DIRECT ENERGY CONVERSION TECHNOLOGIES

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R.K. SINGAL, PHD
&
M. TABATABAIAN, PHD, PENG
(Faculty, British Columbia Institute of Technology)

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Boston, Massachusetts
New Delhi

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info@merclearning.com
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CONTENTS

CHAPTER 1

ENERGY CONVERSION TECHNOLOGIES

1.1 INTRODUCTION

The energy available in natural form is not directly usable with practical efficiency. Fossil energy is chemical energy of fuels or nuclear energy of fissile materials. The renewable energies like hydro energy and wind energy are available as potential energy and kinetic energy of water and air streams. Solar energy is available as photon energy or thermal energy. The useful forms of energy are electricity for lighting, heating, and motive power for industries, transport, domestic, and commercial activities. Therefore, the natural forms of energy are to be converted into usable forms with the aid of suitable plants and technologies. Even after the conversion, the power density (power per unit area) is relatively low for renewable energy technologies (e.g., wind turbine ~350, solar photovoltaic ~150 W/m^2). The power density of a wind stream is proportional to air density and cube of its speed and that of solar radiation is about 1 kW/m^2.

1.2 ELECTRICITY GENERATION

Electrical energy is the most convenient form of usable energy and is produced in a power plant and usually transmitted to demand sites. There are many types of power plants, as described in following sections.

1.2.1 Utility Plants or Central Power Plants

These are large capacity power plants usually located near the source of natural energy. The electricity generated is transmitted over long distances to the consumers. Depending on the form of input energy, these plants may be thermal power plants, nuclear power plants, or hydropower plants.

1. Steam Power Plant

The flow diagram of a thermal power plant or steam power plant with various stages of energy conversion is shown in Figure 1.1. Various energy forms are listed in this figure (chemical/Ch.E., thermal/Th.E., potential and kinetic PE/KE, mechanical/Mech. E.). The Fleming's rule is the right-hand rule convention for electric generators, whereas the left-hand rule is used for electric motors.

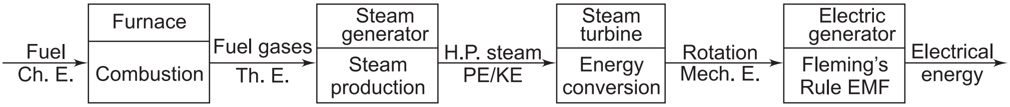


FIGURE 1.1 Steam power plant.

The pulverized coal or lignite is burned in the furnace of a steam generator. The chemical energy of fuel is released as thermal energy during combustion and hot flue gases are used to generate steam. The enthalpy of high-pressure steam is converted into mechanical energy in a steam turbine, which in turn rotates an electric generator. The electricity thus produced is transmitted over long distances and distributed to the consumers for industrial, domestic, and commercial applications.

2. Gas Turbine Plant

The flow diagram of a gas turbine plant is shown in Figure 1.2.

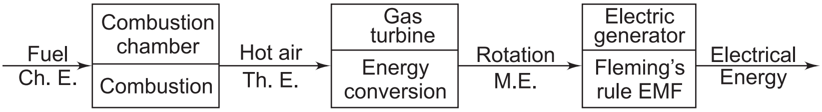


FIGURE 1.2 Gas turbine plant.

The natural gas or furnace oil is combusted in a combustion chamber to heat compressed air. The enthalpy of hot air is converted into mechanical energy in a gas turbine, which in turn rotates an air compressor and electric generator. The electricity thus produced is transmitted over distances and distributed to the consumers. For example; Surgutskaya GRES-2, Russia has an installed capacity of approximately 5.6 GW, and Futtsu power station in Japan has an installed capacity of more than 5 GW. These power stations are among the biggest in the world.

3. Diesel Engine Plant

The flow diagram of a diesel engine power plant is shown in Figure 1.3.

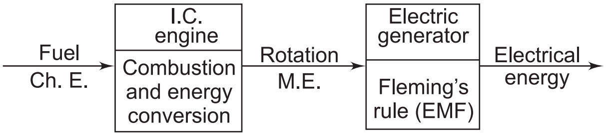


FIGURE 1.3 Diesel engine plant.

In a diesel engine plant, both combustion and energy conversion of heat into mechanical energy take place inside the cylinder of the engine. The electrical generator is rotated by the engine to produce electricity. The power produced is used locally; mainly as backup power. Diesel engines are usually used for low-power demand areas far from electric grid transmission lines.

4. Nuclear Power Plant

The flow diagram of a nuclear power plant is shown in Figure 1.4.

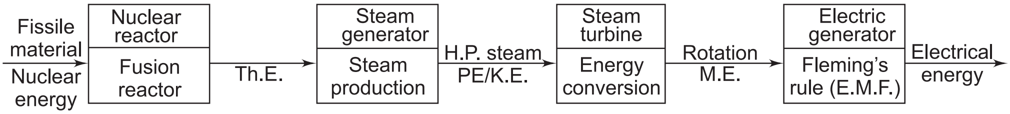


FIGURE 1.4 Nuclear power plant.

The nuclear power plant is like a steam power plant where nuclear fission takes place in a nuclear reactor and thermal energy produced is used to raise steam in a steam generator which is further used in turning a steam turbine in a steam power plant. The electricity produced in the generator is transmitted over long distances through a grid. For example; Kashiwazaki-Kariwa, Japan has an installed capacity close to 8 GW and Bruce Nuclear Generating Station, Ontario, Canada has more than 6 GW. These power stations are among the biggest in the world.

5. Hydro-Electric Power Plant

The flow diagram of a hydro-electric power plant is shown in Figure 1.5.

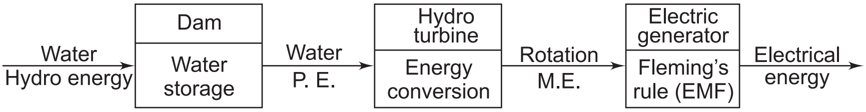


FIGURE 1.5 Hydropower plant.

The water streams in hills/mountains are collected behind a dam. The potential energy of stored water is conducted to a hydro turbine where potential energy of water is converted to kinetic energy through penstocks and used to rotate the turbine. The mechanical energy of the rotation of a turbine is used to run an electrical generator to produce electricity. The electricity generated is transmitted over distances and distributed to consumers of electric energy. The plant is site-specific and limited by the resources. For example; the Three Gorges hydroelectric power plant in China has an installed capacity of 22.5 GW, and the Itaipu hydroelectric power plant located in Brazil and Paraguay has an installed capacity of 14 GW. These power stations are among the biggest in the world.

1.2.2 Captive Stand-Alone Power Plants

Certain metallurgical, telecommunications, and other industries are very sensitive to even short interruption in power supply. Similarly, hospitals and hotels cannot afford power failure even for a short duration. These manufacturing and service industries can install their own power plants to meet their total power requirements. Such plants are called captive or on-site power plants. These may be thermal power plants of smaller capacity. Long transmission lines and associated power and reliability losses are not required. For service industries, diesel engine power plants are very popular.

1.2.3 Cogeneration Plants

There are many industries especially process industries like refineries, fertilizer plants, pharmaceuticals, organic and inorganic chemical plants, sugar mills, paper mills, and so on, that require a bulk of heat energy along with electrical power. Similarly, hospitals, hotels, and other community centers need electricity as well as heat energy for various processes, in order to increase the system-level efficiency. The total energy requirements of heat and electricity can be met from a single plant called a cogeneration plant at a relatively high thermodynamic efficiency.

The most common cogeneration plants use a high-efficiency, high-pressure boiler to generate steam for running a steam turbine. The required heat energy is supplied by a medium- or low-pressure steam extracted from the turbine at suitable points. A schematic diagram of such a plant is shown in Figure 1.6.

