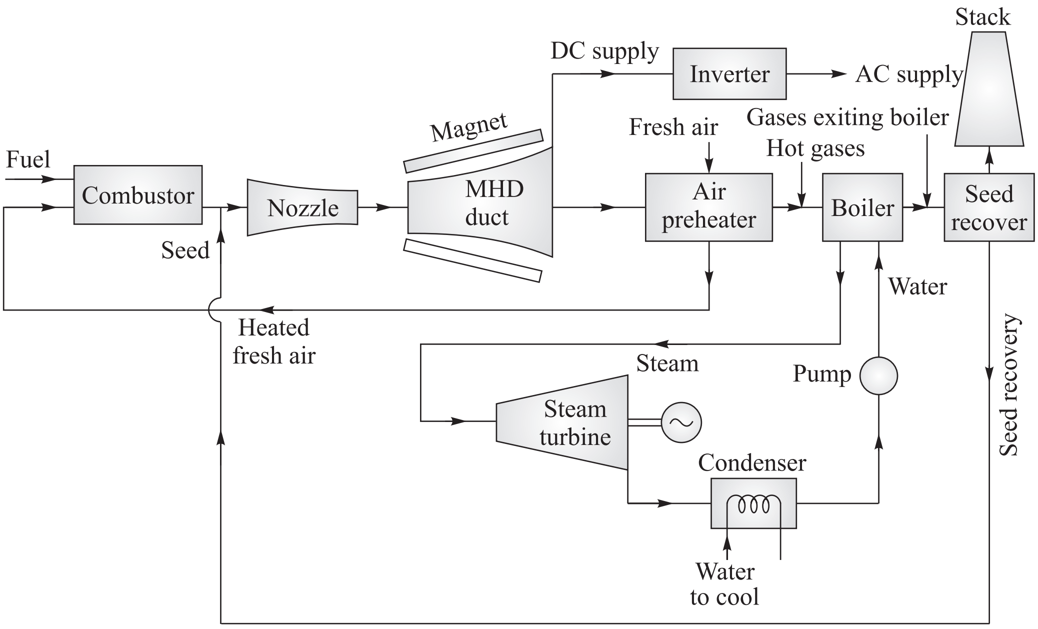


Figure 9.10 An open cycle MHD generator.

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

9.4.7 Closed Cycle System

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

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

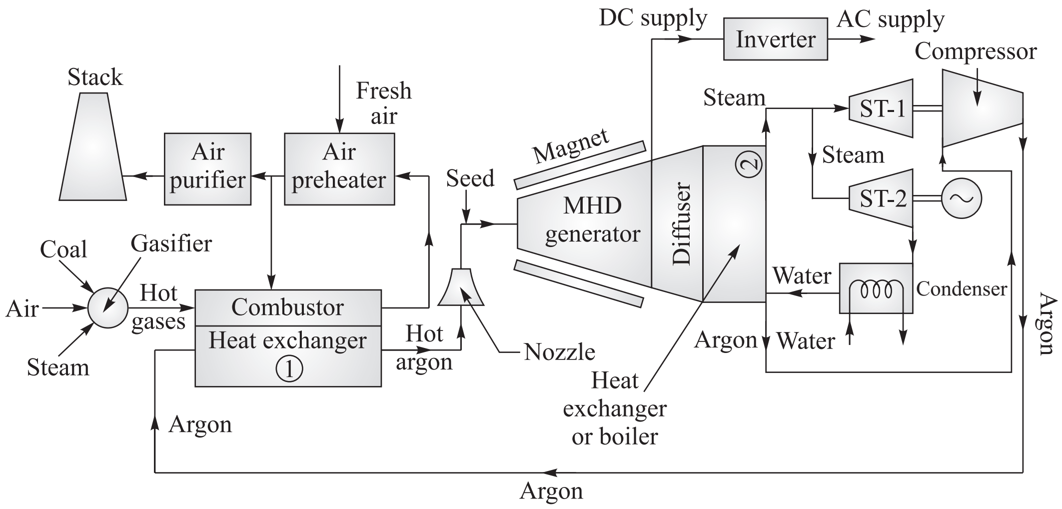


Figure 9.11 A closed MHD system.

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

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

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

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

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

9.4.8 Materials for MHD Generators

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

The requirements of materials are as follows:

(a) **Electrodes**

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

(b) **Duct liner**

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

(c) **Magnet**

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

9.5 THERMIONIC POWER CONVERSION

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

A thermionic generator consists of two metals (called electrodes) which have different values of work function (work function is the energy needed to overcome the force of attraction acting on an electron in order to make it free). These metallic electrodes are sealed into an evacuated glass vessel. The electrode with the larger value of work function is maintained at a higher temperature compared to the electrode having the lower value of work of function. The hot electrode can now emit electrons due to supplied heat energy, and therefore this electrode is called emitter. The colder electrode can collect electrons, and therefore it is called collector. The emitter becomes positive on emitting electrons while the collector becomes negative due to collection of electrons. Owing to collection of charges, a voltage is developed between the electrodes and a direct current starts flowing in any external circuit connecting the electrodes. The developed voltage depends on the difference of work functions of the metal electrodes. The heat energy at the emitter must be sufficient to free electrons from the emitter surface, that is, more than the work function of the emitter electrode. When these electrons strike the collector, their kinetic energy must be higher than the work function of the collector so that electrons can be absorbed in the collector. The heat of absorption must be released from the low-temperature collector. The absorbed electrons cause higher energy level at collector than that at emitter, and so a potential difference is developed between collector and emitter, forcing electrons to move from collector to emitter through an external circuit with load. The output power depends on emitter temperature and work function magnitude between emitter and collector. Thermal efficiency of a thermionic power conversion system is in the range of 5–25% (Figure 9.12).

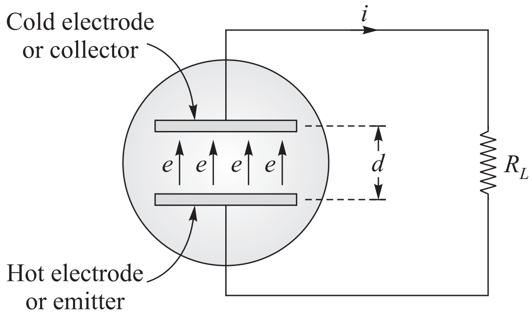


Figure 9.12 Principle of working of a thermionic converter.

The emission of electrons from emitter to collector is found to be inhibited by space charge created in the gap between emitter and collector. The space charge can be reduced by decreasing the gap and introducing a small quantity of cesium in the gap, which has low ionization potential.

9.5.1 Merits of Thermionic Converter

- **Mention the merits of a thermionic converter.**

The merits of a thermionic converter are as follows:

(i) It has no moving part.
(ii) It has quiet operation.
(iii) It has a long operation life.
(iv) It is reliable in operation.
(v) It has high power density.
(vi) It needs moderately high temperature difference between electrodes.
(vii) It can develop sufficiently low to high power when used in series.
(viii) It has comparatively low cost.
(ix) It has reasonable efficiency.
(x) It can withstand harsh environments.
(xi) It is more suitable at high temperatures compared to a thermoelectric converter.
(xii) Its efficiency increases with the increase in temperature.

9.5.2 Applications of the Thermionic Converter

- **What are the potential applications of thermionic converters?**

The thermionic converters can be used for harnessing primary heat and waste heat. The corresponding systems are based on cycles which are called topping cycle and bottoming cycle respectively. The applications of the thermionic converter are as follow:

(i) It can be used as a topping cycle system with a solar collector to generate electricity instead of a solar photovoltaic system. It can convert 20–25% solar energy into electricity and the rest of energy can be used as thermal energy for water or space heating in residential buildings.

(ii) It can also be used to harness primary heat utilising gas, oil or other fuels to generate electric power.

(iii) It has high power to weight ratio with low noise. It has great potential to be used in aerospace and military installations.

(iv) It can easily be used for portable power generation.

(v) It can be used to harness waste heat of various propulsion systems.

(vi) It can be used with conventional power plants to increase their efficiencies without any additional chemical emission.

CHAPTER 10

TIDAL POWER

10.1 INTRODUCTION

Tides are produced by gravitational attraction of the moon and the sun acting on the rotating earth. Tides are periodic rise and fall of the water level in the oceans due to various positions of rotating moon and sun. Oceans cover nearly 71% of earth's surface. The water level difference is caused in oceans due to the tides and tides contain a large amount of potential energy. The difference in the level between the high and the low tide is called the tidal range and tidal range of 5–15 m can be easily used to drive turbine coupled with generator to generate electric power.

10.2 ORIGIN OF TIDES

- **Discuss the origin of tides.**

or

- **What do you understand by spring and neap tides? How are these caused?**

Tides are produced due to gravitational pulls exerted by both the moon and the sun. As moon is nearer to the earth, the gravitational pull of moon is about 2.33 times stronger than that of the sun. Owing to the gravitational pull of the moon, surface water on the earth facing moon is pulled and raised towards the moon, and so water moves from poles to equator where the moon pull is maximum. This movement of water results in the formation of a high tide at the earth surface facing the moon. A corresponding high tide is also formed on the opposite side of the earth as solid earth is pulled away from the water surface, which results in the apparent rise of water as shown in Figure 10.1.

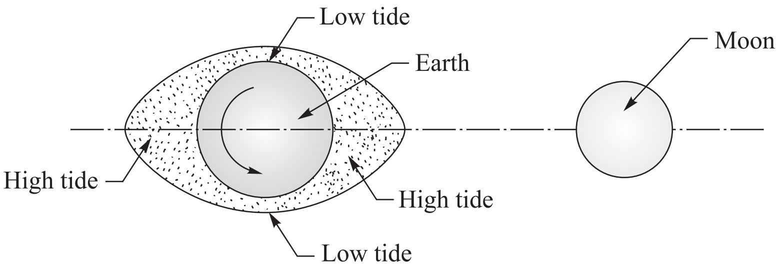


Figure 10.1 Origin of tides.

As moon takes 24 h and 50 min to complete a rotation on its axis, high tide is formed about two times at a place in its one rotation; that is, a high tide due to moon is formed after a period of 12 h and 25 min. The effect of gravitational pull by the sun is the same, but it is 2.2 times lesser than what is exerted by the moon. Earth revolves around the sun in 24 h. Owing to this slight difference in periods of rotation, solar tides move in and out of phase with lunar tides (Figure 10.2).

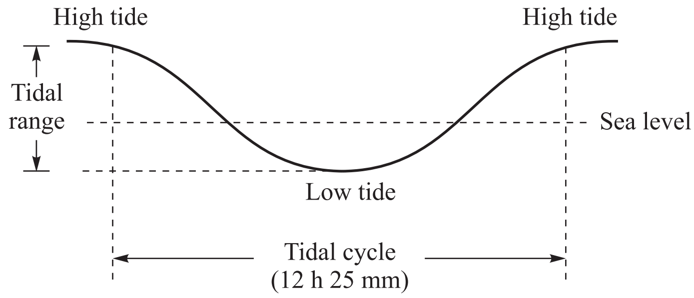


Figure 10.2 Tidal range and tidal cycle.

Spring tides

When earth, sun and moon are aligned during rotation in a line as shown in Figure 10.3, these celestial bodies produce tides having maximum tidal heights as both solar and lunar tides are in phase. The spring tides are produced twice in a lunar month.

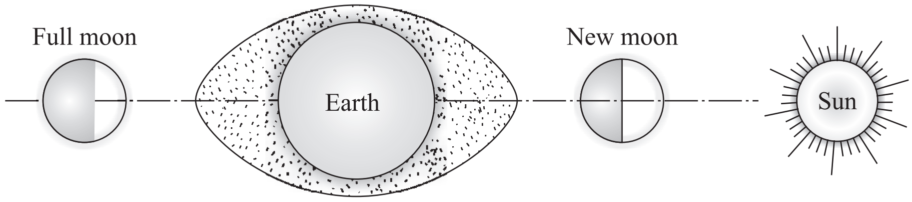


Figure 10.3 Formation of spring tides.

Neap tides

When sun-earth and moon-earth directions are perpendicular as shown in Figure 10.4, lunar and solar tides are completely out of phase. The celestial bodies produce tides having minimum tidal heights, which are called neap tides. Neap tides are produced twice in a lunar month.

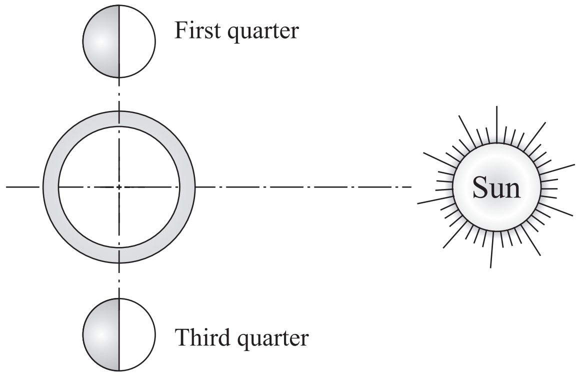


Figure 10.4 Formation of neap tides.

Tidal variation in a lunar month

The tidal variation resulting in spring and neap tides in a lunar month is shown in Figure 10.5.

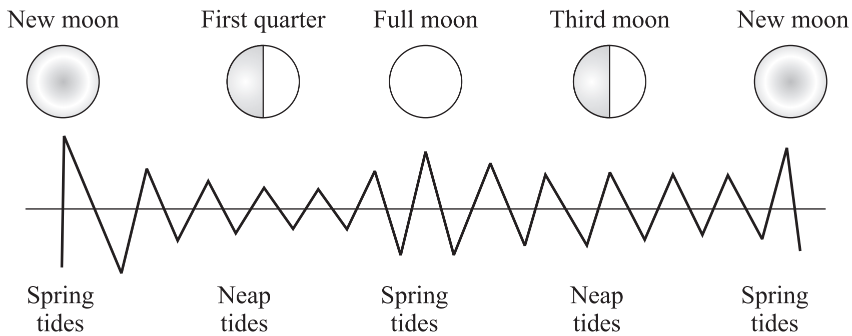


Figure 10.5 Tidal variation in a lunar month.

10.3 TIDAL ENERGY

- **What is the source of tidal energy? What is the minimum tidal range required for the working of a tidal plant? How much is the potential in tides?**

or

- **Derive an expression for power generated by a tidal system.**

The source of tidal energy is the difference in water levels between high tides and low or ebb tides. During one tidal cycle of 12 h and 25 min, the water level rises to maximum during high tides, then it starts falling to a minimum level at low tides and finally it starts rising again to a maximum level at high tides. The difference in water levels between high tides and low tides is the potential energy of water which can be harnessed. This harnessed energy is called the tidal energy. In a tidal power plant, a reservoir behind an embankment or barrage is filled up during high tides and stored water is made to flow out from the reservoir into sea through turbines coupled to electric generators during low tides. The tidal range can be as high as 15 m, but minimum tidal range must be at least 5 m for the working of a tidal plant.

Potential or tidal range power

Consider entrapped water at high tides in a reservoir having surface area A. The tidal range is R, which is also the height of water in the reservoir from the water level at low tides as shown in Figure 10.6. Consider a water layer of small height dh at a height or head of h from turbine inlet. The potential energy of this layer is given by

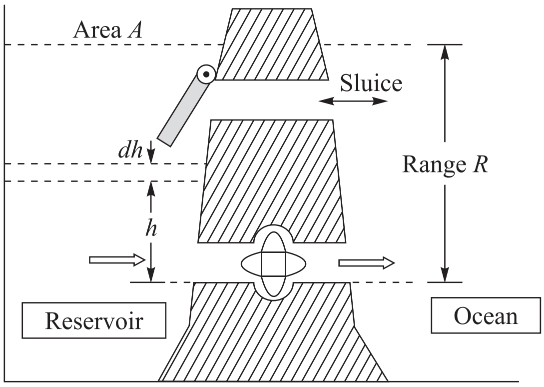


Figure 10.6 Power generation from tidal water.

$$dE = dmgh$$

where dm = mass of water layer of height dh

$$= (\rho A dh) \times g \times h$$

$$\therefore \qquad E = \int_0^R \rho.A.g.h.dh = \frac{1}{2}\rho A g R^2$$

- **A tidal power plant has reservoir of area 50 × 10⁶ m². The tide has tidal range of 10 m. The turbine can be operational with a head of 3 m or more. The turbine generator has efficiency of 80%. Estimate the total power in one filling and employing cycle.**

$$E = \rho g A \int_3^{10} h dh$$

$$= \frac{1}{2}\rho g A[10^2 - 3^2] = \frac{91}{2} \times \rho g A$$

$$\text{Power} = \text{Energy per unit time} = \frac{E}{t}$$

where t is the duration of tide

$$t = 6 \text{ h and } 12.5 \text{ min} = 22{,}350 \text{ S}$$

$$\therefore \qquad \text{Power} = \frac{91 \times 9.81 \times 1025 \times 50 \times 10^6}{2 \times 22{,}350}$$

$$= 1.024 \text{ MW}$$

10.3.1 Modes of Operation of Tidal Power Plant

- **What are the different modes of operation of a tidal power plant?**

The modes of the operation of a tidal power plant are as follow:

(i) **Ebb generation.** The reservoir or basin is filled up during high tides. The stored water is made to flow out of the reservoir to ocean through turbines during low tides. The power generation is possible during ebb tides.

(ii) **Flood generation.** The sea water is made to flow through the turbines into the reservoir or basin during high tides. This process is just reverse of ebb generation. The power generation is possible during high tides.

(iii) **Two-way generation.** 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. The power generation is possible during both low and high tides.

(iv) **Pumping and turbining.** The reservoir is filled using (i) rise of sea water during high tides and (ii) pumps to pump sea water into the reservoir. The turbine acts as a pump to pump water into reservoir during high tides and as a prime mover to the generator during low tides.

10.3.2 Components of the Tidal Power Plant

- **What are the main components of the tidal power plant?**

The components of a tidal power plant are as follow:

(i) **Dam or dyke.** The function of a dam or dyke is to form a barrier between the sea and the reservoir/basin. Dam is also built between basins in case the plant has more than one basin.

(ii) **Sluiceways.** Sluiceways are provided in the dam so that water can enter into basin during high tides. These may also be provided to empty the basin during low tides. Sluiceways are controlled through gates.

(iii) **Powerhouse.** A powerhouse consists of turbines, electric generators and other auxiliary equipment. The water with high potential energy is made to run through turbines to run generators for power production.

10.3.3 Feasibility of the Tidal Power Plant

- **What are factors affecting the feasibility of a tidal power plant?**

The feasibility of a tidal power plant depends on the following factors:

(i) **Tidal range.** The minimum tidal range for economical power production from tidal energy is 5 m.
(ii) **Cost.** The site should be such that it needs a minimum cost to construct a dam to create a basin of a required storage capacity of water in ocean.
(iii) **Shipping traffic.** The site of the tidal plant should not cause any interruption to the shipping traffic running through estuary.
(iv) **Safety.** The site of the tidal plant should be well protected, especially from high wave action during storms.
(v) **Silt.** The silt content in water in estuary at the tidal site should be small to avoid excessive silt deposition in the brain. The silt removal from basin is a costly preposition.

10.3.4 Merits of Tidal Energy

- **What are the merits of tidal energy?**

The merits of tidal energy are as follows:

(i) It is free from pollution.
(ii) It is inexhaustible.
(iii) The site of the plant can be generally dam at bays and its construction does not uproot the villages or disturb the ecology of the place.
(iv) No submerging of land occurs while constructing basins.
(v) Its operation is not adversely affected by variations of weather, such as the failure of monsoon. Tide cycle is always definite.
(vi) Basins can also be used for fish farming.

10.3.5 Limitations of Tidal Energy

- **Discuss the limitations of tidal energy conversion plants.**

The limitations of tidal energy are as follows:

(i) It can be harnessed only if natural sites are available.
(ii) Its suitable sites are mostly bays which are far away from the load centres. Therefore, the transmission cost of power is high.
(iii) Its operation is uneven as turbines have to work with varying water heads. The power output is variable.
(iv) The construction period of a dam for basin is long. The basin and plant construction is costly.
(v) Sedimentation and silt deposition in the basin take place in regular manner which is costly to be removed.
(vi) Power output varies with lunar cycle.

(vii) Supply of power depends on the timing of tides and it is not continuous.
(viii) Sea water is corrosive. The life of tidal power equipment is affected by the corrosive nature of sea water.
(ix) Efficiency of plant is affected due to variable tidal range.
(x) More turbines are to be used to obtain sufficient power as water head is small.

10.4 CLASSIFICATION OF TIDAL PLANT

- **How are tidal plants classified on the basis of basins used?**

The tidal plants are classified on the basis of basins used as

- Single basin system
- Double basin system

10.4.1 Single Basin System

- **Explain the various methods of tidal power generation. What are the limitations of each method?**

or

- **Explain the working of a single pool (basin) tidal system.**

Single basin system is the simplest system to generate tidal power. The single basin tidal plant has only one basin to store water. The basin is separated from the ocean/sea by a dam. The turbines and generators are mounted within the ducts inside the dam. The single basin system can be further classified into single ebb cycle system, single tide cycle system and double cycle system.

In single ebb cycle system, the sea water fills up the basin through sluice valves when water level rises in high tides. The stored water in basin is made to run the turbines when the level of sea water decreases during low tides as shown in Figure 10.7(a). The turbines generate power using generators. The power output from this system is intermittent as power can be generated only during low tides.

In single tide cycle system as shown in Figure 10.7(b), the water is made to enter into basin through turbines during high tides. When high tides period is over, the sea level starts falling, which reduces the head on turbines. The power generation is stopped as sea level reduces with the onset of low tides. The basin is drained of water through the sluiceways as sea level is lower during low tides. The power output is, therefore, intermittent.

In double cycle system as shown in Figure 10.7(c), reversible turbines are installed. The power is generated during both filling and emptying of the basin. Filling of basin is done during high tides when water level in basin is low. The water is made to flow through the turbines into basin to run generators. Emptying of basin is done during low tides when sea level is low and level in basin is high. The water is made to flow out of the basin through turbines into sea to run generators. The flow of water is, therefore, used in both directions to drive the reversible turbines. In this system also, continuous power generation is not possible as it takes some time to change from filling to emptying modes of the basin.

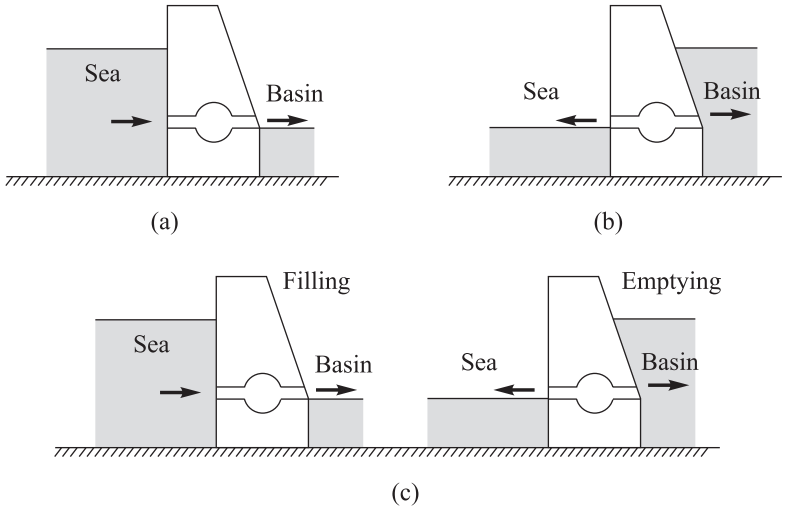


Figure 10.7 Single basin arrangements. (a) Single ebb cycle (b) Single tide cycle and (c) Double cycle system.

10.4.2 Double Basin System

- **Explain the working of a double basin tidal system.**

The double basin power plant has two basins at different levels (Figure 10.8). The dam is provided between basins and sea as well as between basins. One basin is called upper basin as the water level in this basin is always maintained higher than that in the lower basin. The lower basin discharges water to the sea at low tides, while the upper basin is filled up with sea water at high tides. The turbines are provided in the constructed dam separating upper and lower basins. When water is made to flow through turbines from upper basin to lower basin, the turbines run and generators coupled with them generate power.

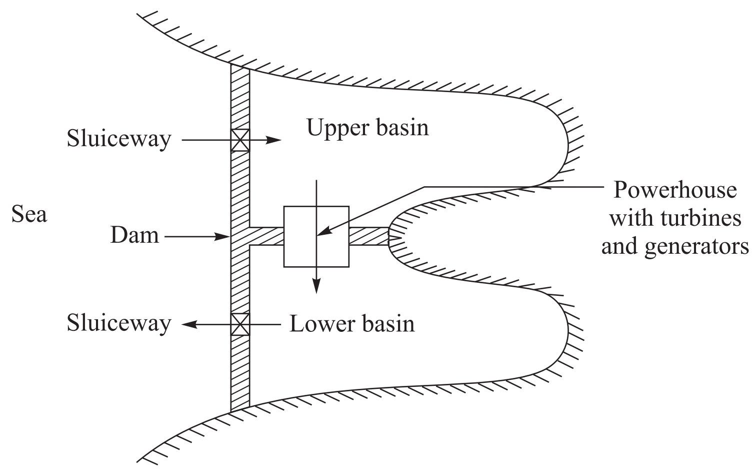


Figure 10.8 Double basin system.

10.5 SITE REQUIREMENTS

- **What are the site requirements to construct a tidal power plant?**

The site requirements are as follow:

(i) High tidal range
(ii) Short length of dam to create a basin of reasonable storage. It is possible at a narrow inlet to an estuary or bay
(iii) Nearer to load location
(iv) Should be protected from high waves
(v) Should not hamper shipping traffic.

10.6 TIDAL POWER DEVELOPMENT IN INDIA

- **Describe potential sites in India which are suitable for tidal power development.**

The sites suitable for tidal power development in India are as follows:

(i) Gulf of Kutch (Gujarat)
(ii) Gulf of Khambhat (Gujarat)
(iii) Sundarbans delta (West Bengal)
(iv) Gulf of Cambay (Gujarat)
(v) Pitts Creek (West Bengal).

CHAPTER 11

GEOTHERMAL ENERGY

11.1 INTRODUCTION

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

11.2 RESOURCES OF GEOTHERMAL ENERGY

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

or

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

or

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

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

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

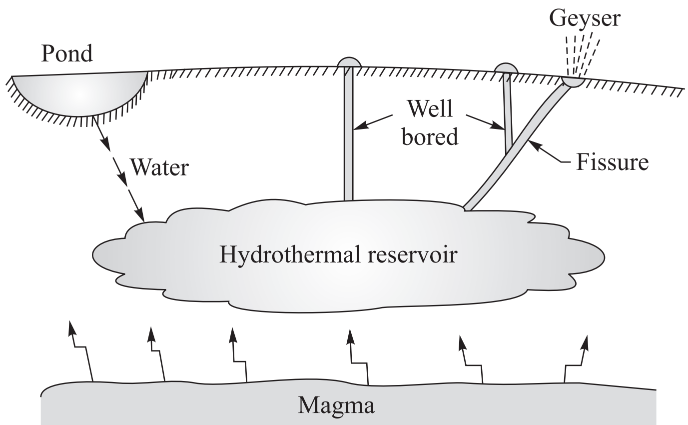


Figure 11.1 A hydrothermal resource.

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

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

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

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

Hot springs and steam ejector

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

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

11.3 GEOTHERMAL POWER PLANTS

11.3.1 Hydrothermal Resources

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

or

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

or

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

or

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

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

Vapour dominated plant

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

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

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

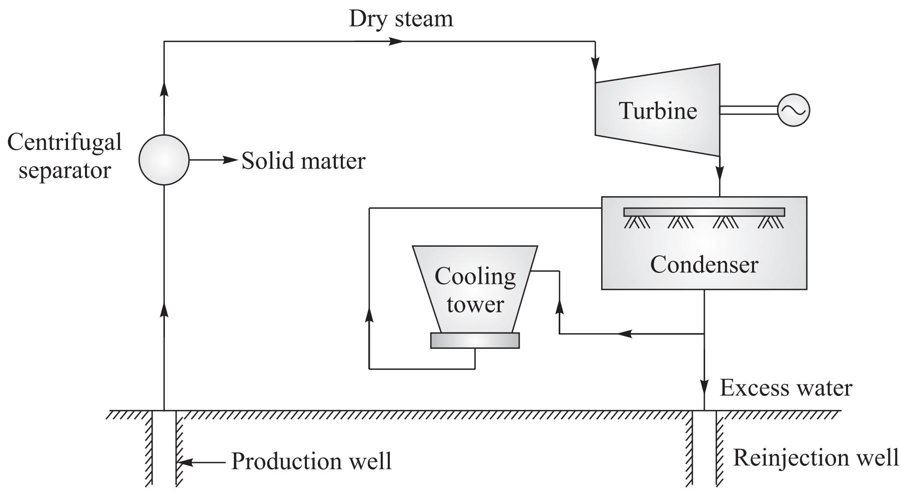


Figure 11.2 Dry steam hydrothermal plant.

Wet steam or liquid dominated

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

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

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

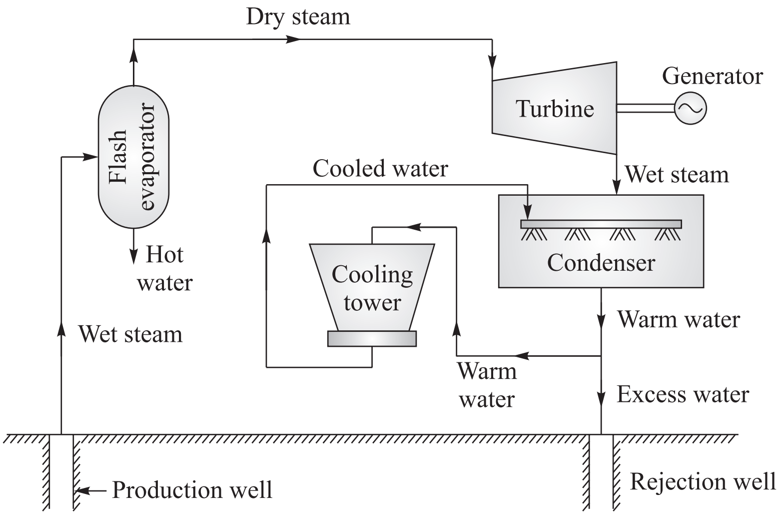


Figure 11.3 Single flash steam system in liquid dominated high-temperature plant.

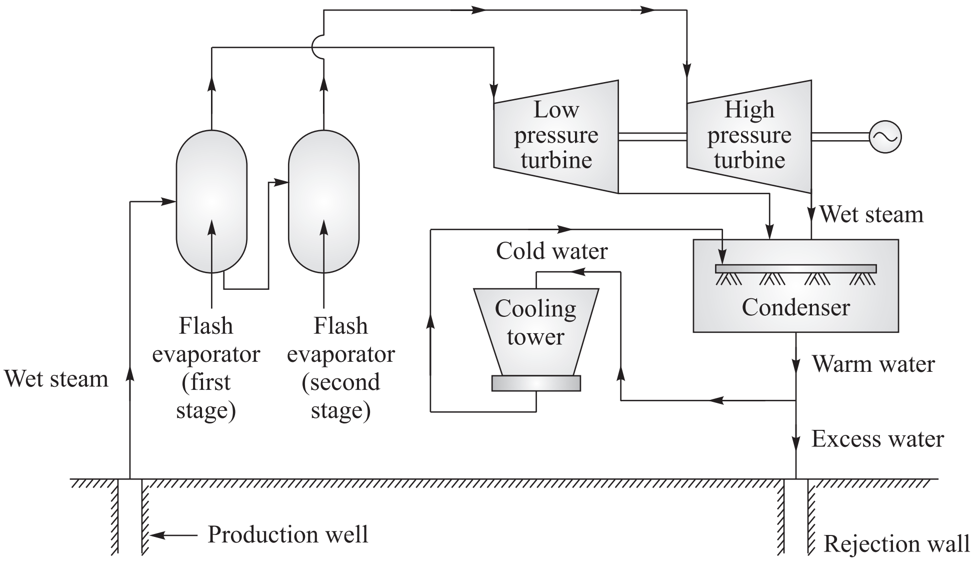


Figure 11.4 Double flash steam system in liquid dominated low-temperature plant.