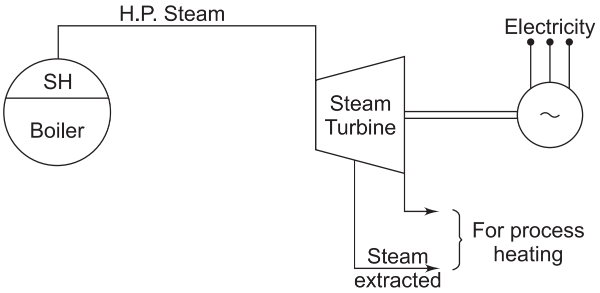


FIGURE 1.6 Steam turbine cogeneration plant.

The cogeneration plant can also be based on a gas turbine (Figure 1.7) where air exhausted from the turbine is utilized for process heating. Similarly, in a diesel-engine cogeneration plant, exhaust gases from the engine and jacket cooling water can be used to meet the heat requirements (Figure 1.8). Also, more advanced technologies like thermoelectric systems can be used to convert heat to electricity, directly.

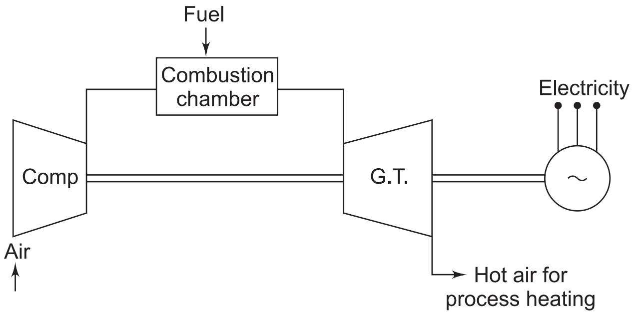


FIGURE 1.7 Gas turbine cogeneration plant.

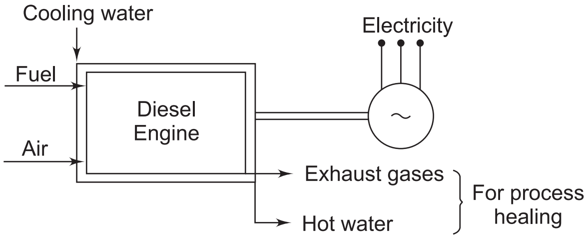


FIGURE 1.8 Diesel engine cogeneration plant.

1.2.4 Autonomous Power Plants

These are small capacity power plants which normally work on local sources of energy. These plants generate electricity for local use and transmission losses are avoided. These plants can be:

- solar power plants
- wind power plants
- biomass power plants
- mini hydropower plants, so-called run-of-river

These plants are normally designed as hybrid systems. The intermitting solar energy and wind energy is compensated by standby power plants. The plant uses the solar energy or the wind energy when it's adequate and available. A diesel engine or small hydropower plant is used at other times. In such hybrid schemes, there is no need for storage of energy.

1.2.5 Combined-Cycle Power Plants

The gas turbine power plants working on Brayton cycle are high temperature plants. The temperature at the inlet to a gas turbine may be of the order of 1200–1300 K. The exact temperature of air is also very high of the order of 700–900 K. In order to utilize this high-grade energy, the outlet gases may be used to raise steam in a boiler to run a steam turbine plant. Such arrangements are called combined cycle power plants. Due to high temperature range of utilization of heat for a combined plant, the thermal efficiencies of gas turbine plant and steam turbine are almost added resulting in very high thermal efficiency of the combined-cycle power plant. There can be many arrangements, but a schematic diagram of a typical combined-cycle power plant is shown in Figure 1.9.

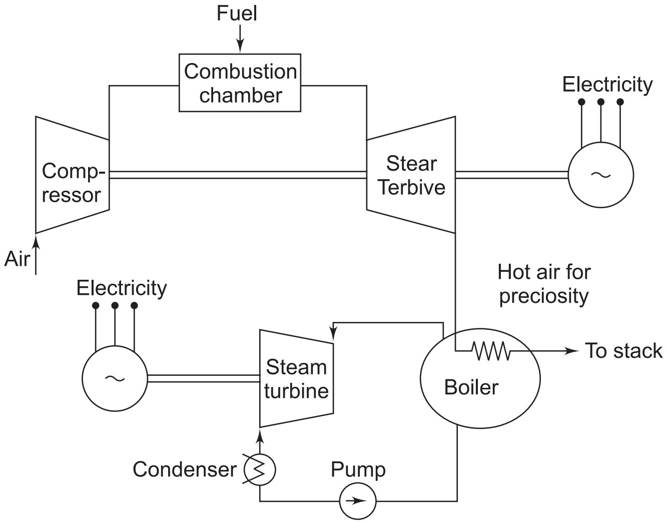


FIGURE 1.9 Combined-cycle power plant.

1.3 TRANSPORT ENERGY

There are more than one billion vehicles in the world today. Cars and trucks alone consume one-third of world's oil production. There are aero-engines, marine engines, automobile engines, engines for earthmoving, and material-handling machines. The total capacity of these mobile machines or power packs is many times the total installed capacity of the power plants used for electricity generation.

The engines used for transport vehicles are gas turbines for ships and aircrafts and piston-cylinder internal combustion engines using gasoline/petrol, diesel, and compressed natural gas as fuel for these vehicles. In addition to consumption of these hydrocarbons, these engines emit greenhouse gases causing thermal pollution and adversely affecting the global climate. In addition, nitrous oxides are also emitted and are primary components of troposphere ozone. The emission of carbon by vehicles cannot be absorbed by the present forests, totally.

1.4 LIMITATIONS OF CURRENT POWER GENERATION SYSTEMS

The current power generation systems are based on thermodynamic cycles subjected to theoretical and physical limitations as well as the cost. The power supply at the same time is not fully reliable, mainly since it is plant-centered and connected to demand sites by transmission lines.

1.4.1 Carnot Limitation

The steam turbine power plants based on coal or nuclear fuels, gas turbine plants, and diesel engine plants work on the principle of conversion of thermal energy into electrical energy. The maximum possible cycle efficiency is limited by Carnot efficiency of $(1-T_{min}/T_{max})$, for reversible ideal cycles. T_{min} is the temperature at the heat sink reservoir and T_{max} is the temperature at the heat source reservoir. In addition, the entropy generation through the conversion process decreases the efficiency further to a lower level. Specific heat rates of most modern thermal power stations are in the range of 8400–10,000 kJ/kWh generated and about 65–70% of heat available from the fuel is lost to cooling water in the condenser and exhaust stacks.

1.4.2 Metallurgical Limitation

T_{min} is site-specific and depends on the temperature of cooling water available. T_{max} is limited by the availability of engineering materials for boiler tubes and turbine blades. This is called *metallurgical limitation*. For example, for boilers and combustors the adiabatic flame temperature can be calculated to give the maximum temperature they may receive during operation.

1.4.3 Mechanical Links and Plant Reliability

There are many mechanical links in modern thermal, nuclear, and hydropower plants in the form of boilers, steam generators, penstocks, pumps, compressors, generators, and so on. There is loss of reliability and mechanical losses get added up with every additional component designed into the system, specifically for rotating systems. The efficiency increases of these mechanical components by the advancing state of related technologies is of interest to the industry.

1.4.4 Ecological Balance

Modern power plants are large plants and disturb the ecological balance of the site. The need of a large dam in a hydropower plant results in submergence of large fertile areas under the water reservoir, displacement of huge population, loss of crops and forests. In addition, the resulted high water table may have adverse effects on the crops.

The thermal discharges from a thermal power plant into rivers or lakes serving as source of cooling water and fly ash discharges from the stacks can adversely change the environment. For solar and wind power technologies the NIMBY (not-in-my-backyard), land use, and the manufacturing and site ecological footprint are considered.

1.4.5 Plant Costs

Huge capital requirements on boilers, turbines, generators, cooling water treatment and supply systems, cooling towers, and so on, as well as the availability of fuel and cooling water are main constraints in setting thermal power plants. The construction costs of a dam for a hydropower plant or wind power plant are very high.

1.4.6 Transmission and Distribution System

One of the most expensive forms of energy transmission is that of electric power from power plants. A huge investment in procuring rights of way, installing towers, erecting lines, and providing protection against lighting and other problems is required. The erection and repair costs for overhead lines are very high and overhead lines are prone to breakdown which disrupts power supply on a large scale.

In addition to high investment costs, considerable power losses occur during transmission. The modern transmission lines power losses are as high as 8–10%. This is due to high pilferages and voltage drops. The investment costs on transmission lines contribute 30% of power generation plant cost in developed countries.

The power distribution system can be very complex for a metropolitan city or industrial estate. In addition to huge investments, the erring distribution system causes frequent disruptions in power supply resulting in production losses.

1.5 DIRECT ENERGY CONVERSION SYSTEMS

Many of the disadvantages of current power generation systems can be overcome by small power packs which have higher thermodynamic efficiencies and are free of rotating prime movers and generators. These are installed locally at the consumer points not needing transmission and distribution systems or cooling water. Examples of these systems are described in the following sections.

1.5.1 Fuel Cell

If an electric current is passed through a dilute solution of an acid or an alkali by means of two platinum electrodes, hydrogen is produced at the cathode and oxygen at the anode. If this process is reversed by removing the power supply and connecting the two electrodes through a suitable resistance (or electrical load), the presence of hydrogen at one electrode and oxygen at the other will produce a small current in the external circuit and water being produced as a by-product. This reverse process of electrolysis is the essence of the fuel-cell technology as chemical energy stored in hydrogen and oxygen have been combined to produce electricity.

The fuel cells do not have moving components and it is quieter as it requires less maintenance during normal operation. Fuel cells like proton-exchange membrane, PEMs convert chemical energy directly to electrical energy at room temperatures. These are very efficient systems with high efficiency of up to 87%, theoretic.

Hydrogen and oxygen were selected as reactants for the fuel cells used for spacecraft power supplies because of relatively high reactivity of hydrogen. The reactants for commercial fuel cells can be cheap and readily available natural gas or petroleum derivatives as fuel and air as oxidant.

The fuel cells can be installed at residential building, commercial buildings as on-site power units. The local trains and buses, trucks or personal cars can be propelled by fuel cells, as well.

1.5.2 Solar-Cell Photovoltaic

The solar cell utilizes energetic photons of the incident solar radiations directly on a *p-n* junction of solar cell to produce electricity at high conversion efficiencies. The technology of solar cell is well developed as a part of satellite and space-travel technology. It is also a direct conversion technology and does not use a working fluid like steam or gas and is subject to approximate Carnot limitation or endoreversible efficiency $\left(1-\sqrt{T_{min}/T_{max}}\right)$. It is simple, convenient, lacking moving parts, and dependable. The solar cell is modular, so that arrays of identical modules can be assembled to meet various power needs ranging from small residential systems installed on rooftops to relatively large central systems.

Effort at reducing costs include search for lower-cost cell-manufacturing techniques and new and cheaper materials than silicon.

1.5.3 Thermoelectric Power Units

When two dissimilar materials are joined together to form a loop and the two junctions are maintained at different temperatures, an electromagnetic force will be developed around the loop. This is called the Seebeck effect. The principle is used in thermo-couples to measure temperatures. The electricity produced by the device is proportional to the temperature difference between the hot junction and cold junction and therefore is subject to Carnot limitation. The cold junction is maintained either by cooling water or atmospheric air and source of heat can be oil or gas burner, direct solar radiators by paraboloid concentrator, or heat of radioactive decay of isotopes. But the device is very simple, without any moving parts and hence very dependable without much need of operation and maintenance attention. Due to material constraints, the present conversion efficiencies are very low of the order of 3%. With the development of new materials in the field of ceramics and semiconductors, the thermoelectric generator is projected with high potential in the field of base load and peak load power generation. The present applications are restricted to small units operating in remote areas as signaling and navigational device.

1.5.4 Thermionic Converter

A thermionic generator converts heat directly into electricity by using thermionic emission. An emitter which is a metallic cathode is heated until electrons cross the surface Ferric barrier and are collected at the opposite colder anode. The container holding the two electrodes is filled with ionized cesium vapor to minimize energy losses of the electrons crossing the gas between the electrodes. The emitter is positively charged, and the collector is negatively charged. It is a low-voltage high-current device limited by Carnot law. Thermal efficiencies of 10–20% have been realized and higher efficiencies are possible in future.

This device is being designed for space power applications. For the time being, it is used to supply power to boats, power tools, and irrigation pumps.

1.5.5 Magneto-Hydro-Dynamic Generator

Magneto-hydro-dynamic (MHD) is a direct heat-to-electricity conversion technique based on Faraday's law which states that when an electric conductor moves across a magnetic field, a voltage is induced in it and produces an electric current. Here the conductor is an ionized gas which is passed at high velocity through a powerful magnetic field. A current is generated and can be extracted by placing electrodes in a suitable position in the stream and produces direct-current power.

MHD is the most promising direct conversion technology where the mechanical link can be by-passed. It can overcome some of the limitations of conventional power generation. By hybridization of MHD and thermal power plants, the efficiency can be raised from 40% to 55%, thus better utilizing the fuel resources and reducing the environmental pollution.

EXERCISES

1. Discuss various types of power plants currently used for bulk electricity generation.
2. What are the main limitations of current power generation systems? How can these limitations be overcome by direct-energy conversion devices?
3. Discuss the intermittency related to solar and wind power plants. What solutions could be proposed to overcome this short-comings? Discuss energy storage versus hybridization of these technologies.
4. What are the basic principles of the following technologies?
   a) Fuel cell
   b) Solar cell/PV
   c) Wind turbine/power
   d) Thermoelectric generator
   e) Thermionic generator
   f) MHD generator

CHAPTER 2

SOLAR CELLS

2.1 INTRODUCTION

The solar cell is based on the photovoltaic/PV energy conversion phenomenon. It is a direct energy conversion technology. Electricity is directly produced from sunlight without the use of a working fluid such as steam or gas. There is also no need for an intermediate thermodynamic/mechanical cycle such as the Rankine or Brayton cycle.

Photovoltaic systems are simple, convenient, and dependable without the need of moving parts. The basic unit of a photovoltaic system is called a *solar cell*. These are assembled in arrays of identical modules to produce different power capacities to maintain a required voltage. The power plants may range from small residential systems installed on roof tops to large central systems at utility scale level.

2.2 PHOTON ENERGY

Light is radiant energy. This is transferred in discrete pieces and not continuously, although it has some continuum-like behavior, as well. The smallest unit of energy is called *quantum*. The quantum of radiant energy is called a *photon*. The photon energy is proportional to the frequency of radiation. This is called *Planck's law*.

$$E_P = h\nu = h\frac{c}{\lambda}$$

where E_p = Photon energy

h = Plank's constant

$= 6.62607015 \times 10^{-34}$ (J.S)

$= 4.13566765 \times 10^{-15}$ (eVs)

ν = Frequency of radiation (Hz)

c = Speed of light

$= 2.99792458 \times 10^{8}$ (m/s)

λ = Wavelength of radiation (m).

Light has dual characteristics. It consists of photons particles that have energy and wave-like behavior having a frequency and wavelength for each part of its spectrum. The radiation from the sun is composed of the photons, each carrying a quantity of energy exactly equal to its frequency times Plank's constant.