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

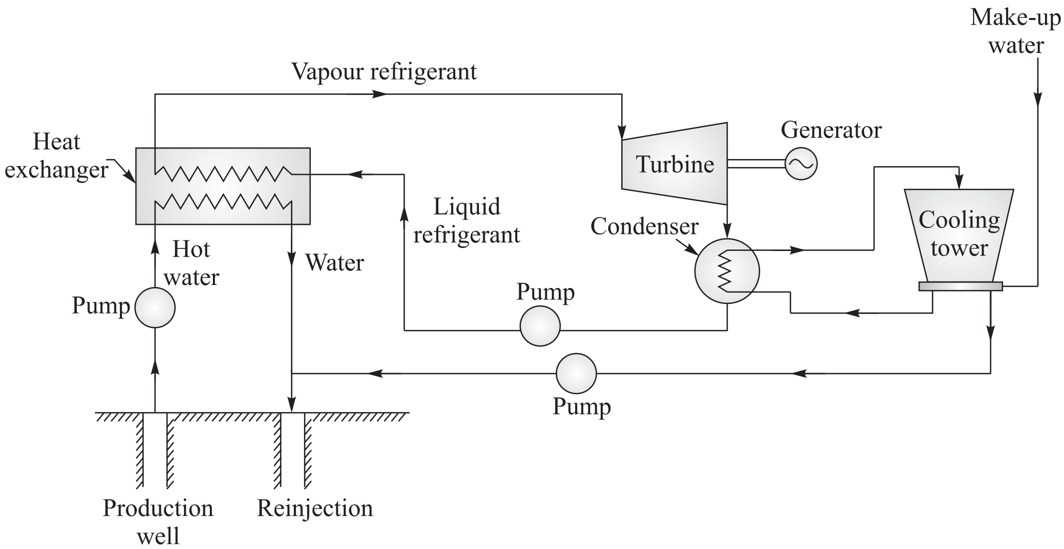


Figure 11.5 Binary fluid hydrothermal system (low temperature).

11.3.2 Hot Dry Rock Resource

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

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

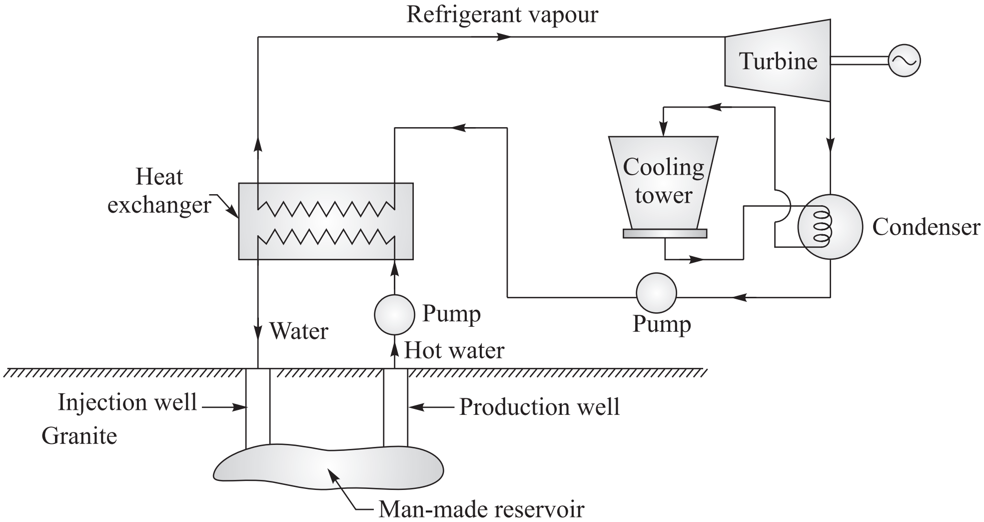


Figure 11.6 High dry rock binary fluid system.

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

11.3.3 Comparison of Geothermal Power Plant with Convention Thermal Power Plant

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

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

(i) The temperature and pressure in the geothermal power plant are less (about 170°C and 8 atm) compared to those in the conventional thermal plant (temperature about 540°C and pressure about 160 atm). The efficiency of geothermal plant is about 15% while it is about 40% in case of the conventional thermal plant.

(ii) The size of a geothermal power plant depends on the amount of geothermal energy available. The size of a geothermal plant is generally small on account of smaller thermal potential of the site.

(iii) Geothermal power plant needs a larger flow of geothermal fluid due to lesser temperature and pressure compared to conventional power plant.

(iv) Geothermal power plant has to be located where geothermal fields exist. It is technically infeasible to transport geothermal energy over long distance. The transmission cost of power for geothermal power plant is more.

(v) Hydrothermal plant does not need water for cooling purpose unlike conventional power plant.

(vi) Hydrothermal plant causes lesser pollution compared to conventional power plant.

(vii) Hydrothermal plant does not need any supply of fuel.

11.3.4 Non-Electrical Applications of Geothermal Energy

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

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

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

(ii) The hydrothermal fluids can be used as a heat source for space and water heating.

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

11.3.5 Advantages and Disadvantages of Geothermal Energy

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

or

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

The main advantages of geothermal energy are as follows:

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

The major disadvantages of geothermal energy are as follows:

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

11.3.6 Materials for Geothermal Plant Equipment

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

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

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

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

11.3.7 Environmental Problems from Geothermal Energy

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

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

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

11.3.8 Criteria for Selection of Geothermal Site

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

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

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

11.3.9 Potential of Geothermal Energy in India

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

or

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

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

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

Following hydrothermal plants are being planned:

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

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

11.3.10 Exploration and Development of Geothermal Resources

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

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

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

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

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

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

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

CHAPTER 12

Wave Energy

12.1 INTRODUCTION

Waves in ocean are caused by the transfer of wind energy to the water surface in the ocean. Depending upon the wind speeds and the distance over which wind interacts with water surface, stronger and higher waves can be formed. The wave energy depends upon amplitude of the wave and period of the motion. Wave power is commonly expressed in kilowatt per metre, that is, the rate of energy transfer across a line of 1 m length parallel to the wave front. Wave energy consists of kinetic energy resulting from wave propagation and potential energy resulting from lifting of water mass with respect to mean sea level. The wave velocity depends upon wavelength. The longer is the wavelength, the faster it moves. Waves after formation continue to travel even when wind dies down. This is the reason why a long swell can be seen even when sea is calm. Wave can rise up to 10 m height and its average wavelength can be about 100 M. Along the India coast, the potential of wave energy is about 5–15 kW/m. India has coastline of nearly 6000 kM.

12.2 WAVE ENERGY AND POWER

- **Show that wave velocity does not depend on the amplitude of the wave.**

or

- **Find the expressions for potential energy, kinetic energy and total energy per unit width of wavefront.**

or

- **Show that wave power is directly proportional to the square of amplitude and inversely proportion to the period of wave.**

Unlike tides which exhibit a regular but long periodic motion, waves keep ocean water in continuous motion. The vertical rise and fall of successive waves can be used to produce power.

The wave in sea is similar to a progressive wave whose crest line moves in the direction of propagation of wave as shown in Figure 12.1. The wave form repeats after a period. The direction of propagation is perpendicular to the crest line. A sea wave can be assumed to be a sinusoidal wave having frequency (f), wavelength (λ), amplitude (a), velocity (c), period (T), angular frequency $\left(\omega = \frac{2\pi}{\tau}\right)$ and wavenumber $\left(k = \frac{2\pi}{\lambda}\right)$. As wave moves in linear direction (along x-axis), every water particle at the surface undergoes a circular motion of radius a (amplitude of wave) with angular speed ω. The displacement above sea level of a particle is given by the following equation:

$$y = a \sin (kx - \omega t)$$

or

$$y = a \sin \left(\frac{2\pi}{\lambda} \times x - \frac{2\pi}{T} \times t\right)$$

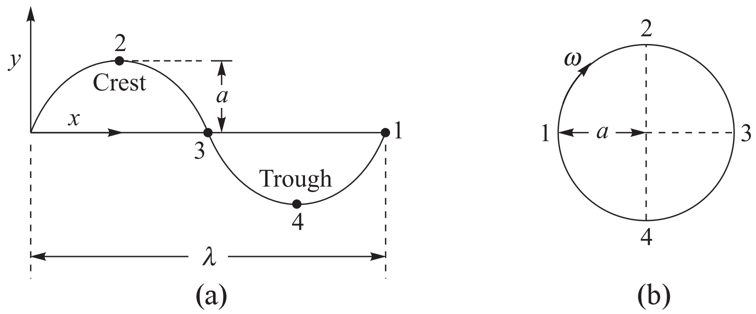


Figure 12.1 Propagation of wave. (a) Wave motion, and (b) Particle motion.

When $t = T$, then $x = \lambda$ and $y = 0$; that is, the waveform assumes its original position. The wave motion is in x-direction with velocity $c = \frac{\lambda}{T}$. Although wave propagates in x-direction, no flow of water takes place. The wavelength of travelling wave can be given as

$$\lambda = \frac{2\pi g}{\omega^2}$$

and

$$T = \frac{2\pi}{\omega} = \sqrt{\frac{2\pi \lambda}{g}}$$

or

$$\lambda = 1.5613 \, T^2.$$

The wave velocity can also be given as:

$$c = \frac{\lambda}{T}, \quad \text{but} \quad T = \frac{2\pi}{\omega}$$

$$\therefore \qquad c = \frac{\omega \times \lambda}{2\pi}$$

The above relation shows that the wave velocity does not depend upon the amplitude of the wave.

Potential energy

The potential energy of wave results due to water being lifted above the sea level ($y = 0$). Consider a differential volume of water of height y, thickness dx and width L, then

$$\text{Volume of water} = yLdx$$

$$\text{Weight of water} = yLdx \times \rho g$$

$$\text{Potential energy} = \Delta\ \text{PE} = mg \cdot \frac{y}{2}$$

or

$$\Delta\ \text{PE} = yLdx\ \rho g \cdot \frac{y}{2}$$

$$= \frac{1}{2}\ \rho.g.L.y^2.dx$$

$$= \frac{1}{2}\ (\rho gL).a^2 \sin^2 (kx)\ dx \text{ where } k = \frac{2\pi}{\lambda}$$

$$\text{PE} = \frac{1}{2}\ \rho gL \int_0^{\lambda} a^2 \sin^2 (kx)\, dx$$

$$= \frac{1}{2}\ \rho gL\ a^2 \int_0^{\lambda} \frac{1 - \cos 2\,(kx)}{2}\ dx$$

$$= \frac{1}{4\,k} \rho gL\ a^2 \left[kx - \frac{1}{2} \sin 2\,(kx) \right]_0^{\lambda}$$

$$= \frac{1}{4}\ \rho gL\ a^2 \lambda$$

The surface area of wave

$$A = \lambda L$$

$$\text{PE} = \frac{1}{2}\rho g a^2(\lambda L)$$

$$= \frac{1}{2}\rho g a^2 A$$

$$\therefore \quad \frac{\text{PE}}{A} = \text{potential energy density} = \frac{1}{4}\rho g a^2$$

Kinetic energy

The kinetic energy of the wave is the energy of the water between two vertical planes perpendicular to the direction of wave propagation in x-direction which are one wavelength apart. In harmonic motion, average kinetic energy and potential energy of the wave are equal. Hence, kinetic energy per unit area is:

$$\frac{\text{KE}}{A} = \frac{1}{4}\rho g a^2$$

Total energy

$$\frac{\text{TE}}{A} = \frac{\text{PE}}{A} + \frac{\text{KE}}{A}$$

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

$$= \frac{1}{2}\rho g a^2$$

Power

The power per unit surface area is the total energy per unit area and per unit time period.

$$\frac{P}{A} = \frac{\text{TE}}{A \times T}$$

But $T = \frac{1}{f}$, where f is the frequency

$$\therefore \quad \frac{P}{A} = \frac{\text{TE}}{A} \times f$$

$$\therefore \qquad \frac{P}{A} = \frac{1}{2} \times \frac{\rho g a^2}{T}$$

$$= \frac{1}{2} \rho g a^2 f$$

- **A 4 m wave has period of 10 s. Find the energy and power density of the wave. Take water density as 1025 kg/m³.**

Given $T = 10$ s, $2a = 4$ m and $\rho = 1025$ kg/m^3.

$$\lambda = 1.56 \times T^2$$

$$= 1.56 \times 10^2$$

$$= 156 \text{ m}$$

Now wave velocity is given by

$$c = \frac{\lambda}{T}$$

$$= \frac{156}{10}$$

$$= 15.6 \text{ m/s}$$

Now $\qquad a = \frac{4}{2} = 2$ m

Wave frequency becomes

$$f = \frac{1}{T} = \frac{1}{10} = 0.1$$

Energy density is given by

$$\frac{E}{A} = \frac{1}{2} \rho g a^2$$

$$= \frac{1}{2} \times 1025 \times 9.81 \times 2^2 \text{ J/m}^2$$

$$= 20{,}110.5 \text{ J/m}^2$$

Power density becomes

$$\frac{P}{A} = \frac{E}{A} \times f$$

$$= 20{,}110.5 \times 0.1$$

$$= 2011.05 \text{ W/m}^2$$

12.3 WAVE ENERGY DEVICES

- **What do you understand by wave energy devices? How are these classified? Explain the working principle of a few wave energy devices.**

or

- **Describe the construction and working of any one type of wave energy conversion machine.**

Wave energy devices are used to convert wave energy into mechanical energy. The fluctuating mechanical energy has to be smoothed out to drive a generator.

Wave energy devices can be classified in several ways. However, they are mainly classified in two ways: on the basis of location in sea and on the basis of actuating motion used in capturing wave energy. On the basis of location, these devices can be (i) offshore or deep water devices (depth more than 40 m) and (ii) shoreline devices. On the basis of actuating motion, these devices can be (i) heaving float type, (ii) pitching type and (iii) heaving and pitching float type.

Heaving float type

These devices have a float placed on the surface of water which heaves or moves up and down with wave due to rise and fall of water level. The up and down motion of the float is used to operate the piston of an air pump as shown in Figure 12.2. The air pump can be anchored to sea bed. Several floats operated air pumps can be used to store wave energy in the compressed air form which can be used to generate electricity with the help of an air turbine coupled to a generator.

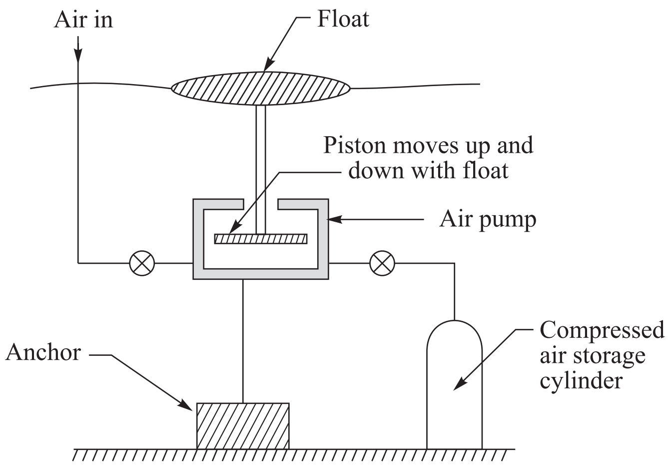


Figure 12.2 Float type wave energy conversion device (air pump).

The motion of float can also be used to run a hydraulic pump so that water can be pumped into an onshore reservoir as shown in Figure 12.3. The water having higher potential energy can be used to run a turbine. A generator coupled with turbine can generate electric power.