Example 2.1: *Calculate the photon energy of a mono energetic radiation beam having a wavelength of half a micrometer.*

Solution:

$$\lambda = 0.5\ \mu\text{m}$$
$$= 0.5 \times 10^{-6}\ \text{m.}$$
$$c = 3 \times 10^{8}\ \text{m/s}$$
$$h = 4.1357 \times 10^{-15}\ \text{eVs}$$

The energy of photon,

$$E_p = h\frac{c}{\lambda}$$
$$= 4.1357 \times 10^{-15} \times \frac{3 \times 10^{8}}{0.5 \times 10^{-6}}$$
$$= 2.48\ \text{eV} = 3.9734 \times 10^{-19}\ \text{J.}$$

An electron volt is a unit of energy equal to the energy acquired by a single electron charge when accelerated through an electric potential of 1.0 V.

2.2.1 Photon Flux

Photon flux is the number of photons crossing a unit area perpendicular to the beam radiation per unit time. The photon flux, ϕ_p is a useful quantity in the photovoltaic cell calculations.

The solar energy flux E'' can be calculated as:

$$E'' = \sum_i \phi_{p_i} h\nu_i$$

where i is the frequency or energy range.

Using average values of frequency and corresponding wavelength

$$E'' = \phi_p\, h\, \nu_{av}$$
$$= \phi_p h\left(\frac{c}{\lambda_{av}}\right)$$

The terrestrial insolation and average photon energy decrease as air mass (AM) and angle of latitude (ϕ) increase. AM can be calculated as $1/\cos(\theta) = \sqrt{1+(S/h)^2}$, where θ is the Zenith angle, S is the shade length of a stick with height h inserted perpendicular to the ground site location.

Example 2.2: *Calculate the extraterrestrial photon flux.*

Solution: Outside the earth's atmosphere

$$AM = 0$$
$$\phi = 0$$

The solar energy flux

$$E'' = S = 1359 \text{ W/m}^2$$
$$= 0.1359 \text{ W/cm}^2$$

where S = solar constant.

The average photon energy

$$h\,\nu_{av} = 1.48 \text{ eV}$$

$$\therefore \quad \phi_P = \frac{0.1359}{1.48} \times \frac{1}{1.6021 \times 10^{-19}}$$
$$= 5.8 \times 10^{17} \text{ photon/s.cm}^2$$

At $AM = 3$ and $\phi = 5$

$$\phi_p = 2.9 \times 10^{17} \text{ photon/s.cm}^2.$$

When the sun's photon flux strikes a p-n junction (see Section 2.5) made of a semiconductor material, there is an electric current flowing through a load connected across the junction. The electric power produced is proportional to photon flux.

2.3 SOLID-STATE PRINCIPLES

Solid-state principles are important for study of photovoltaics. These principles consist of crystal structure, mechanical and thermal properties, electrical and magnetic properties, band theory and imperfections related to the silicon-based materials used for manufacturing PV/solar cells.

2.3.1 Solid-State Phenomenon

A metallic crystalline solid contains atoms that have nuclei surrounded by electrons that are tightly bound to them (the solid metal). There are outer electrons that are weakly bound to the nuclei. The outer electrons are called valence or conduction electrons. These are free to migrate in the interior of the metal as these have no forces acting on them by the other free electrons or bound electrons or ionized positively charged nuclei.

These free electrons have the following characteristics:

- an equipotential field in which they move
- a constant electrostatic potential energy E_i
- the electrostatic potential energy independent of the location inside the crystal
- not belonging to any specific atom
- belonging to the electro crystal
- cause electric and heat conduction in the metals
- they do not have attractive forces as there are no positive ions on the surface of the metal
- they are easily moved by the electric fields inside the metal
- encounter an energy barrier at the surface
- require more energy to get out of the surface of the metal

The free electrons form the so-called electron gas that is confined inside the metal. The wave functions for these free electrons overlap and the behaviour is described by quantum mechanics principles. The free electrons follow the *Pauli Exclusion principle*, a quantum mechanics principle, which states that no two electrons can exist in the same state at the same time and in the same atom.

2.3.2 Fermi Energy

Fermi energy is the highest possible energy level that free electrons can have at zero Kelvin temperature, in a solid. The electron gas does not follow the energy distribution law of ordinary gas given by the Maxwell-Boltzmann law.

The energy distribution is given by the *Fermi-Dirac distribution law* as given in the following. The law holds good for temperatures below 3000 K.

$$n\,(\mathrm{E})\,d\,E = \left[\frac{4\pi}{h^3}(2m_e)^{3/2}\right]\frac{E^{1/2}}{1+e^{(E-E_f)/kT}}\,dE$$

where dE = Energy range

$n\,(dE)$ = Number of electrons per unit volume in dE.

h = Plank's constant

$= 6.626 \times 10^{-34}$ (J.S.)

m_e = Mass of electron

$= 9.13 \times 10^{-28}$ g.

k = Boltzmann constant

$= 1.38 \times 10^{-23}$ (J/K)

E_f = Fermi Energy.

The Fermi energy is a constant and nearly independent of temperature.

2.3.3 Energy Distribution of Electron Gas

The energy distribution of electron gas is shown in Figure 2.1 for different temperatures ($T_2 > T_1 > 0$). The Fermi-Dirac probability distribution is given by the function,

$$P\,(E) = \frac{1}{1+e^{(E-E_f)}/kT}\,.$$

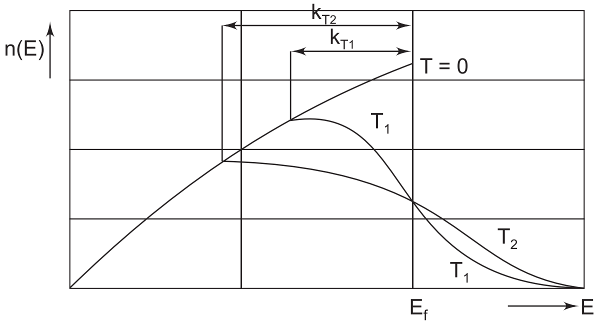


FIGURE 2.1 Energy distribution of electron gas.

The quantity $E^{1/2}$ gives the parabolic rise of the curve from $E = 0$. Free electrons do not have zero energy at close to absolute zero temperature.

It has finite energies up to a maximum of E_F, *i.e.,* Fermi Energy.

$$P\,(E) = 1 \text{ between } E = 0 \text{ to } E = E_F$$
$$P\,(E) = 0 \text{ for } E > E_F$$
$$P\,(E) = \frac{1}{2} \text{ for } E = E_F$$
$$P\,(E) = A\,e^{-E/kT} \text{ for } E >>> E_F$$

= Maxwell-Boltzmann distribution probability for classical gases

A = a constant

2.3.4 Fermi Energy Calculation

The Fermi energy, E_F can be calculated from the following equation:

Total number of free electrons per unit volume

$$n = \int_o^{E_F} n(E)dE = \frac{4\pi}{h^3}(2m_e)^{3/2}\int_o^{E_f} E^{1/2}dt$$

$$= \frac{8\pi}{3h^3}(2m_e)^{3/2}E_F^{\;3/2}$$

$$\therefore \qquad E_F = \frac{h^2}{2m_e}\left(\frac{3n}{8\pi}\right)^{2/3}.$$

The Fermi energy can be expressed in electron volts (eV). An electron volt is a unit of energy equal to the energy acquired by a single electron charge when accelerated through a potential of 1.0 V.

$$1 \text{ eV} = 1.6021 \times 10^{-19} \text{ J}$$
$$= 4.44 \times 10^{-26} \text{ kWh}$$

One million electron volt

$$MeV = 1.6021 \times 10^{-13} \text{ J}$$

The Fermi energy has the following values for different metals.

$$E_F = 7 \text{ eV for copper}$$
$$E_F = 3.1 \text{ eV for sodium}$$

The average energy of a free electron at $T \cong 0$ is equal to 3/5 E_F. This value is much higher than kinetic energy of a particle in a classical gas even at high temperatures.

$$E_F = \frac{3}{2}kT \text{ for classical gas}$$
$$E_F = 0 \text{ at } T = 0$$
$$E_F = 0.1 \text{ eV at } T = 1160 \text{ K.}$$

It is clear from the above relations that at zero Kelvin the classical mechanics gives the wrong result (i.e., zero energy for all particles) but quantum mechanics gives a realistic result of having non-zero energy levels.

2.3.5 Behavior of Free Electrons

For solar cells, the behavior of free electrons is important at temperatures higher than $T = 0$. At moderate temperatures (see Figure 2.1), there is slight rounding-off of zero temperature distribution curve. As the temperature increases, the value kT increases.

$$kT = (E - E_F)$$

when $E = F_F$, $P(E) = \frac{1}{2}$

The free electrons whose energies are much higher than Fermi energy (E_F) remain locked in the same energy state as those occupied at $T = 0$ irrespective of the temperature. There is a fraction of free electrons with energies within kT of the Fermi energy which occupy higher energy states than Fermi energy. These electrons can be elevated to higher energies by collision with high-energy protons from the sun (solar cell) or by thermal excitation (thermionics).

2.4 THE BAND THEORY

Photovoltaic devices and the thermoelectric devices are based on band theory which distinguishes the behavior of conductors, insulators, and semiconductors. The electrical conductivity can be very different by factors as high as 10^{30}.

The valence electrons in a gas occupy a set of single-energy levels as shown in Figure 2.2 (*a*). Where these atoms are brought together in a crystalline solid, the energy levels spread into energy bands due to interactions of atoms as shown in Figure 2.2 (*b*). The regions between the energy bands are called *forbidden bands* as these cannot be occupied by electrons.

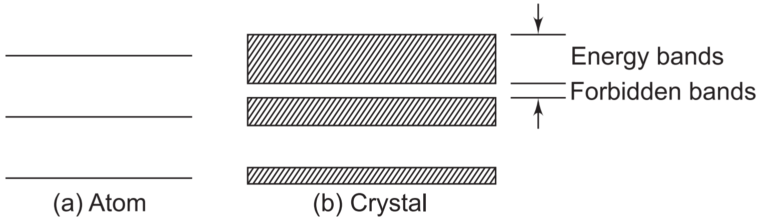


FIGURE 2.2 Electron energy levels.

2.4.1 Energy Bands for Different Materials

The widths and spacings of the energy bands and forbidden bands depend on the crystalline structure. Energy bands may be fully occupied, partially filled, or completely unoccupied. The comparison for an electrical conductor (sodium) and an insulator (diamond) is shown in Figure 2.3. The occupied bands are shown as shaded.

The high conductivity of a metallic crystal is due to not completely filling of uppermost band with electrons. An external field when applied causes the electrons in the uppermost band to gain some energy. This energy is enough to promote them to the continuum of available states immediately above this band. Distribution of electrons among the available states may be slightly varied by energizing them. The shift is controlled by the Fermi-Dirac statics (Section 2.3).

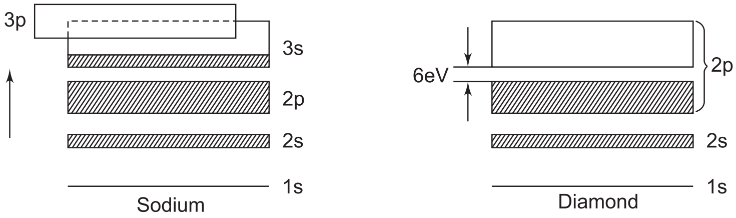


FIGURE 2.3 Comparison of electron bands.

For sodium, the 3*s* band is partially filled, 3*p* band is unoccupied and the two bands overlap. The number of unoccupied levels readily available for the 3*s* band electrons is, therefore, large which results in high electrical conductivity. However, diamond has two 2*p* energy bands, one filled, one unfilled, separated by a forbidden band that is 6 eV wide. This gap is much larger than kT at room or higher temperatures. Thermal excitation, or weak electrical or other fields will not impact enough energy to promote the electrons to the unoccupied 2*p* band and create electron flow or an electric current.

The same applies to photons of visible light that cannot lose energy to the electrons, which is the reason why diamond is transparent to visible light.

The uppermost filled, or partially filled energy band is called the valence band and next empty but available energy band is called the conduction band. A substance is a conductor if these two bands are separated by a very narrow forbidden gap or if they overlap. A substance is an insulator if they are separated by a large gap.

2.5 SEMICONDUCTORS

There is a class of crystalline solids where the forbidden band between the valence and conductance is small, that is about 1 eV. For example, silicon has the gap of 1.1 eV and germanium 0.7 eV.

These solids behave as insulators at low temperatures. At very high temperatures, an appreciable number of electrons receive enough thermal energy and are promoted into the conduction band. The number of electrons promoted into conduction band depends upon the gap width and temperature. The material becomes a conductor. Such a material in pure form is called an *intrinsic semiconductor*.

2.5.1 Types of Semiconductors

Some impurities are added in the intrinsic semiconductors that add some energy level in the forbidden band between the valence band and conduction band. These semiconductors with impurities are called *extrinsic semiconductors*. The controlled amount of impurities is added during manufacturing.

There are two types of semiconductors: *n*-type semiconductors and *p*-type semiconductors. In *n*-type semiconductors, the allowed energy level is near the bottom of the conduction band. This is called donor level. Since the gap is very narrow, there is an abundance of electrons that are excited at room temperature and promoted into conduction band. In intrinsic materials, only a few electrons can be elevated from the valence to conduction band.

In *p*-type semiconductors, the allowed energy level is near the top of the valence electron. The impurity creates an electron deficiency. At room temperature, electrons are easily excited from the valence band to the acceptor level. There is a deficiency created in the valence band.

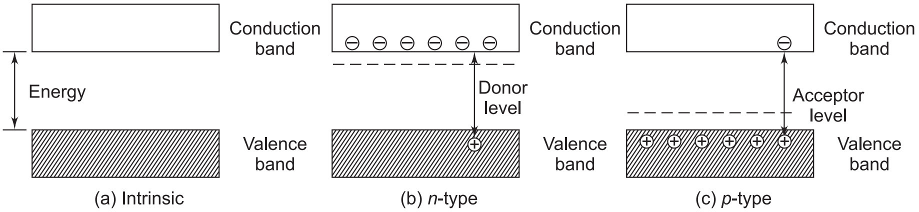


FIGURE 2.4 Electron energy bands for semiconductors.

The absence of an electron is called *a hole* and may be considered a positively charged particle. The conduction in *p*-type semiconductor is due to movement of holes to the valence band.

In both types of semiconductors, the conductivity depends upon the type and amount of impurities.

2.6. *p-n* JUNCTION

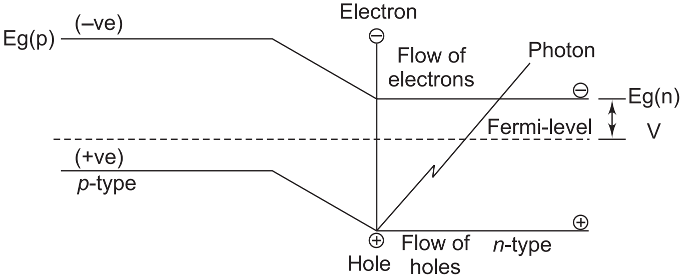


FIGURE 2.5 Electric field in *p-n* junction.

If a *p*-type semiconductor is brought in close contact with a *n*-type semiconductor, a *p-n* junction is formed. Positive and negative charges are created by the absorption of photons from the sun. An electric field is created. The electrons are swept in one direction and positive holes in the other direction. Each solar cell will produce power at about 0.5 V with current proportional to the area of the cell.

2.7 THEORY OF SOLAR CELLS PHOTOVOLTAICS

A solar cell is composed of *p-n* semiconductor junction as shown in Figure 2.6. Solar cells can be manufactured from different semiconductor materials and their combinations. The voltage generated by a solar cell depends on the semiconductor material. The electric current produced depends on the intensity of solar radiation and the cell surface area receiving the radiations. Pure semiconductor materials are needed for achieving high energy conversion efficiency, this adds to the manufacturing costs.