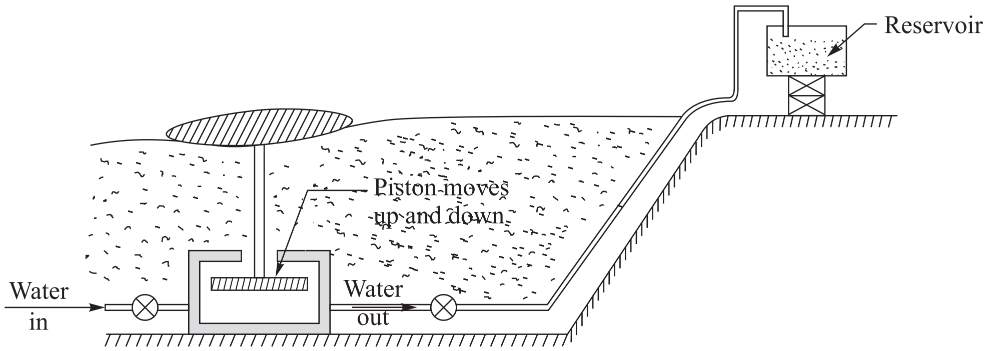


Figure 12.3 Float with hydraulic pump to convert wave energy.

Pitching type

In pitching type wave energy conversion devices, floating pieces (called nodding ducks) are used to be deflected in the direction of wave motion. These floating pieces or ducks are hinged to a common flexible linkage so that the deflection of these pieces can be converted into rotary motion of a shaft, which is moved by the flexible linkage with a ratchet and wheel mechanism. The floating pieces change direction depending upon the passing of peak or trough of the wave over them. The flexible linkage oscillates with nodding ducks, thereby moving the rotary shaft with ratchet and wheel mechanism. Power collected by the rotary shaft from nodding ducks through flexible linkage helps in driving a generator.

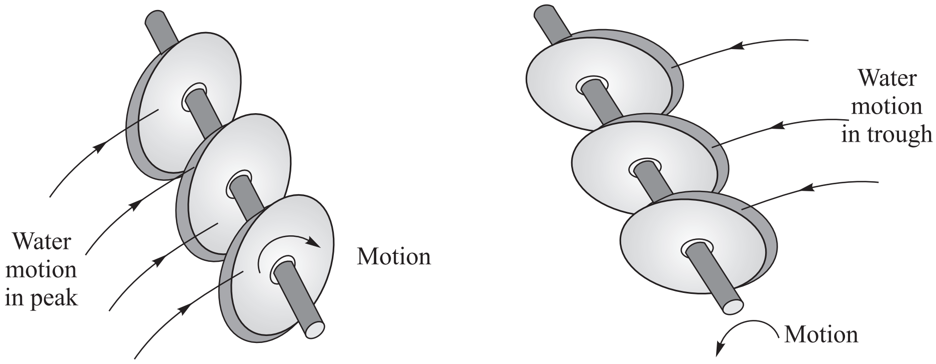


Figure 12.4 Nodding duck assembly or pitching type wave energy conversion.

Heaving and pitching float type

In these types of wave energy conversion devices heaving and pitching motion of a float is used to extract energy from waves. A specially shaped float known as dolphin rides the wave. The device uses both heaving of connecting rod and pitching motion of the float when waves pass through it. The two motions are converted into unidirectional motion with the help of the rachet and wheel arrangement. The motion is used to operate floating and stationary generators as shown in Figure 12.5.

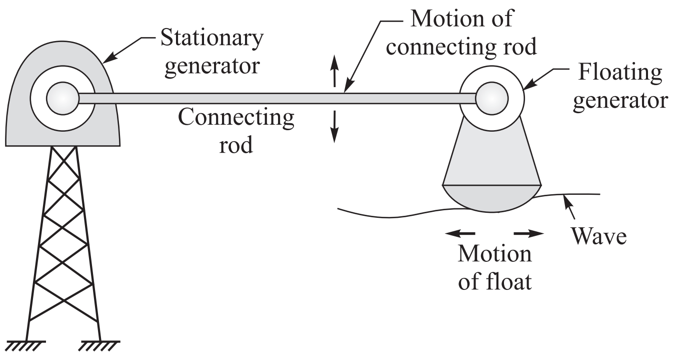


Figure 12.5 Dolphin wave converter using motion of connecting rod and motion of float.

12.3.1 Advantages and Disadvantages of Wave Energy

- **What are the advantages and disadvantages of wave energy?**

The advantages are as follows:

(i) It is a free and renewable energy source.
(ii) It is pollution free.
(iii) It is highly suitable to develop power in remote islands, on drilling platforms and on ship where other alternatives are impossible.
(iv) Wave energy conversion devices help in reducing the erosion of costal region.
(v) Waves are continuously formed and power can be extracted continuously. No storage of power is required.

The disadvantages are as follows:

(i) Sea water is corrosive and life of equipment used in conversion devices is limited.
(ii) Marine growth such as algae adversely affects the working of wave energy conversion devices.
(iii) Wave energy conversion devices obstruct shipping traffic.
(iv) Strong waves during storms can damage the wave energy conversion devices.
(v) Installation of conversion devices is costly.
(vi) Repair, replacement and maintenance are difficult to perform.
(vii) Peak power is available in open sea, where it is difficult to construct, operate and maintain conversion devices as well as transmit power to shore.
(viii) The slow and irregular motion of wave creates problem to run electrical generator which requires high and constant speed motion.
(ix) It may cause disturbance to marine life.

- **Why is the wave energy steadier compared to wind energy?**

Wind interacts with sea water and generates wave. The wave can convey this energy derived from the wind over great distances as dissipation of wave energy is very small because wave propagates on surface water. Hence, wave energy is more steadier and it is a source of energy even when wind stops.

CHAPTER 13

OCEAN THERMAL ENERGY

13.1 INTRODUCTION

Ocean thermal energy is created by solar energy when ocean water absorbs solar radiation. The absorption of solar radiation causes a moderate temperature gradient to develop in water from the top surface to the bottom of the ocean. This temperature gradient can be utilised using a heat engine to generate power. This process of conversion is called ocean thermal energy conversion (OTEC). The surface water acts as the heat source and the deep water acts as the heat sink and heat engine can operate between these source and sink.

A minimum temperature difference of 20°C is required between source and sink so that heat engine can effectively operate to generate power.

13.2 WORKING PRINCIPLE OF OCEAN THERMAL ENERGY CONVERSION

- **Explain the working principle of OTEC plant.**

or

- **Discuss the technology of ocean thermal energy conversion plant.**

Ocean thermal energy conversion is an indirect method of utilising solar energy. A large amount of solar energy as thermal energy is collected and stored in tropical oceans. The surface of water acts as the collector of solar heat. The upper water layer in the ocean acts as an infinite heat storage reservoir or a hot temperature source while the deep water layer in ocean acts as a low temperature sink. Solar heat absorption in the ocean water takes place according to Lambert's law of absorption. According to this law, each layer of equal water thickness in ocean absorbs the same fraction of solar heat when solar radiation passes through ocean water. The radiation intensity (I) in water falls with depth (y) according to the following relation:

$$\frac{dI}{dy} = \mu I_0$$

where I_0 is the solar radiation intensity at $y = 0$,
μ is the absorption coefficient

On integration, we get

$$I = I_0 e^{-\mu y}.$$

The above relation shows that the radiation intensity falls exponentially with the depth (y). Most of the solar radiation is absorbed very close to the upper surface compared to deep water. Therefore, the maximum temperature exists just below the upper surface due to solar heating and the lowest temperature exists at deep water due to the absence of solar heating. The temperatures are maintained as high at surface and low at deep water as no thermal convection currents between warmer and light water at the top and colder and heavy water at the bottom of the ocean can take place. The warm water stays at the top and cold water stays at the bottom, thereby forming two infinite heat reservoirs of constant temperature, that is, a heat source at the top at about 27°C and a heat sink at about 4°C at some depth from the top. These reservoirs are maintained by the absorption of solar radiation on a regular basis. A heat engine can work between this heat source and heat sink to convert heat into mechanical work. The efficiency of heat engine is limited to Carnot engine efficiency, which is given by

$$\eta = \frac{T_1 - T_2}{T_1}$$

where T_1 is the source temperature in Kelvin and T_2 is the sink temperature in Kelvin.

In case we take T_1 = 27°C and T_2 = 7°C, we have

$$\eta = \frac{(27 + 273) - (7 + 273)}{(27 + 273)}$$

$$= 6.67\%$$

The ocean thermal energy can be converted into mechanical or electrical energy when the temperature difference between the warm water at surface and the cold water at the depths is about 20–25°C. This temperature difference generally exists in tropical oceans. The utilisation of this ocean thermal energy where a suitable temperature difference exists between the warm surface water and the cold water at the depths in tropical oceans by its conversion into mechanical work forms the basis of OTEC system. The warm surface water can also be used to heat some low boiling point refrigerant to obtain high pressure vapours which can run a gas turbine to obtain mechanical work.

13.3 OCEAN THERMAL ENERGY CONVERSION SYSTEMS

- **What are different types of OTEC power plants? Describe their working in brief.**

or

- **What are the main types of OTEC power plants? Describe the working of anyone type in brief.**

OTEC plants can operate using open cycle or closed cycle. The open cycle is also known as the Claude cycle while the close cycle is also known as Anderson cycle.

Open cycle

Warm water from the top surface is evaporated to obtain low pressure steam by using a flash evaporator maintained at partial vacuum as water can evaporate at the lower temperature when pressure is lower than atmospheric pressure. The low pressure steam obtained from flash evaporator is expanded in a turbine to extract machanical energy. The steam after energy removal in turbine is condensed into water in a condenser which is cooled by cold water drawn from the depths in the ocean. The working of an open cycle OTEC plant is shown in Figure 13.1.

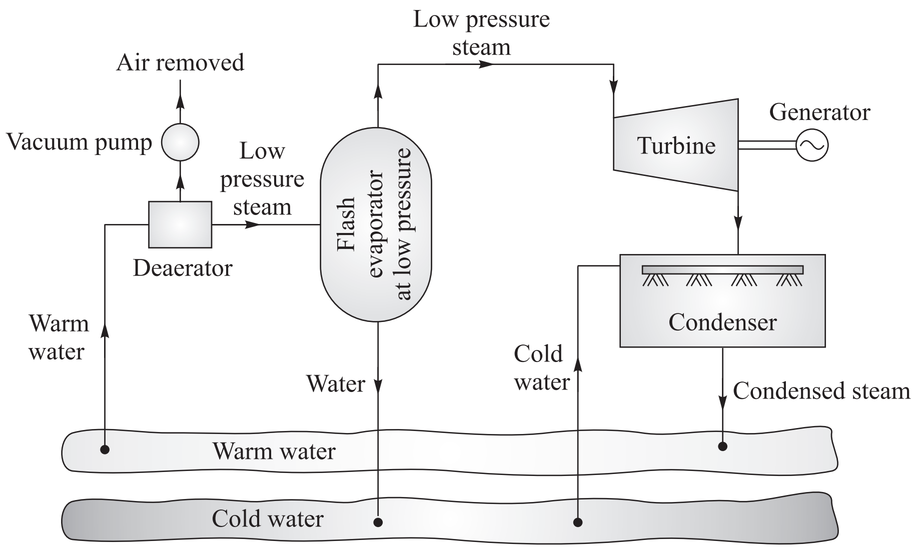


Figure 13.1 Open cycle OTEC plant.

Closed cycle

In the closed cycle, warm surface water is used to evaporate a low boiling point refrigerant (ammonia or freon) and refrigerant vapour is made to flow through the turbine to extract energy. The vapour coming out from the turbine after performing work is cooled and condensed in a condenser cooled by cold water pumped from the ocean depths. The closed cycle is shown in Figure 13.2. Such plant is much compact in size and less costly compared to open cycle OTEC plant.

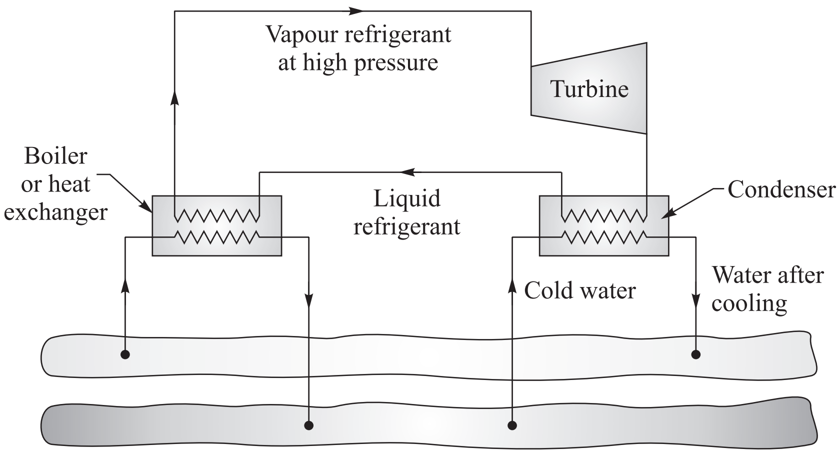


Figure 13.2 Closed cycle OTEC plant.

13.4 STATUS OF OTEC PLANTS

- **Name some power plants installed in the world based on ocean thermal energy.**

Many countries are actively involved in research and development of OTEC plants. The plants that have been planned and launched are as follows:

(i) France has built a 5 MW OTEC shore plant in Tahiti.
(ii) A 50 kW floating plant has been built at island of Nauru in Japan. Another 20 MW power plant is to be built by Tokyo Electric Company.
(iii) A 10 MW closed cycle plant in Caribbean or Pacific ocean and a 500 kW closed cycle onshore plant in Hawaii have been planned by the United Kingdom.
(iv) A 100 kW on shore plant has been completed at Bali. Another 10 MW floating plant is under planning by the Dutch.
(v) A 22 kW OTEC plant at Cuba was built in 1930.
(vi) A 10 MW OTEC plant at Guam has been planned.
(vii) A 1 MW OTEC plant at the coast of Lakshadweep Island has been planned.

13.5 MERITS AND DEMERITS OF OTEC PLANT

- **What are the merits of the OTEC plant?**

or

- **What are major limitations of the OTEC plant?**

or

- **What are the possible environmental effects as a result of the operation of an OTEC?**

The advantages of OTEC are as follow:

(i) The plant can supply steady power without any fluctuation in all the vagaries of weather.
(ii) The power output does not vary from season to season.
(iii) The plant needs usual thermodynamic devices and equipment, such as turbine, heat exchanger and condenser.
(iv) The useful by-products from the OTEC plant are desalinated water and nutrients from marine culture.
(v) The plant can be constructed on shoreline or on floating platform.
(vi) The plant of any size or capacity can be constructed at a suitable site.

The demerits of OTEC plant are as follows:

(i) As low temperature difference exists in upper surface and deep water, thereby plant has a very low efficiency in converting ocean thermal energy. Hence, a large plant size at huge cost has to be constructed to meet the power requirement.
(ii) The design, operation and maintenance of flash evaporator in the open system are problematic.
(iii) The design of steam turbine to operate at low pressure is problematic.
(iv) The large size of heat exchanger to work as boiler is problematic while designing the closed system.
(v) The development of pumps suitable for handling large amounts of water is problematic.
(vi) Long-distance cable to transmit power to shore is required.
(vii) The plant has to withstand severs ocean conditions and storms. The plant equipment has to resist the corrosive effects of ocean water. The plant has to remove algae growth on a regular basis.
(viii) The whole plant has to be constructed on floats. Equipment has to be installed at a great depth to reach the cold water level.
(ix) The plant at shoreline may require pipes of large diameter and length for handling water.

The environmental impacts due to construction of OTEC plant are as follow:

(i) The marine life (eggs, larvae and fish) can be destroyed due to water circulation.
(ii) The plant may affect ecosystem and impact coral. It can also influence ocean currents and climate.
(iii) The plant releases a large quantity of cold water into warmer surface environment which may adversely affect the marine life.
(iv) The carbon dioxide dissolved in warm water is released to the atmosphere in open cycle, which has greenhouse effect on environment.