Direct conversion of solar radiation into electricity can be studied with the help of solid-state principles.

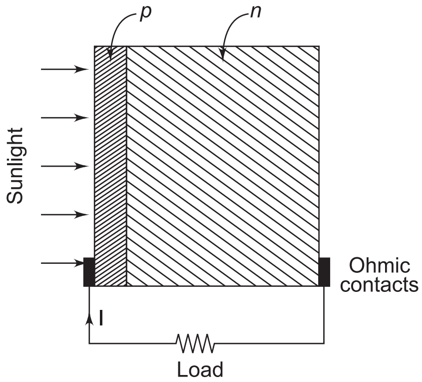


FIGURE 2.6 Cross-section of a solar cell.

2.7.1 Types of Solar Cells

The main types of solar cells along with their brief performance specifications are given in Table 2.1.

Table 2.1 Types of Solar Cells

S.No.	Particulars	Band gap (e V)	Maximum Efficiency (%)
1.	Monocrystalline silicon cells	1.12	24
2.	Polycrystalline silicon cells	1.12	17.8
3.	Amorphous silicon cells	1.75	13
4.	Cadmium tellmide (CdTe) cells	1.44	15.8
5.	Concentrator cells	–	32.3

There are gallium arsenide (Ga As) cells, multi-junction cells, copper iridium di-selenide (CID) cells, etc. At present silicon solar cells occupy more than 60% of the world market.

For single-crystal silicon, *p* is obtained by doping silicon with boron and is typically 1 μm thick; *n* is obtained by doping silicon with arsenic and is typically 80 μm thick. Thin film cells are composed of copper sulphide for *p* typically 0.12 μm thick, and cadmium sulphide for *n*, typically 200 μm thick.

2.7.2 Operation of Cell

The sun's photons strike the cell on the micron-thin *p* side and penetrate to the junction. There they generate electron-hole pairs. When the cell is connected to the load, the electron will diffuse from *n* to *p*. The direction of the current *I* is conventionally in the opposite direction of the electrons.

2.7.3 Performance Characteristics

Typical voltage-current characteristics of a solar cell are shown in Figure 2.7 at two different solar radiation levels. The point of maximum power is where the cell produced power reaches its maximum value. This point can be obtained by drawing the power versus voltage (or current).

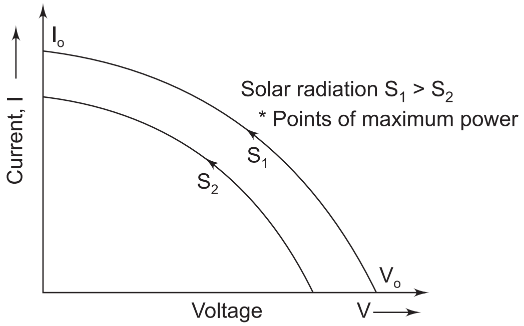


FIGURE 2.7 Performance characteristics of a solar cell.

V_o = Open-circuit voltage

I_o = Short-circuit current

$P_m = (VI)_{max}$ = Point of maximum power.

2.7.4 Solar Energy Utilization

Table 2.2 shows the breakdown of solar energy wavelength distribution. It also shows fraction utilization by a cell and percent solar energy converted to electricity.

Table 2.2 Spectral Solar Energy Conversion

Wavelength range (μ*m*)	Solar energy (%)	Fraction converted by cell/photovoltaic	Solar energy converted by % age
< 0.3	0	0	0
0.3–0.5	17	0.36	5
0.5–0.7	28	0.55	15
0.7–0.9	20	0.73	15
0.9–1.1	13	0.91	12
> 1.1	22	0	0
Total			47

Solar cells do not convert all solar radiation falling upon them to electricity. Weak, low frequency (long wavelength) photons do not possess enough energy to dislodge electrons. However, strong, high-frequency (short wavelength) photons are too energetic and although they dislodge electrons, some of their energy is left over unused.

2.7.5 Solar Cell Efficiency and Losses

Efficiency is defined as the ratio of electric power output of the cell, module or array to the power content of sunlight over its total exposed area. The maximum theoretical efficiency of solar cells is approximately 47%. Efficiencies of modules or arrays are, therefore, lower than that of the cells because of the areas between the individual cells, hence power losses due to electrical resistance. The fraction of cell area to total areas is called the *packing factor*.

The actual efficiency of a solar cell is low because of the following losses:

1. Part of the solar energy is reflected to the sky.
2. Some portion of solar energy is absorbed by non-photovoltaic surfaces.

3. Some solar energy is converted into heat.
4. At high temperatures, there is a recombination of the electron hole pairs. Cells are usually laboratory rated at 1000 W/m^2 and 28°C. The cells normally operate at 50 to 60°C. This may reduce the efficiency by 1 to 2%, as per manufacturer's secifications
5. The efficiency is also affected by various electrical losses.
6. There are additional losses due to mismatch between individual cells in a module and between modules and array.
7. Mass production of cells also lowers the cell efficiency.

Energy Balance of an Array

Typical energy balance of a nonconcentrating silicon photovoltaic conversion array is shown in Figure 2.8.

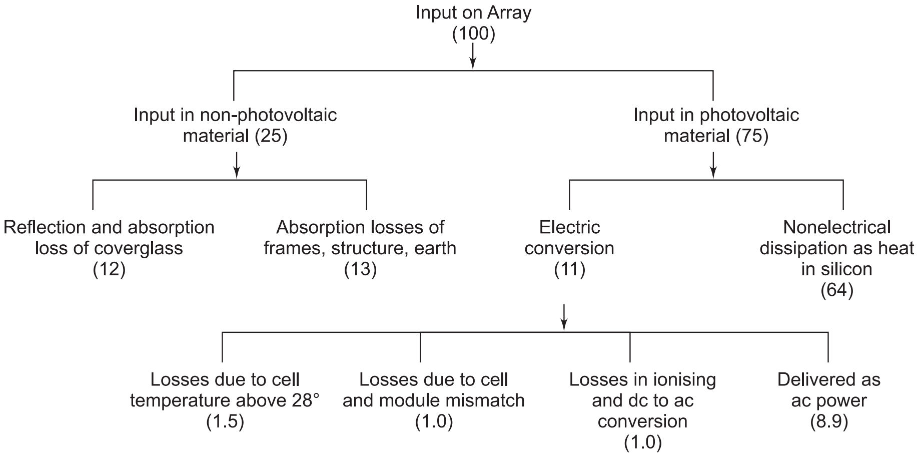


FIGURE 2.8 Energy balance of a solar array.

The resultant array efficiency is only close to 10 per cent after deducting various losses as shown.

2.7.6 Methods of Increasing Cell Efficiency

The following methods are used to improve solar-cell efficiency.

1. *Use of alternative materials.*
2. *Concentration of incident solar energy*: The cell efficiency can be improved using concentrated sunlight. The cells are located at the foci of parabolic or trough concentrators. Cell efficiency of 25% can be achieved with a concentration of about 500 suns. Concentrators are cost effective.
3. *Thermovoltaic system*: Highly concentrated light is used to heat a refractory material. The hot material reradiates the solar energy to silicon cells at longer wavelengths. Such wavelengths are more effective to generate electricity by silicon cells. Although there are material problems as the temperatures required are 1870 to 1925°C.
4. *Cascade systems*: Multijunction solar systems are used. Each cell is subjected to different regions of solar spectrum at which it operates most efficiently. Such a system can yield conversion efficiencies even higher than 25%.

2.8 PERFORMANCE ANALYSIS

A solar cell uses a *p-n* junction as shown in Figure 2.9. The current and voltage relationship is given as follows.

$$I_j = I_o\left[\left(\frac{eV}{e^{kT}}\right) - 1\right], [A]$$

where I_o = saturation current of diode. This is also called dark current when a large negative voltage is applied across the diode.

V = Voltage across junction [V].
e = Electronic charge
= 1.60219×10^{-9} [Coulomb]
k = Boltzmann constant
= 1.38066×10^{-23} [J/K]
T = Temperature [K]

The equivalent electrical circuit of a solar cell is shown in Figure 2.9.

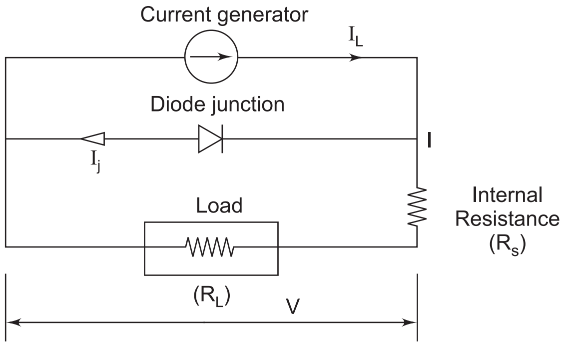


FIGURE 2.9 Electrical circuit diagram of a solar cell.

When light impinges on the *p*-*n* junction, electron-hole pairs are created at a constant rate resulting in an electrical current flow across the junction. The net current (I) is the difference between the normal diode current (I_j) and light generated current (I_L). The internal series resistance (R_s) is due to high series resistance of the diffused layer which is in series with the junction. For an ideal cell, $R_s = 0$.

The photovoltaic current or light generated current I_L is branched into current I in the external circuit and I_j, the diode current. The current-voltage characteristic curve is shown in Figure 2.7.

The following current-voltage relationship is valid at a constant cell temperature and a constant intensity of solar radiation:

$$I = I_L - I_j = I_L - I_o\left[\left(\frac{eV}{e^{kT}}\right) - 1\right]$$

The open circuit voltage V_o for an ideal cell *i*

$$V_o = \left(\frac{kT}{e}\right)\ln\left[\frac{I_L}{I_o} + 1\right]$$

$$L_L >> I_o$$

$$\therefore \qquad V_o = \left(\frac{kT}{e}\right)\ln\frac{I_L}{I_o}.$$

The maximum power of the cell,

$$P_{\max} = V_{mp} \times I_{mp}.$$

where V_{mp} = Voltage at maximum power point
I_{mp} = Current at maximum power point

The maximum efficiency for the cell,

$$\eta_{\max} = \frac{V_{mp} \cdot I_{mp}}{P_{sun}} = \frac{P_{\max}}{P_{sun}}$$

$$= \underbrace{\left[\frac{I_L E_g}{eP_{sun}}\right]}_{} \underbrace{\left[\frac{\mathrm{I}_{mp} \cdot \mathrm{V}_{mp}}{I_L \mathrm{V}_o}\right]}_{\substack{\text{Fill factor}\\ \text{(FF)}}} \underbrace{\left[\frac{e\mathrm{V}_o}{E_g}\right]}_{\substack{\text{Voltage Factor}\\ \text{(VF)}}}$$

where E_g = Forbidden energy band

FF = Fill factor

$$= \frac{I_{\mathrm{mp}} . V_{\mathrm{mp}}}{I_L V_o} = 0.8 \text{ for a properly designed cell}$$

$$P_{\max} = I_L \times \mathrm{V}_o \times FF$$

$$VF = \text{Voltage factor} = \frac{e\mathrm{V}_o}{E_g} = 0.5 \text{ for a silicon cell.}$$

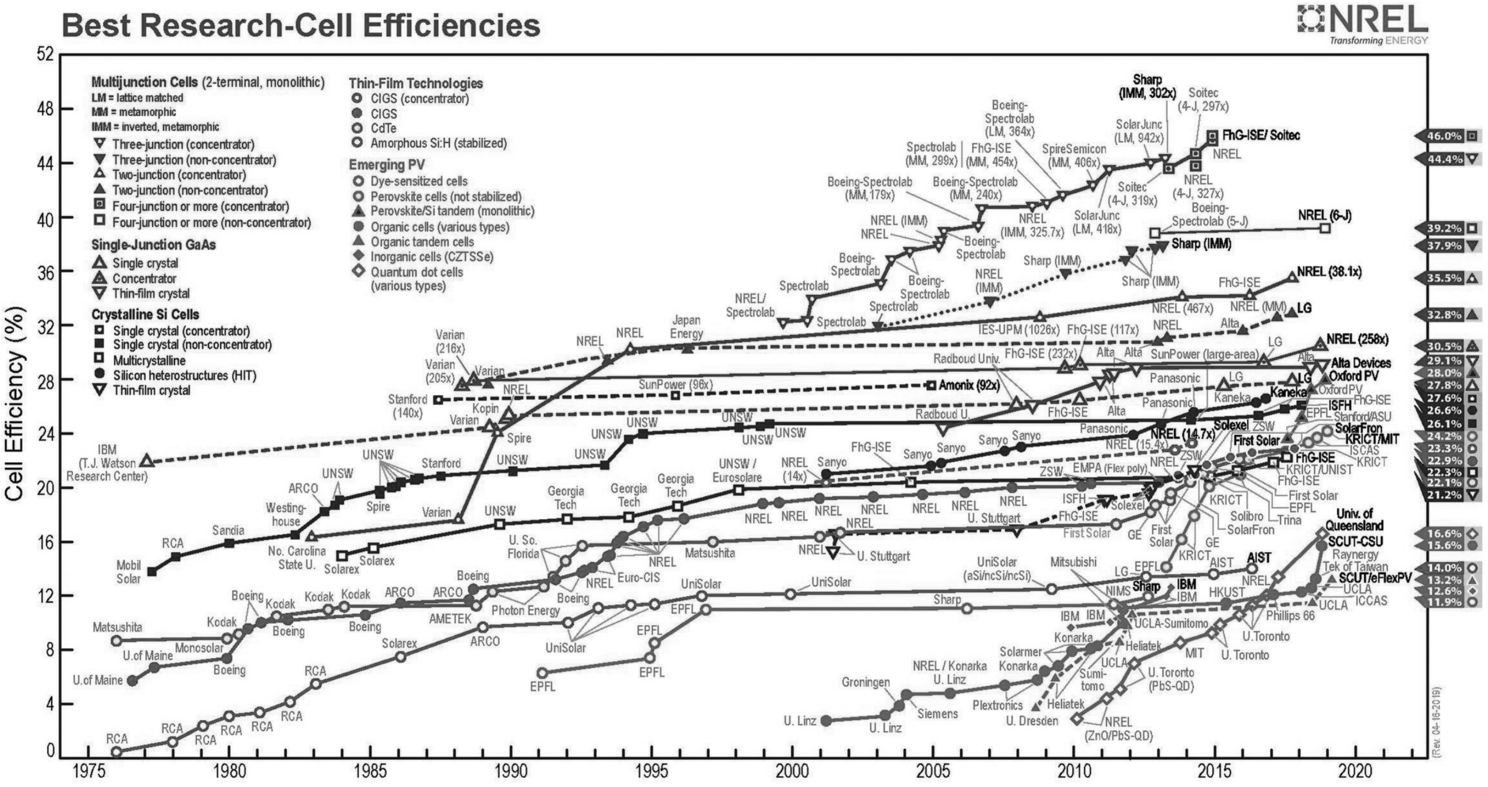
2.9 SOLAR CELL MATERIALS

Silicon solar cells occupy more than 60% of photovoltaic market. Basic types of silicon solar cells are:

1. Monocrystalline silicon solar cells.
2. Polycrystalline silicon solar cells.
3. Thin film or amorphous silicon cells. The chart given below shows the efficiency for several solar-cell technologies (ref. NREL).