CHAPTER 14

ENVIRONMENT AND KYOTO PROTOCOL

14.1 INTRODUCTION

Environment means surroundings which include air, soil and water. Nature originally provided surroundings to living beings in a clean form. Owing to various man-made reasons, the quality of environment is continuously deteriorating. A number of activities involving energy generation and utilisation adversely affect the environment. Ecology is concerned with the relationship between living beings and environment. The environment or nature has a self-cleaning capability and environment recycles its resources to maintain equilibrium through various processes such as water cycle and carbon cycle. However, the ecological balance gets disturbed whenever human interference exceeds the limit.

14.2 ENVIRONMENTAL ASPECTS

14.2.1 Greenhouse Effect

- **What do you understand by the greenhouse effect? How is it caused?**

A greenhouse is an enclosure or hut made of transparent glass panes to prevent any escape of heat. The greenhouse can maintain a controlled and warm environment inside the enclosure when outside climate is cold. The greenhouse behaves differently for incoming visible or shortwave radiation compared to outgoing or escaping infrared or longwave radiation. The greenhouse allows visible radiation to enter, but it prevents infrared radiation from escaping and so heat remains entrapped in the enclosure. The carbon dioxide layer forms an envelope around earth's atmosphere which behaves similar to the glass panes of the enclosure. The layer prevents the escape of heat from the earth, thereby leading to global warming. This phenomenon is known as greenhouse effect. Normal concentration of CO_2 in the outer atmosphere is 0.03% which helps in maintaining average surface temperature of about 15°C on the earth. In the absence of this layer, earth's surface temperature will be about –25°C. Any increase in the concentration of CO_2 from 0.03% will lead to further warming of the earth above 15°C with disastrous consequences. Other gas besides CO_2 which produce greenhouse effect are methane, nitrous oxide, hydrofluorocarbons, sulphur hexafluoride and perfluorocarbons. All these gases are known as greenhouse gases (GHG). The carbon dioxide emission is mainly caused by the burning of fossil fuels in industry. The developed countries are more industrialised. This is the reason why CO_2 emission from developed countries accounts for 80–85% of total greenhouse gas emission of the world.

14.2.2 Global Warming

- **What are the consequences of global warming?**

Owing to more emission of greenhouse gases, the average global temperature is increasing at a rate of 0.2°C per decade. The global warming can lead to the melting of polar snow, which will increase the water level in the oceans. Increase in water level in oceans will inundate low-lying areas and most of the islands of the world.

14.3 KYOTO PROTOCOL

- **Explain Kyoto Protocol agreement for reduction of greenhouse gases.**

or

- **Explain emission or carbon trading.**

or

- **What do you understand by the clean development mechanism?**

The Kyoto protocol is a legally binding agreement on international level accepted by most of the countries to reduce greenhouse gas emission and risk of global warming. It came into force on 16 February 2005. The greenhouse gases are carbon dioxide, methane, nitrous oxide, hydrofluoro carbons, hexafluoride and perfluorocarbons. About 183 countries including India have ratified this protocol.

The major feature of the Kyoto Protocol is that it sets binding targets for industralised countries to reduce greenhouse gases emission so that global warming can be monitored and controlled. The protocol recognises and accepts that the developed countries are principally responsible for the current high concentration of greenhouse gases in the outer atmospheric layer of the earth as a result of more than 150 years of industrial activities. Hence, Kyoto Protocol places a heavier burden on the developed countries under the principle of "common but differentiated responsibilities". The Kyoto Protocol lays down that the developed countries are required to reduce their emission of greenhouse gases by an average of 5.2% below the year 1990 levels by the year 2012.

The Kyoto Protocol mechanism

The agreement lays down that member countries must meet their target to reduce greenhouse gases primarily through their own measures. However, the Kyoto Protocol offers them several other means or measures to meet their targets using any of the following three market-based mechanisms:

(i) Emissions trading or carbon trading mechanism
(ii) Clean development mechanism (CDM)
(iii) Joint implementation (JI) mechanism

Emission trading or carbon trading

The member countries of the protocol have accepted emission targets for limiting or reducing the greenhouse gas emissions. These emission targets are called allowed emission or assigned amounts. Therefore, every member country has been assigned allowed emissions as assigned amount units (AAUs). A country cannot generate greenhouse gases more than the assigned amount units.

The countries are allowed to use the option of emission trading or carbon trading to meet their obligations if they maintain or increase their greenhouse gas emissions. Emission or carbon trading allows nations that can easily meet their targets to sell emission credits to those that cannot meet their emission targets.

The Kyoto Protocol sets specific emission targets to each industrialised nation, but it excludes developing countries from any emission target. To meet their targets, most member nations have to adopt the following measures:

(i) Place restrictions on the industry causing major pollution problems
(ii) Manage transportation to reduce emission from automobiles
(iii) Adopt renewable energy sources in place of fossil fuels.

Clean development mechanism

This mechanism is laid down in Article 12 of the protocol and it allows a country with the emission reduction or limitation commitment to implement an emission reduction project in developing countries. Such projects can earn saleable certified emission reduction (CER) credits. Each CER credit is equivalent to the reduction of 1 ton of CO_2 emission and this can be counted towards meeting assigned GHG (greenhouse gases) emission targets. A *clean development mechanism* activity may be a rural electrification project using solar panel or it may be the adoption of more energy efficient boilers, thereby reducing the greenhouse gas emissions. The clean development mechanism must ensure a sustainable development to provide reduction in emission. However, every nation has flexibility in deciding the procedure or means to meet its emission limitation targets.

Joint implementation

The joint implementation has been defined in Article 6 of the Kyoto Protocol. It allows a country with an emission reduction or limitation commitment under the protocol to earn emission reduction units (ERUs) by executing an emission reduction or removal project in another country. Each ERU is equivalent to the reduction of 1 ton of CO_2 gas. The ERUs are counted towards the emission limitation target of a country.

CHAPTER 15

SMALL HYDRO RESOURCE

15.1 INTRODUCTION

For harnessing hydropower, both major and minor hydro resources are important and needed to be developed. However, major or large hydro projects involve construction of large dams which have many social and environmental consequences. These include submerging and loss of forest or agricultural land, the need to rehabilitate or relocate villagers from the submerged area, the risk of increasing seismicity as large amounts of water is stored in the reservoir, excessive siltation at the dam site and the adverse effect on fish population. Till 1972, most countries had tried to develop the large hydropower projects as these plants could produce energy at low cost to compete with thermal power. However, with the present trend of depleting fossil fuels and their steady price rise, all countries have started focusing more on the development of small hydropower resources which were previously regarded as uneconomical. There is also remarkable advancement in technology concerning the production of turbines suitable for utilising efficiently heads and small discharges, which has changed the public attitude and their confidence in the success of developing small hydropower installations to a large extent. The equipment to construct and run such plants are now readily available.

Hydropower projects of ratings less than 10 MW are regarded are small hydro plant (SHP). Small hydropower resources are considered as non-conventional and these resources have attracted favourable attention after the oil crisis of 1973. The small hydropower projects are extremely suitable for hilly, underdeveloped and remote areas as these resources eliminate the need of long transmission system. These projects have also lower gestation period and lower investment or cost as no large dam or reservoir is needed for such projects. Small hydro plants can be built by local-staff and smaller organisations using locally made machinery. Hence, decentralised small hydropower or mini hydel schemes are attractive option for energy supplies in rural areas.

15.2 CONVERSION OF HYDROPOWER

• How is the electric power generated from hydropower?

Electric power is generated when water from height is made to flow through hydraulic turbine. The hydraulic turbine converts the potential energy of water or kinetic energy of flowing stream into mechanical energy on its rotating shaft. The old-style water wheels used the impulse generated by the weight of falling water for their rotation, but modern hydraulic turbines operated on the principle of impulse and reaction to convert kinetic energy and potential energy respectively into mechanical energy. The work done per second or power given by the flowing water can be given by the following expression:

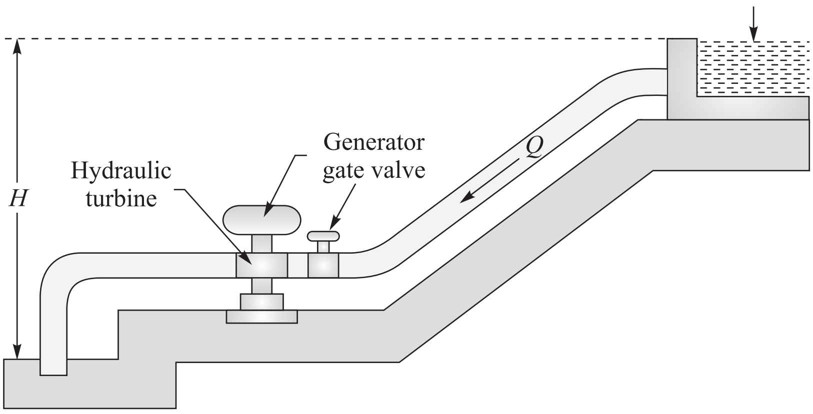


Figure 15.1 Conversion of hydropower into electricity.

$$\text{Power, } P = \text{Potential energy of flowing water in turbine}$$

$$= \text{mass} \times \text{coefficient of gravitational acceleration} \times \text{head}$$

$$= m \cdot g \cdot h$$

But $$m = \text{discharge} \times \text{density}$$

$$= Q \times \rho$$

$$P = \rho Q g H$$

An electric generator is directly coupled to the hydraulic turbine which converts the mechanical energy into electric energy.

• What are the factors affecting the hydropower?

The hydropower which can developed from water depends on the head or potential energy of the water and discharge through the turbine.

15.2.1 Turbines

- **What are the principles on which turbines work?**

The turbines can work on the principles of impulse and reaction. In impulse turbine, the complete potential energy or head of water is firstly converted into kinetic energy using a nozzle outside the turbine. The fast jet of water emerging from the nozzle is used to strike the vanes of the turbine to impart motion. In reaction turbine, nozzle is not used and vanes (guide or stationary vanes and movable vanes on the rotor) are shaped in the form of nozzles to convert potential energy of water into kinetic energy when water flows from the inlet to the outlet of the turbine. The turbines can be (i) water wheel (ii) impulse turbine (iii) Francis turbine and (iv) Kaplan turbine as shown in Figure 15.2.

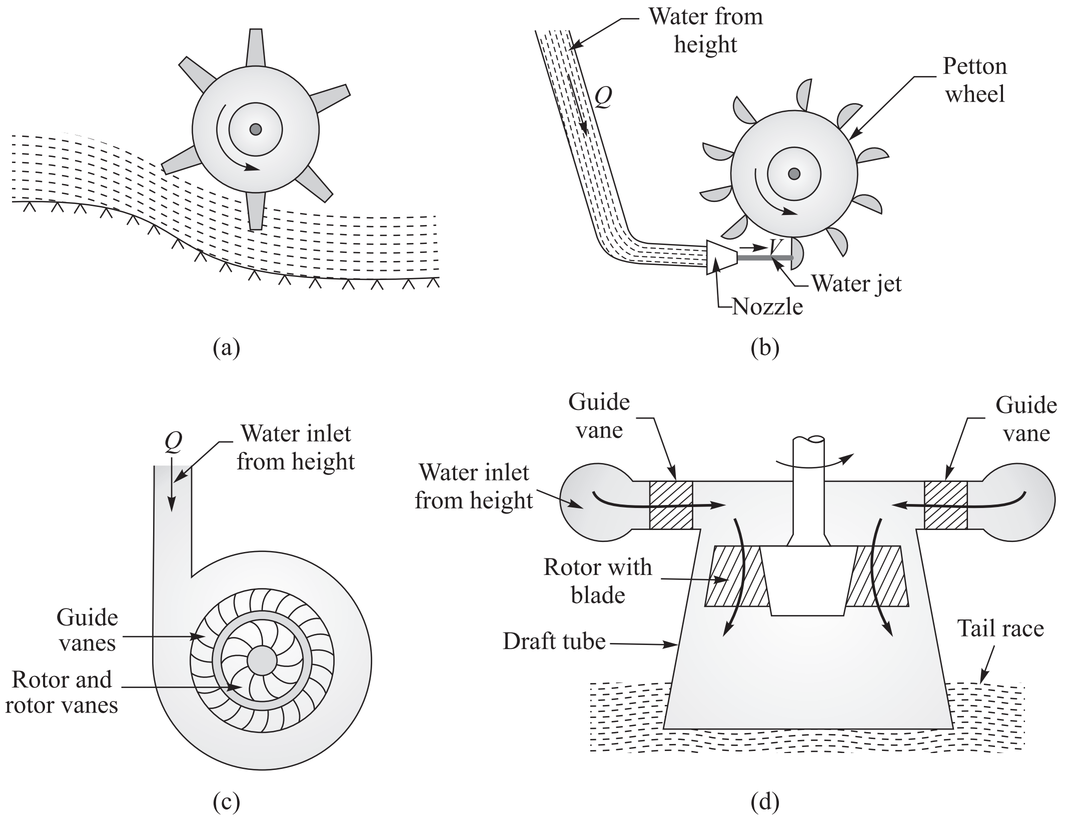


Figure 15.2 Types of hydraulic turbines. (a) Water wheel, (b) Impulse turbine, (c) Reaction turbine (Francis) and (d) Reaction turbine (Kaplan).

15.2.2 Speed Control of Turbines

- **How is the speed control achieved in turbines?**

There is a tendency in turbine to speed up when the load on turbine falls and turbine slows down when load is increased. It is necessary to run the turbine at a constant speed by using a governor. The governor can (i) reduce or increase the water flow through a nozzle of an impulse turbine, (ii) change the passage between the guide vanes to reduce or increase water flow in a radial flow reaction turbine (Francis turbine) and (iii) change the passage between both guide and runner vanes to reduce or increase the water flow through the axial flow reaction turbine (Kaplan).

15.2.3 Suitability of Turbines

- **How are turbines classified? How is a turbine selected for a site?**

The Turbines are classified according to their specific speeds. The selection of turbine on the basis of specific speed is made in the following ways:

(i) **Low specific speed.** Impulse turbines have a low value of specific speeds and these turbines are suitable to work under high head and large discharge conditions. The specific speeds of these turbines vary from 8 to 50.

(ii) **Medium specific speeds.** Reaction turbines such as Francis turbines have specific speeds varying from 51 to 225. These turbines are suitable to work under moderate head and discharge conditions.

(iii) **High specific speeds.** Reaction turbines such as Kaplan turbines have high specific speeds varying from 250 to 850. These turbines are suitable to work under low head and large discharge conditions.

15.3 SMALL HYDROPOWER PLANTS

- **How do you classify small hydropower plants?**

The hydropower plants having capacity below 10 MW are classified as small hydropower plants. As these plants have small generation capacity, there is no need for large reservoir or dam to store water. Any seasonal variation in water flow in the water stream affects the power output from these plants. Perennial streams flowing in hilly areas with steep gradients are the most suitable sites for such plants. These plants can, therefore, meet the power requirements of most of the hill areas. Several international agencies are providing technical and financial assistance for the construction of small hydropower plants in developing countries so as to improve the quality of life in underdeveloped areas. Small hydro resources are largely free from any pollution and their potential is, therefore, increasingly being utilized.

Depending on the capacities, small hydropower plants can be classified as follows:

(i) **Micro hydel plants.** The plants generating power up to 100 KW are called micro hydel plants.

(ii) **Mini hydel plants.** The plants generating power above 100 kW but less than 1000 kW (1 MW) are classified as mini hydel plants.
(iii) **Small hydel plants.** The plants generating power in the range of 1–10 MW are classified as small hydel plants.

Depending upon available heads, the small hydropower plants (micro, mini and small) can also be classified as follows:

(i) Ultra-low heads up to 3
(ii) Low heads from 3 to 30
(iii) Medium heads between 30 and 75
(iv) High heads above 75

The small hydel schemes can also be classified as follows:

(i) **Independent schemes.** In these schemes, the stream flow is captured, regulated and developed for the purpose of power generation only. The low head schemes are unsuitable to be developed as independent power generation schemes.
(ii) **Subordinate schemes.** As the name suggests, the main purpose is not to generate electricity, but to supply water for irrigation or drinking. These schemes are suitable for micro and mini hydel plants because of the availability of small slopes in the canal system.

15.3.1 Demerits of Small Hydropower Sources

- **Why does the potential of small hydropower sources remain untapped?**

or

- **What are the demerits of small hydropower sources?**

The potential of small hydropower resources remains untapped for the following reasons:

(i) Small hydel plants entail high cost of power generation per unit
(ii) High managerial and administrative costs due to installation at isolated and remote areas
(iii) Low load factor or utilization of power
(iv) Unstable operation of isolated system due to changes in stream flow in different seasons. Generation depends upon availability of flow
(v) Susceptible to losses due to extreme climatic conditions leading to flooding, thereby damaging the equipment

15.3.2 Merits of Small Hydropower Resources

- **What are the merits of small hydropower resources?**

or

- **What are the major advantages of mini/micro hydro resources?**

The advantages of small hydel plants are as follows:

(i) The plants can be built locally at low cost.
(ii) It can be considered as a renewable energy resource.

(iii) It is a non-polluting resource.
(iv) Its installation does not require long gestation period. Installation may be also within 6–24 months.
(v) Its operating costs are low as skilled manpower is not required for operation and maintenance.
(vi) It is an ideal decentralised power generation resource which is meant to supply energy to local areas, thereby eliminating distribution losses and costs.
(vii) The project neither submerges any area nor displaces any nearby villagers as necessary in the case of a large hydropower with the construction of dam.
(viii) Small hydropower plants can be developed to augment hydropower capacity of existing irrigation dams.

15.3.3 Bulb Turbine

- **What do you understand by bulb turbine?**

Bulb turbines with their coupled generator are enclosed in a shell-like structure called bulb. The bulb turbine is so designed that it can be conveniently installed horizontally in any low depth streams. It is capable to work efficiently even where low heads are available. It can work with a head of 1/2 to 95 m. It can generate power as low as 5 kW and as high as 50 MW.

15.3.4 Components of a Small Hydropower Plant

- **What are the various components of a small hydropower plant or a micro hydel scheme?**

or

- **Discuss the main features of the micro hydel schemes.**

The components or features of the micro hydel schemes and their layout are shown in Figure 15.3. The components of the scheme and their features are explained below:

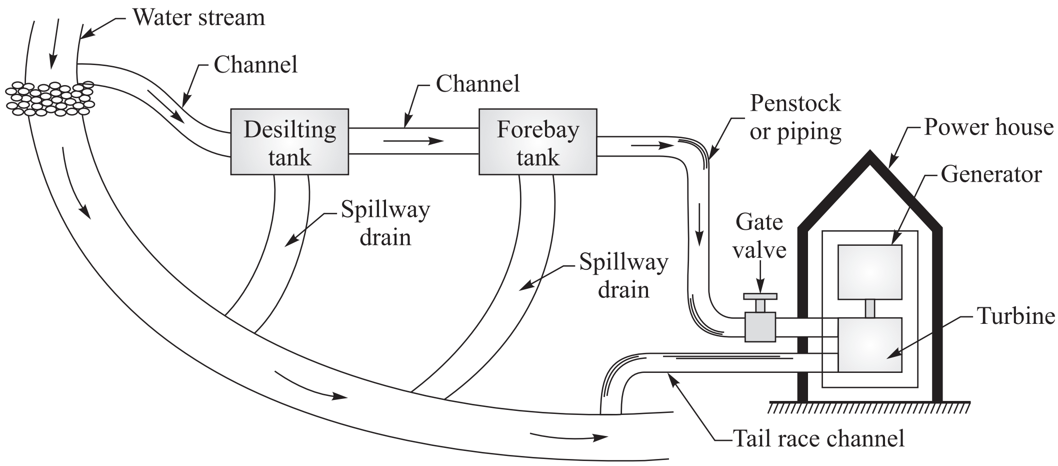


Figure 15.3 A typical layout of a micro hydro power plant.

(i) **Diversion structure.** Small dams, barrages, solid boulder structures or trench type weirs are usually constructed to divert the required flow from the water streams into the intake structures. The diversion structure should be designed in such a way that it can be supplied water in all seasons and it should be reasonably safe against large floods.

(ii) **Desilting tank.** It is necessary to remove and trap the suspended matters, silt and pebbles so that no erosion or damage to the turbine can take place by these matters. The desilting tank is provided in the initial length of water channel. The velocity of water flow is reduced considerably in desilting tank for desilted matters to settle down. These are flushed out whenever required using spillway drain.

(iii) **Water channel or conductor system.** It is designed to ensure that the water flow can take place with least loss of head and loss of water. RCC duct, steel pipe and open tiled channel can be used as water conductor system.

(iv) **Forebay tank.** Forebay is provided as a reservoir to hold sufficient water so that it can meet the water requirement to run the turbine for 4–6 h. It is also meant to ensure minimum head over the penstock intake is maintained so as to prevent any air entry into penstock. An overflow arrangement in the forebay tank is provided to discharge surplus water when water is not required by the turbine.

(v) **Penstock.** The water from forebay tank is carried through penstock or pipeline to the turbine. MS pipes or RCC pipes can be used as the penstock.

(vi) **Powerhouse.** It houses turbine with coupled generator.

(vii) **Tail race channel.** The water exiting from the turbine is discharged through the tail race channel to water stream.

15.3.5 Designing of a Micro Hydel Scheme

- **What are the various factors considered in designing a micro hydel scheme?**

The factors considered while designing a micro hydel scheme are as follows:

(i) **Water discharge (Q).** The minimum discharge data from water stream are to be determined to calculate possible minimum power generation. Data for atleast 1 year are needed.

(ii) **Gross head and net head.** The actual available head for power generation is always less than gross head due to various losses taking place from the forebay tank to the turbine's tail race. The total head is the difference of height from the level of water in tail race to the level of water in the forebay tank.

(iii) **Demand versus power generation.** The demand of electricity can be estimated from the number of dwelling units, population, industry, institutions and anticipated future growth. Demand or load factor is an important factor while deciding the design of micro hydel scheme. The power potential of a scheme is given as follows:

$$P = \text{efficiency} \times \text{discharge} \times \text{net head}$$

$$= \eta \times (Q \times \rho) \times H$$

15.4 CONCEPT AND POTENTIAL OF MICRO HYDEL IN INDIA

- **What is the concept and potential of micro hydel schemes in India?**

or

- **Discuss various micro hydel power stations installed in India.**

The concept and potential of micro hydel in India are discussed next.

Independent schemes

The north and north-eastern areas in India are hilly and mountainous. These areas are sparsely populated and have accessibility problems. Extension of transmission lines from plains to hilly and isolated areas is difficult and expensive. These isolated areas have hilly streams which can be utilised for generation of power through micro hydel. The power can be distributed to the surrounding villages through isolated power grids or transmission lines.

Subordinated schemes

A large irrigation network has been developed in India which can be considered a potential source to generate power by using small or micro hydel plants.

In the irrigation canals, it is possible to obtain a head of 2 m or above. By using these heads with sufficient discharge of water, it is possible to generate sufficient power to meet local demands.

The potential of small hydropower in India is estimated to be around 5000 MW, with about 3000 MW power expected in low head regions. The Department of Non-Conventional Energy Sources (DNES) is also undertaking research and development work of micro hydel plants as it is doing for other renewable energy resources. The locations and other details about micro hydel power stations as installed in India are given in Table 15.1.

TABLE 15.1 Micro hydel power stations installed in India

Head	*Location*	*Installed capacity* (kW)	*Net head* (m)	*Discharge* (m^3)
High	Jubbal (HP)	1 × 100	88	0.17
Medium	Manali (HP)	2 × 100	40	0.8
Ultra-low	Kakroi (Haryana)	3 × 100	1.9	31.15
Low	Ralia, Bhatinda	1 × 200	3	8.5
Low	Ganga canal, Saharanpur	2 × 125	35	5.66

15.5 RESEARCH AND DEVELOPMENT IN INDIA

- **What are the main research and development activities going on in India in the area of micro hydel schemes?**

or

- **What are the main problems being faced for the development of small hydropower resources?**

The micro hydel schemes are highly suitable source of renewable energy and these schemes generally involve moderate investment to provide electricity to undeveloped areas. However, the development of micro hydel schemes is not getting proper attention due to certain constraints such as low load factor, unavailability of equipment suiting to ultra-low head region, higher cost of control and management, changes in flow of water stream depending upon seasons and uneconomical cost of power production.

DNES has tasked the Alternate Hydro Energy Centre (AHEC) at IIT Roorkee to develop new and improved equipment and design to be used in the construction of micro hydel schemes in low and ultra-low head regions such as in hilly areas and irrigation canals. The major achievements reported to be made by AHEC are as follows:

(i) Indigenous design and development of single and three phase electronic output controllers to be used with micro hydro schemes which are cost-effective
(ii) Suitable development of induction generators for micro hydel schemes
(iii) Suitable development of turbines without wicket gates for micro hydel schemes
(iv) Suitable design of intake from water streams. The vertical drop intake with vortex helps in improving the performance of intake structure as it helps in self cleaning operation
(v) Suitable designing of vertical fixed wheel gates to ensure control of micro hydel schemes in emergency
(vi) Designing of silt excluder with guide vanes which is cost-effective

AHEC is reported to be currently engaged in the following research and development activities:

(i) In the modification of pumps so that these can be used as turbines in a cost-effective way
(ii) In the development of micro-processor based control system so as to provide proper protection to micro hydel station
(iii) In the development of turbines which can convert the kinetic energy of flowing water into the mechanical work
(iv) In the development of variable speed but constant frequency generator for micro hydel plants
(v) In finding solutions to site-specific problems

15.6 MICRO HYDROPOWER FOR SOCIO-ECONOMIC DEVELOPMENT

- **Micro hydropower is an option for socio-economic development comment.**

There is hardly any electric energy supply to the rural areas in many developing countries. Less than 10% of the rural population has no access to the benefits of electricity. Rural electrification using conventional means such as grid connection or diesel generators is a costly proposition. However, nature has provided abundant water resources which can be used for power generation in poor countries. Hence, decentralised small hydel plants or micro hydro schemes are attractive option to use these water resources by installation of micro hydel plants. These plants can ensure the socio-economic development in the isolated and remote mountainous areas.

It is reported that thousands of micro hydel plants are operating successfully in countries such as China, Nepal, Sri Lanka, Pakistan, Vietnam and Peru. Their success indicates that in certain circumstances, micro hydel plants can be profitable in financial terms. Even unprofitable micro hydel plants have shown strong positive impacts on the lives of poor people. The micro hydel plant can be installed to achieve a wide range of quite different objectives. Hence, each micro hydel plant is to be evaluated in terms of a specific objective. It is wrong to expect that the micro hydel plant should achieve many conflicting objectives. For instance, it may not be possible to supply electricity to poor rural population in remote areas with the help of micro hydel scheme and make a high return on investment. It is also advocated that the investment in micro hydel schemes should be seen as a part of social infrastructure similar to the provision of health services, roads and schools. In Sri Lanka, many micro hydro plants have been installed primarily to improve the quality of life by providing electricity. While installing micro hydel plants, the key question should be "How long will the plant last?", rather than "How high is its rate of return or how quickly the investment will be paid back?". It is reported that micro hydel plants are now being seen in terms of securing livelihoods and the development of small profit-making business. The country such as Nepal has demonstated that small business can survive using micro hydro power such as used for milling grains. Nearly 900 micro hydro plants had been installed in Nepal by 1996 for grinding grain and these are operating profitably. Micro hydel schemes have an impressive record of poverty reduction performance in Nepal and Ethiopia. Micro hydel schemes are indeed a relatively efficient method for poverty reduction in terms of cost per person moved across the poverty line. Besides poverty reduction, there are other benefits such as time saving as one no longer has to carry kerosene or other fuels, improved education due to the availability of electric light and improved health and agricultural production due to irrigation facilities made possible by running pumps through electricity generated from micro hydel plants.

CHAPTER 16

ENERGY MANAGEMENT

16.1 INTRODUCTION

The fundamental goal of energy management is to produce goods and provide services both at the minimum cost and at minimum risk or adverse effect to environment. Energy management involves the strategy of adjusting and optimising energy by using systems and procedures which can reduce energy requirements per unit of output while holding or reducing total cost of the production from these systems. Energy audit is a systematic approach to analyse the use of energy for decision-making in the area of energy management.

Energy economics is the field that studies human utilization of energy resources and energy commodities and the consequences of that utilization. Energy commodities (gasoline, diesel fuels, natural gas, coal, electricity) can be used to provide energy services for human activities such as lighting, space heating, water heating, cooking and motive power. Energy resources (crude oil, natural gas, coal, biomass, hydro, uranium, wind, sunlight and geothermal deposits) can be harvested to produce energy commodities. Energy economics involves the study of economically efficient provision and the use of energy commodities and resources as well as the factors that may lower the economic efficiency of energy commodities and resources.

Energy is an important element of the infrastructure sector and its availability has to be ensured on a sustainable basis. But the demand for energy is growing manifold and the energy sources are becoming scarce and costly.

Among the various strategies that have to be adopted to meet this energy demand, the efficient use of energy and its conservation emerges to be the least costly preposition apart from being friendly to the environment. The steps to create sustainable energy system begin with the judicious and wiser use of resources as energy efficiency is the mantra that can lead the world to the sustainable energy management.

16.2 ENERGY ECONOMICS

16.2.1 Definitions

- **Define energy economics, energy, energy commodities and energy resources.**

Energy economics

It is the field that studies human utilization of energy resources and energy commodities. It also includes the study of consequences of the utilization of energy resources and energy commodities.

Energy

It is the capacity to do work, such as lifting, accelerating, transporting, heating and cooling. All energy commodities and energy resources embody a significant amount of physical energy and thus offer the ability to perform work.

Energy commodities

These can be used to provide energy services for human activities, such as lighting, water heating, motive power and cooking. Gasoline, diesel, natural gas and electricity are energy commodities.

Energy resources

These can be harvested to produce energy commodities. Crude oil, coal, biomass, uranium, wind and sunlight are energy resources.

- **What do you understand by the term energy economics?**

Energy economics is the field that studies forces that compel economic agencies (firms, individuals and government) to supply energy resources, to convert those resources into other useful energy forms, to transport them to the users, to use them and to dispose of the residuals. It also studies roles of alternative market and regulatory structures on these activities, economic distributional impacts and environmental consequences. Furthermore, also studies (i) economically efficient way of provision and use of energy commodities and resources and (ii) factors which may not allow this economic efficiency. Thus, energy economics is the study of human activities using energy resources from naturally available forms through complex conversion processes to forms which can provide energy services.

16.2.2 Energy Commodities and Energy Resources

- **How are energy commodities and energy resources classified?**

The energy commodities and resources can be differentiated on the basis of physical energy embodied by them. The physical energy can be of the following kinds:

(i) **Chemical energy.** Oil, natural gas, coal and biomass embody chemical energy

(ii) **Mechanical energy.** Wind, ocean waves and running water in streams have mechanical energy
(iii) **Thermal energy.** Geothermal deposits, sunlight and oceans have thermal energy
(iv) **Electrical energy.** Electricity has electrical energy
(v) **Nuclear energy.** Uranium, thorium and plutonium have nuclear energy

The energy commodities and resources can also be classified on the basis of physical forms:

(i) **Liquids.** Crude oil, refined petroleum products and water are liquids
(ii) **Solids.** Coal, biomass, wood and uranium are solids
(iii) **Gaseous.** Natural gas and winds are gases

Resources can also be classified on the basis of sustainability as renewable and depletable. Furthermore renewable resources can be classified as storable and non-storable.

16.2.3 Energy Conversion Processes

- **Why is it necessary to convert energy? What is the fundamental property of energy?**

The fundamental property of energy is given by the first law of thermodynamics. According to this law, energy can neither be created nor be destroyed. Energy can be converted from one form to another, and such conversion helps in making it suitable for human needs. For example, when wood is burned, chemical energy stored in wood is converted into thermal energy. Similarly, petrol and diesel embody chemical energy which is liberated in the form of thermal energy during combustion in IC engines. In thermal plant, thermal energy of fuels is converted into electric energy which enables to power a motor (mechanical energy), heat a room (thermal energy) and light a bulb (thermal energy).

Energy conservation or energy interchangeability is the fundamental property of the energy which specifies that (i) no energy can be created or destroyed, but it can be converted from one form to another and (ii) energy comes from the physical environment and released back into the physical environment when it is used. Hence, energy interchangeability leads to energy economics which encourages various human activities, thereby utilizing energy resources available in natural forms in the physical environment and their conversion into the suitable forms which can provide energy services to the mankind.

16.2.4 Demand for Energy

- **What are the factors influencing the demand of energy?**

or

- **How is energy demand derived?**

Energy demand is derived from customer's need to use energy to obtain desired services. Energy demand depends upon the following factors:

(i) Consumer's demand for desired services
(ii) Availability and properties of energy conversion technologies
(iii) Costs of energy conversion technologies used for energy.

Petrol as a fuel (energy) is needed by consumers to run automobiles, thereby converting petrol to mechanical energy for motive power (desired service). The cost of energy or petrol depends upon the distance travelled. Hence, demand for petrol is derived from the demand by the consumer for the best mileage by the automobile. Similarly, a consumer purchases electricity to run air conditioner, refrigerator television, and so on. Hence, the demand for electricity is derived form the demand by consumers for the desired services such as (i) cooling and preservation of food items by refrigerator (ii) comfortable space by air conditioner and (iii) entertainment and information by television. In each case, efficiency of energy conversion by equipment also plays an important role in determining the requirement or demand of an energy. The fuel efficient cars are preferred by the customers on this account. Any increase in energy price tends to reduce the demand for a particular energy as well energy service rendered by it. For example, high price of natural gas may motivate consumers to invest in home insulation instead of using natural gas for heating.

16.2.5 Energy Demand Substitution

- **Explain how energy commodities can be economic susbtitutes for one another.**

Same energy service can be provided by several different energy commodities. For example, homes can be heated using any of energy commodities such as oil, wood, natural gas and electricity. Therefore, these energy commodities are economic substitute for one another. The consumer will decide or prefer an energy commodity depending upon its price in respect to other substitutable energy commodities. However, substitutability of these energy commodities is limited by the availability of energy conversion technology or device. One type of conversion technology or device can be used for only one particular energy commodity. For example, an oil furnace can use only oil for heating home as it cannot use gas, electricity or wood. However, the degree of substitutability or replaceability can be increased by the development of new conversion alternatives. For example, automobiles are powered by petrol or diesel fuels, but it is reported that technologies have currently been developed to power these automobiles with electricity, natural gas, hydrogen or other energy commodities. Once these technologies of conversion are successful, petrol, diesel and other energy commodities will become easily substitutable in transportation.

16.2.6 Energy Efficiency Standards to Optimise Consumer Choices

- **Explain how energy efficiency standards help to optimise consumer choices.**

It has been found that customers do not understand the conversion efficiencies of alternative technologies and they may indifferently purchase a wrong conversion equipment. There is a need to educate customers about the efficiencies of different conversion technologies and equipment. It is made essential that manufacturers should specify the conversion efficiencies on their manufactured equipment. The legislative requirement of labelling has been imposed on manufacturers. The specifying of conversion efficiencies on the equipment has helped the consumers to choose among various alternative energy conversion equipment with different efficiencies available in the market. New cars coming in market have to display stickers showing their expected mileage per litre of fuel under different running conditions. Similarly, refrigerators and air conditioners have labels that indicate energy consumption per hour. This labelling is mandatory and energy efficiency standards have been laid down for all household appliances. The imposition of Corporate Average Fuel Efficiency Standard (CAFE) for automobiles is a legislative requirement so that automobile manufactures should not produce automobiles which are less efficient than optimal.

16.3 ENERGY CONSERVATION

- **What do you understand by energy conservation?**

Energy conservation implies reduction in energy consumption without compromising on quality or lowering the quantity of production. This means that by reducing losses and wastages, as well as by increasing the efficiency, it is possible to increase the production from a given amount of energy input.

Energy has become the basic requirement of today's life. It is the backbone of present-day civilization. It is an indispensable component of industrial production, employment generation, economic growth, our environment and comfort. Our higher standard of living and higher per capita gross domestic product (GDP) directly depend on higher per capita consumption of energy. However, higher per capita energy consumption means new facility for the energy generation, which is an expensive and long-term option. But energy conservation is a cost-effective and short-term or immediate option. Since the available conventional energy resources are fast depleting and cost of energy is increasing, it is highly important that measures should be taken to conserve energy. It is estimated that 10–20% energy can be saved without major investment in case suitable measures to conserve energy are taken. Rich and developed countries have to contribute more in energy conservation by reducing their consumption of energy through self-discipline and strict measure. To implement measures for energy conservation, some investment has to be made, but this investment is very small compared to energy cost which may be saved through conservation. Energy saved or conserved may be considered as energy generated or earned without any cost.

16.3.1 Aspects of Energy Conservation

- **What are the important aspects of energy conservation?**

or

- **What are the benefits of energy conservation?**

or

- **For solving problem of increased energy demand evaluate the benefits of energy conservation compared to increasing the generation capacity.**

When usable energy is conserved and it is not allowed to be wasted this saving has direct impact on the economy, environment and long-term availability of non-renewable energy resources. Energy conservation can be achieved by reducing energy consumption. The reduction in energy consumption is possible by reducing energy losses and wastage using energy efficient means of generation and utilization of energy. Any movement for energy conservation can significantly reduce the need for fresh investment in energy supply systems in coming years. Energy conservation using energy efficient means will not only reduce the need to create new capacity requiring high investment but also result in substantial environment benefits. The important aspects or benefits of energy conservation are:

Economic aspects

Energy conservation finally leads to economic benefits such as reduction in cost of production and new job opportunities due to new investment in more efficient energy equipment and technologies. The cost of energy forms a significant part of the total cost of the product. The cost of energy can be reduced using efficient energy technologies. Any reduction in manufacturing cost helps in production of cheaper and better quality products. The manufacturer needs to be competent to produce quality product at minimum cost to survive in the competitive market.

Environment aspects

Energy utilization process affects the environment to some extent. The extent of degradation or pollution of environment depends on the energy conversion process the efficiency of technology used for conversion. However, it is found that a part of energy in the form of heat escapes into the surroundings in every energy conversion or utilization process. Hence, whenever energy is generated and utilized, it is carried out at the expense of adverse environment effects. Whenever we are conserving energy, we are in fact minimising the degradation of the environment.

Depletion of conventional energy resources

The conventional energy resources are derived from fossil fuels which are non-renewable and depleting resources and their consumption is also increasing. Owing to both depletion and scarcity, the prices of conventional energy resources are rapidly increasing. Their consumption should be reduced by abandoning wasteful practices in energy utilization so that convention energy resources can be conserved by all means for future generations.

16.3.2 Principles of Energy Conservation

- **List down the various principles involved in energy conservation.**

or

- **What do you understand by grading or financial value of energy?**

or

- **Explain the concept of daylight saving as a means of energy conservation.**

Energy has to be conserved and its expenditure has to be minimised. Expenditure should be reduced using new and efficient technologies, avoiding energy wastage, self-discipline and recycling of waste. On basis of these approaches there are various principles of energy conservation. They are discussed next.

Recycling of waste

By recycling the waste, it is possible to make any product with lesser energy compared to the energy required to produce from raw materials. Recycling can help to save the invisible energy which was used in extraction of fresh material from the raw source. The recycling of waste has three major benefits: (i) saving of energy as the total energy needed in recycling process does not require the part of energy needed for extraction of fresh material from raw source, (ii) saving of energy to be spent on processing the fresh material as fresh material is not required to be extracted from raw source due to recycling of waste and (iii) solving the problem of waste disposal as well as saving of energy required for transportation and disposal of waste. It has been reported that the recycled aluminium cans can be produced with only 6% of the energy needed to make them from fresh aluminium ores.

Energy efficient technologies

Modern energy efficient technologies should be adopted to replace the existing old energy inefficient technologies or equipment. Energy consumption can be reduced to a great extent by adopting energy efficient technologies.

Waste heat utilization

The utilization value or grade of heat depends upon the temperature as the heat at higher temperature can be easily converted into work, and therefore it is graded high. However, heat at lower temperature cannot be converted into work and it is graded low as it is less useful. Various industrial processes require heat at different grades. Waste heat from any industrial process requiring high-grade heat can be efficiently used for other industrial process requiring low-grade heat. For example, glass manufacturing requires high-grade heat at 1500°C and it has waste heat at lower temperature of 400–500°C. This waste heat can be utilized to generate steam in boiler to run a turbine for production of electricity, thereby conserving the energy.

Judicious use of higher-grade energy

The usefulness or financial value of energy is specified by grading of energy. The grading of energy in descending order is as follows:

(i) Electrical energy
(ii) Mechanical energy
(iii) Thermal energy
- High-grade thermal energy (500°C and above)
- Medium-grade thermal energy (150–500°C)
- Low-grade thermal energy (80–150°C)

Higher grade energy should not be used for any work which can be performed by lower grade energy. For example, electrical energy is the highest grade energy and it should not be used for heating purpose as cheap lower grade thermal energy obtainable by burning of fuel or solar energy can be more judiciously used for heating purpose.

Judicious use of energy commodity

Energy commodity can be cheap or costly. For example, coal and biofuel are cheap energy commodities or sources compared to oil or natural gas which are costly. Hence, for heating, it is preferable to use cheaper fuel such as coal instead of costly oil or gas.

Cogeneration

In many industrial plants, both electricity and thermal heat are required. In such plants, cogeneration of electrical and thermal energy at a single place should be adopted instead of separate generation of electricity and heat. The cogeneration is economical and it may result in energy saving up to 30%.

Adopting daylight saving time

In summer, daylight saving time can be adopted as done in most of European countries. The sun rises nearly 1 h earlier in summer and national time is set 1 h ahead as the standard time, thereby increasing the number of useful hours of the daylight in a day. This adoption of timing helps in providing extra hours of sunlight in the evenings. Hence, the daily activities of most people are finished much earlier. As a result, electricity for lighting is needed for lesser hours, which results in its saving.

Proper housekeeping

Proper housekeeping can be ensured by turning off lights and other appliances when not needed and it helps in energy conservation.

Training of manpower

Manpower should be trained to adopt the habits and practices to use machinery and equipment efficiently. The machinery and equipment must be switched off during idle or non-productive time.

Proper operation and maintenance

Energy may be lost due to friction or improper insulation. Proper lubrication of moving parts can reduce loss of energy due to friction. Proper insulation of devices can prevent heat loss due to conduction and convection to the atmosphere.

16.3.3 Energy Conservation Act

- **What are the salient features of Energy Conservation Act?**

Recognizing the fact that an efficient use of energy and its conservation is the least-cost option to maintain the gap between demand and supply, Government of India enacted the Energy Conservation Act 2001 and established Bureau of Energy Efficiency (BEE). The mission of BEE is to develop policy and strategies with a thrust on self-regulation and market principles within the overall framework of the Energy Conservation (EC) Act, with the primary objective of reducing energy intensity of the Indian economy. The EC Act provides for institutionalizing and strengthening delivery mechanism for energy efficiency services in the country and the much needed coordination between various entities.

EC Act provides the legal requirement needed to enforce the energy conservation measures. The features of EC Act are as follows:

(i) The establishment of Bureau of Energy Efficiency for the implementation of EC Act
(ii) Declaration of a class of users of energy as a designated consumer. 15 energy intensive industries and establishments to be notified as designated consumers (DCs). DCs have to appoint or designate energy managers for the establishment of energy management system
(iii) Need to get energy audits conducted by accredited energy auditors and implement techno-economic viable recommendations
(iv) To lay down minimum energy consumption standards and labelling for identified appliances, equipment and norms for industrial processes for energy intensive industries
(v) Formulation of energy consumption codes
(vi) Industries to comply with norms of specific energy consumption fixed
(vii) Industries to submit report on steps taken to comply with norms.
(viii) Provision of penalties and adjudication
(ix) The evolution of a self-regulatory system with the BEE acting as a facilitator so that consumers would regulate on their own with a view to save energy
(x) Energy Conservation Building Codes (ECBC) are applicable to new buildings having connected load of 500 kW or more.

16.3.4 Cogeneration

- **What is cogeneration? What are the types of cogeneration principles? Explain different types of cogeneration system.**

or

- **Explain the principle of waste heat utilization and its various applications.**

A procedure for generating electric power and useful heat in a single installation is called cogeneration. The net result of cogeneration is better overall efficiency of energy utilisation.

The cogeneration principles are as follows:

(i) **The topping cycle.** The heat at high temperature is used to generate electricity. The discharged low-grade heat is utilized in performing an industrial process.
(ii) **The bottoming cycle.** The heat at high temperature is used for an industrial process and remaining low-grade heat is then used for power generation.

The cogeneration systems are as follows:

(i) **Waste heat utilization.** In this cogeneration system, electricity is generated in topping cycle and it has heated water as a by-product. This waste heat is now used for (i) space heating and cooling (using absorption cooling method), (ii) greenhouse heating in cold region and (iii) warming water in aquaculture.
(ii) **Total or integrated energy system for residential complex.** In this type of cogeneration system, heat is used to meet the demand of (i) electricity for lighting, refrigeration, other electrical appliances and lifts and (ii) heating (hot water, space heating, cooling and cooking) of a large building complex or a community living. The total energy system is a self-contained system to work independently, while the integrated energy system can buy or sell energy to a utility.
(iii) **Total energy system (TES) for industry.** The cogeneration produces heat to generate electrical power and to supply heat for industrial process. Refineries, chemical plants and paper industries use a large amount of heat and electricity.

- **Describe the working of a gas turbine-based cogeneration system.**

The gas turbine-based cogeneration system is shown in Figure 16.1. The main purpose of this system is to generate electricity and its waste low-grade heat is used for industrial processing. The compressor compresses air which is then heated to high temperature in a combustor. Hot air is passed to a turbine to run an electric generator. The waste hot air is used for industrial processing.

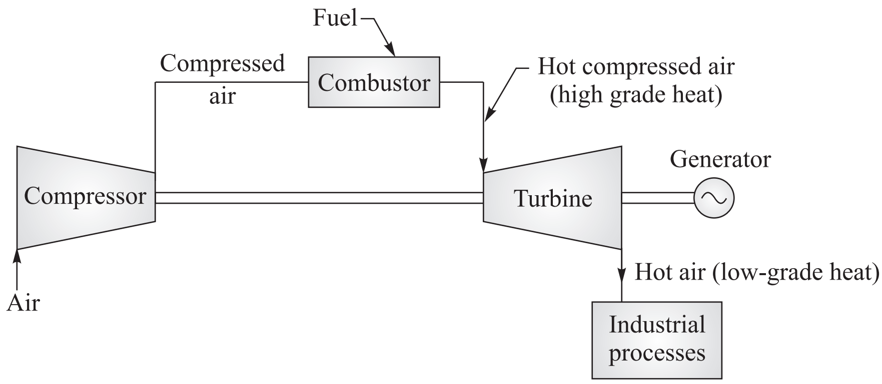


Figure 16.1 Gas turbine-based cogeneration.

16.3.5 Combined or Binary Cycle Plants

- **Why is a binary cycle plant more efficient than an open cycle plant? Comment on the amount of energy saved by using gas–steam binary cycle plant instead of a simple open cycle steam turbine-based generating plant.**

or

- **Why steam turbine cannot be used in a topping cycle in a binary cycle plant?**

In combined cycle plant, electric power is produced using two heat engines in tandem as prime movers. When heat engines are run in tandem, the heat discharged from the first heat engine is not wasted or exhausted into the atmosphere, but the heat discharged serves as the source for the second heat engine. The net result is a greater overall operating efficiency than what is possible with a single heat engine as shown in Figure 16.2.

The steam turbines cannot be operated above the temperature of 540°C due to the deterioration of properties of the turbine material above this temperature. The obtainable temperature by burning fossil fuels in a boiler is very high (more than 1650°C). Hence, in combined cycle system, steam turbine cannot be used in topping cycle due to high temperature generated by fossil fuels. Heat engines or gas turbines are used in topping cycle which can work efficiently at high temperatures. The working fluid (air) leaves the topping cycle at sufficiently high temperature (below 540°C) to generate steam in a boiler of the bottoming cycle for the steam turbine.

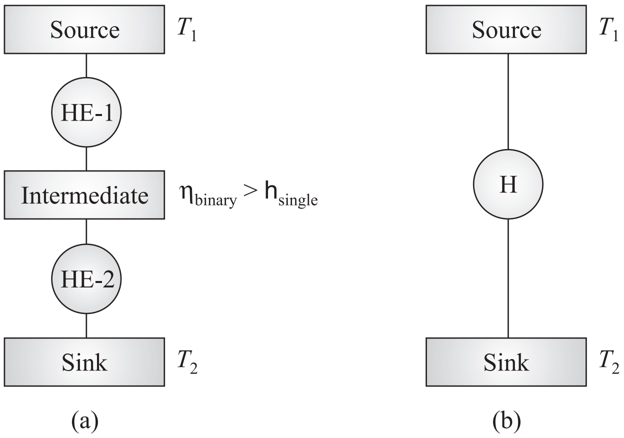


Figure 16.2 Binary cycle plant. (a) Binary cycle and (b) Single cycle.

The binary cycle is most suitable for the combined use of gas turbine and steam turbine in which gas turbine is used in topping cycle. The exhaust gases from gas turbine at temperature below 540°C are used in waste heat boiler in which steam is produced under pressure to run a steam turbine. In addition to using the fuels more efficiently, a binary cycle consisting of a gas turbine and a steam turbine and it requires a lesser amount of condensing cooling water due to a similar amount of heat wasted to the atmosphere. It is reported that the gas turbine based on Brayton cycle and steam turbine based on Rankine cycle have efficiency of 20% and 35%, respectively, while their binary cycle has efficiency of about 40–50%. The binary cycle of a gas turbine and a steam turbine is shown in Figure 16.3. It helps in conservation of energy.

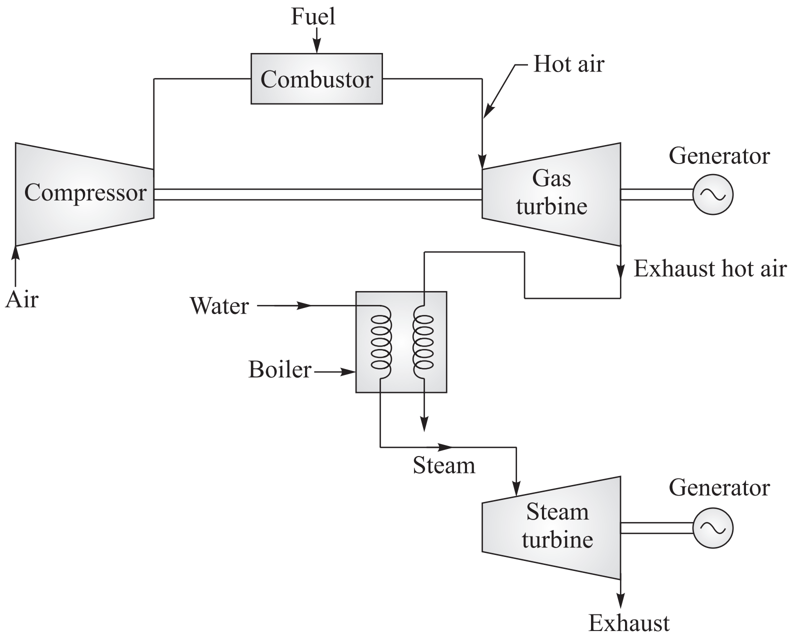


Figure 16.3 Binary cycle with gas turbine and gas turbine.

- **Sketch and explain a binary cycle power plant with cogeneration.**

The binary or combined cycle with cogeneration is show in Figure 16.4. The gas turbine is used in the topping cycle and gases exiting from the gas turbine is used in a boiler to generate steam in the bottoming cycle. The steam is used to run steam turbine to generate electric power. The hot gases exiting from boiler after heating water to steam are used for industrial processing.

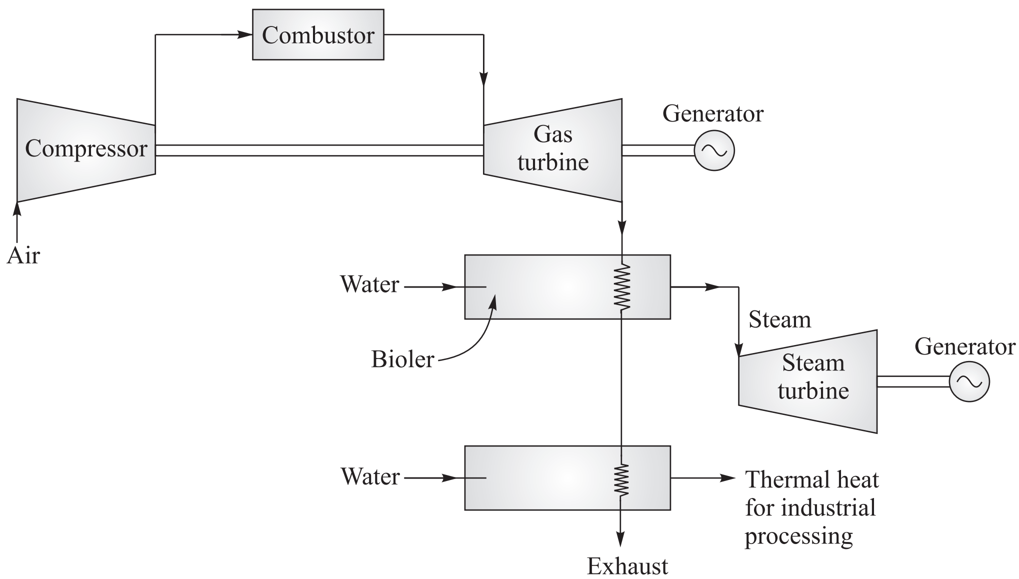


Figure 16.4 Binary cycle power plant with cogeneration.

- **What do you understand by integrated gasification combined cycle (IGCC) generating plant?**

Gasification is the cleanest method of utilization of coal as there is no air pollution due to fly ash. During gasification of coal, fly ash is collected at the bottom of the gasifier and in this method carbon dioxide emissions are also less compared to coal combustion in solid form.

The integrated gasification combined cycle generating plant uses coal after gasification as fuel, which is a cheaper fuel. The higher efficiency of IGGC also results in the reduction of coal consumption.

16.4 ENERGY MANAGEMENT AND AUDIT

16.4.1 Definition and Objectives of Energy Management

- **What do you understand by energy management? What are the objectives of energy management?**

Energy is necessary for economic development and it can be used efficiently with proper management. The energy management should be carried out to produce goods and to provide services with the least cost and least adverse impact on environment. Energy management involves planning, directing and controlling the demand and supply of energy to maximise productivity and comforts and minimise the energy cost and pollution with conscious, judicious and effective use of energy.

The energy management can be defined as the judicious and effective use of energy to maximise profits or minimise costs and enhance competitive positions. It can be also defined as the strategy of adjusting and optimising energy, using systems and procedures so as to reduce energy requirements per unit of output while holding constant or reducing total costs of producing the output from these systems.

The objectives of energy management are to achieve and maintain optimum energy procurement and utilisation throughout the organisation so as to:

(i) To minimise energy costs or waste without affecting production and quality
(ii) To minimise environmental effects.

16.4.2 Energy Audit and Need

- **What do you understand by energy audit? Why is energy audit needed?**

Energy audit is required for energy management. Energy audit is a technical survey of a plant in which the energy consumption is studied machine-wise, section-wise and department-wise to find out the actual energy consumption necessary for the production. As the result of the study, areas are identified where energy is wastefully used and improvements are felt necessary. The corrective measures are recommended on the basis of the findings for adoption on priorities so that the overall plant efficiency can be improved. Energy audit helps to understand more about the ways different energy sources can be used in the industry. It also helps to identify areas where energy waste can occur and where scope for improvement may be possible. The energy audit provides a positive orientation to the energy cost reduction, preventing maintenance and quality control programmes which are vital for production and utility activities. Energy audit attempts to balance total input of energy with its use.

Energy audit is the key to a systematic approach for decision-making in the area of energy management. Energy audit involves the methodological examination and comprehensive review of energy use in industries. Energy audit tries to find out answers to the following questions: (i) How much energy is being consumed? (ii) Where is the energy consumed? (iii) How efficiently is the energy consumed? and (iv) Can there be improvements in energy use? The energy audit results in framing of energy conservation proposals and the proposals with minimum investment are identified to be implemented for energy conservation. Energy audit attempts to balance the total energy inputs to what is essential for production.

Energy audit is defined as per EC Act as "the verification, monitoring and analysis of use of energy including submission of technical report containing recommendations for improving energy efficiency with cost benefit analysis and an action plan to reduce energy consumption".

Need for energy audit

In any industry, there are three top operating expenses, which include (i) cost of energy, (ii) cost of labour and (iii) cost of material. Out of these there expenses, the energy has the maximum potential for cost saving and it is the strategic area for cost reduction using energy management. Energy audit can help to understand more about the ways energy and fuels are used in any industry. This helps in identifying the areas where waste can occur and where scope for improvement exists. Energy audit is the translation of energy conservation ideas into realities by providing technically feasible solutions with economical and other organisational considerations within a specified time frame. Energy audit provides a benchmark, a reference point or a tool in the hands of the management to manage energy in the organisation and also to plan a more effective way to use energy in the organisation.

16.4.3 Types of Energy Audit

- **What are the types of energy audit?**

The types of energy audit to be performed depend on (i) function and type of industry, (ii) depth or details to which audit is needed and (iii) potential and magnitude of cost reduction desired. The energy audit can be:

- Preliminary audit
- Detailed audit

16.4.4 Preliminary Audit

- **What do you understand by preliminary audit? What is its purpose?**

The preliminary audit is carried out in quick or limited time ranging from 1 to 10 days. The purpose of preliminary audit are as follows:

(i) Establish energy consumption in the organisation
(ii) Estimate the scope for saving
(iii) Identify the most likely and easiest area for paying attention to improve
(iv) Identify immediate specially low cost improvements to achieve savings
(v) Establish a reference point or benchmark to measure further improvements for savings
(vi) Identify areas requiring more detailed study and measurement.

The preliminary energy audit uses existing or easily obtainable data. The financial report regarding the preliminary audit is required to be submitted within 2 weeks.

16.4.5 Detailed Energy Audit

- **What do you understand by detailed energy audit? What is its purpose?**

Detailed energy audit is a comprehensive audit to provide a detailed energy implementation plan without energy wastage for an organisation. It evaluates all major energy using systems for their efficiency in saving energy. This type of audit offers the most accurate estimate of energy savings and cost. The audit accounts for the total energy utilised in an organisation. The total energy is estimated based on energy using systems installed in the organisation and the operating conditions or timings of these systems. The estimated energy is then compared with utility bill charges to find energy wastage. The detailed audit involves detailed engineering for options to reduce cost and consumption. The detailed audit may require 1–10 weeks to complete the audit and final report has to be submitted within 3 months. The detailed audit can be carried out in three phases which includes pre-audit phase or phase I, audit phase or phase II and post-audit phase or phase III.

16.4.6 Methodology for Detailed Audit

- **Explain ten steps methodology for detailed energy audit.**

The ten steps methodology for detailed energy audit is given in Table 16.1.

TABLE 16.1 Ten steps methodology for detailed energy audit

Step No.	*Plan of action*	*Purpose*
	Preaudit phase or Phase I	
Step 1	• Plan and organise • Walk-through audit • Informal discussion with energy manager and production or plant manager	• Resource planning. An audit team is organised • Arrange instruments • Organise time frame • Data collection • Study and understand process • Assessment of current level of operation and practices in production
Step 2	• Interaction with all divisional heads and concerned persons	• Seek cooperation of all concerned • Issue questionnaire for each department • Seek to raise awareness of audit and orientation for audit
	Audit phase or Phase II	
Step 3	• Collection of data about process flow and energy utility consumption	• Baseline data collection • Prepare process flow charts • Energy systems diagram, that is, electric power, water, compressed air and steam flow diagrams
Step 4	• Conduct survey and monitoring	• Actual measurements to compare operating data with design data
Step 5	• Conduct experiments for selected higher energy-consuming appliances	• Conduct test for finding load variation in pumps, compressors and other electric equipment. Find furnace and boiler efficiency
Step 6	• Analysis of energy use	• Energy input and output balancing to find loss or waste of energy

(*Contd.*)

TABLE 16.1 Ten steps methodology for detailed energy audit (*Contd.*)

Step No.	*Plan of action*	*Purpose*
Step 7	• Identify and develop Energy Conservation (ENCON) opportunities	• Identification of energy conservation measures • Consider alternative efficient means • Review previously suggested technologies • Conduct brainstorming to find solution • Interact with suppliers for a new technology
Step 8	• Cost and benefit analysis	• Assess cost and benefit of new technology • Select the energy efficient devices • Priorities their procurement as immediate medium and long-term options
Step 9	• Presentation of measures to top management	• Top management takes decision for implementation
	Post-audit phase or Phase III	
Step 10	• Implementation and follow-up	• Insure correct implementation • Assess the energy saving affected.

16.4.7 Energy Efficiency in Indian Industry

- **Is the Indian industry energy efficient? If it is not, what is the reason? How is the energy efficiency improved?**

Indian industry is the major consumer of energy. Its use accounts for about 50% of the total commercial energy consumed in the country. The six key industries consisting of aluminum, cement fertilisers, pulp and paper, steel and petrochemicals are reported to be consuming 65% of the total energy used in Indian industry. Some of the Indian industries are found to be consuming a higher amount of energy compared to similar industries operating in developed and advanced industrial countries. One of the main reason for higher energy use or consumption is the presence of obsolete and energy inefficient processes and technologies in some of these industries. To promote adoption of energy efficient processes and technologies, these industries have been identified by the Indian Government as designated consumers (DC) under schedule of the Energy Conservation (EC) Act. These designated consumers have to comply with various provisions of EC Act, such as (i) to meet specific energy consumption norms, (ii) to conduct regular energy audits, (iii) to implement techno-economic viable recommendations of energy audits and to establish energy management system through appointment of certified energy managers to boost the adoption of energy efficient processes and technologies.

16.4.8 Status of Energy-Efficient Technologies in India

- **Write briefly about the status of energy efficient technologies in India.**

The new generation industrial plants installed recently in India have excellent energy efficiency norms which can be comparable to the best and most energy efficient plants in the world.

Hence, there is deep penetration of advanced and energy efficient technologies in many of the Indian industrial plants. It is found that in cement plants, the technology penetration is very high and the prevalent energy efficiency norms are comparable to the best energy efficient cement plants in the world. It is reported that some of the Indian steel plants are already undergoing a process of modernization where more energy efficient processes and technologies are being adopted. Technology updating is also being reported in the Indian power and pulp and paper sectors. Considerable progress in energy efficient technologies has been reported in thermal and electric utilities. Fluidised bed boilers and furnaces, variable frequency drive, and energy efficient pumps, fans, compressors and cooling towers and being widely used in Indian industries. Energy efficient compact fluorescent lamps and electronic ballasts are becoming extremely popular and increasingly acceptable in domestic, commercial and industrial sectors. Legalised standard and labelling programme of EC Act has further given boost to manufacturing and adoption of energy efficient technologies.

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