2.9.1 Monocrystalline Silicon Solar Cells

Silicon is doped with boron to produce *p*-type semiconductor. A single crystal of 2 m length and 10 to 15 cm diameter is drawn from the molten silicon. It is sliced into 0.3 to 0.5 mm thick wafers or discs. The upper layer of the wafers is doped with phosphorus up to 3 to 4 mm depth to produce *n* type semiconductor. This becomes a *p*-*n* junction. A copper layer is deposited for full area on the back side and 10% area on the front side. These metallic surfaces are used to take off the electric current.



Best Research-Cell Efficiencies

A silicon solar cell of size 10 cm × 10 cm produces a voltage of 0.5 V and power output of 1 W at a solar radiation intensity of 1000 W/m^2. The solar cells are formed into modules by enclosing in an air-tight casing with a transparent cover of synthetic glass. These modules possess high efficiency between 15 and 18% and are used in medium- and large-size plants.

2.9.2 Polycrystalline Silicon Solar Cell

A polycrystalline silicon block (containing many small silicon crystals) is sliced into wafers in the similar manner as single crystal solar cells. The highest efficiency of solar module is 12 to 14%.

2.9.3 Thin-Film Solar Cells

The crystalline solar cells are labor and energy intensive in manufacturing. The thin film cells are produced from amorphous silicon. They have the capacity to absorb some solar radiation due to irregular atom arrangement. A thin 1-mm-thick solar cell is used. Gaseous $Si\ H_4$ is deposited on a glass sheet and the silicon sheet is simultaneously doped to produce *p-n* junction. The efficiency is about 5 to 8%. These are very cheap to manufacture.

Thin-film solar cells are also manufactured from the following materials:

1. Gallium arsenide (Ga As)
2. Cadmium telluride (Cd Te)
3. Copper-indium-selenide (Cu In Se)

2.10 SOLAR ARRAYS

Solar array is an assembly of solar modules, as describe in the following sections.

2.10.1 Solar Modules

Solar cells are connected by conducting wires in a series-parallel combination to form a module. The number of cells in series will determine the module's voltage and the number of cells in parallel determines the module's current. The cells are mounted together under an airtight, mechanically rigid, transparent cover and then is framed with metallic materials like aluminum.

The technical specification of Siemens's solar module M55 containing 36 solar cells connected in series are:

Maximum peak power = 53 W
Open circuit voltage, V_o = 21.7 V
Short circuit current, I_s = 3.4 A
Optimum operating current, I = 3.05 A
Optimum operating voltage, V = 17.4 V
Dimensions = 1293 × 329 × 36 mm.
Mass = 5.7 kg

The Central Electronics Ltd., Sahibabad (U.P.) have developed a solar photovoltaic panel with following specifications:

Maximum peak power = 300 W
System Voltage = 60 V dc nominal
Dimension = 2400 × 2500 mm

2.10.2 Solar Array or Generator

Solar array is made by interconnecting solar modules to supply electricity. The modules are connected both in series and parallel. Connected in series will give a 24-V solar array. In order to increase current and power output, the modules are connected in parallel.

The number of modules connected in series

$$N_{\text{series}} = \frac{V}{V_{\text{mod.}}}$$

where V = Operating voltage of solar generator
$V_{\text{mod.}}$ = Nominal voltage of a module.

The operating current,

$$I = \frac{P}{V}[A]$$

where P = Given power output of the array

The number of modules connected in parallel

$$N_{\text{Parallel}} = \frac{I}{I_{\text{mod.}}}$$

where I = Operating current of generator

$I_{\text{mod.}}$ = Nominal current of a module

Therefore, total number of modules in the solar generator,

$$N = N_{\text{series}} \times N_{\text{parallel}}$$

2.11 SOLAR CELL POWER PLANTS

There are two types of power plants:

1. Autonomous power plants. These are used for local networks.
2. Grid connected power plants. These are used for external networks.

2.11.1 Autonomous Solar Power Plants

The system consists of the following components. The block diagram is shown in Figure 2.10.

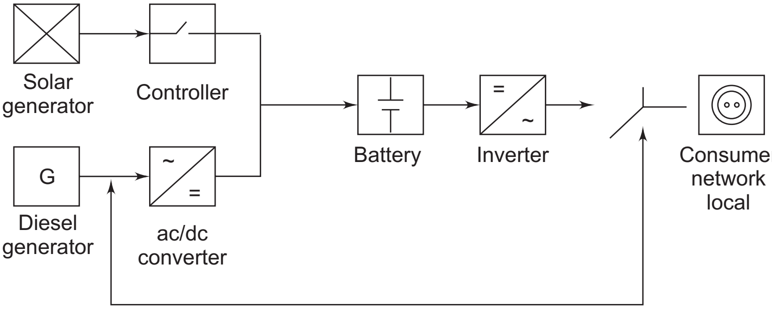


FIGURE 2.10 Block diagrams of autonomous solar-cell power plant.

1. Solar generator or array
2. Storage Battery
3. Charge controller
4. Inverter
5. Standby diesel engine-generator
6. Consumer network

Solar generators can be designed for required electric supply. Autonomous solar power plants are used for the following:

1. Home power supply in rural areas
2. Solar water pumps
3. Telecommunication and relay stations
4. Cattle fencing
5. National parks for street lighting
6. Tourist facilities for remote and hilly areas

2.11.2 Combined Solar-Wind-Diesel Power Plant

A combined power plant of solar, wind, and diesel engine is used for connection to grid. A block diagram is shown in Figure 2.11.

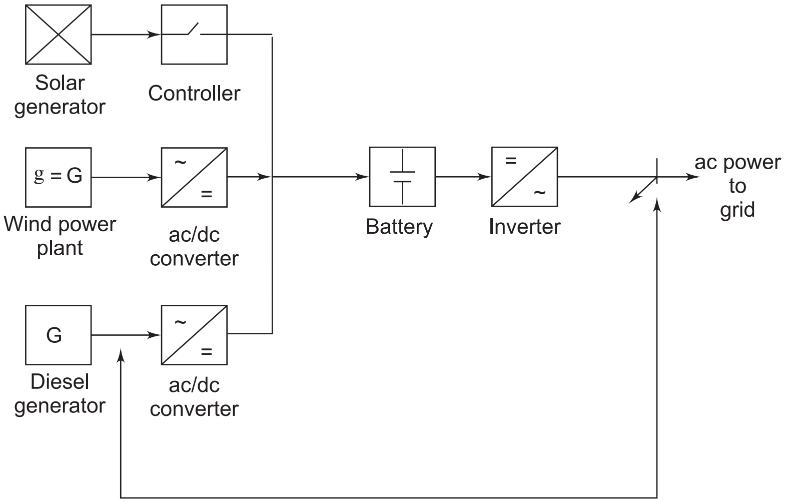


FIGURE 2.11 Combined solar-wind-diesel power plant.

The system consists of the following main components/plants:

1. Solar generator
2. Wind power plant
3. Diesel generator driven by biogas from a sewage plant works as back-up unit

4. Storage battery
5. Inverter
6. Power distribution system

The capacities of different power units may be as follows:

1. Solar generator (40 modules) = 140 kW
2. Wind power plant (Rotor diameter 25 m) = 250 kW
3. Diesel engine = 30 kW

2.12 ENERGY STORAGE

Solar-cell power systems must share conventional power grids or must use electrical storage if their output is to last longer than sunlight, the intermittency effect. Some of the storage schemes are as follows:

1. *Battery*: The storage of electric energy is achieved by conversions to chemical energy in batteries. The most common and highly developed system is the lead-acid battery. Large electric energy storage in lead-acid batteries or other batteries is not economically feasible. Other battery systems with higher energy-to-mass ratios are under development. Currently available and suitable storage batteries have capacities between 40 to 280 Ah.

A storage battery cycle operation consists of a charging process and discharging process.

The amount of energy stored, P_s during charging process,

$$P_s = C\, V_B\ [Wh]$$

where C = Storage capacity $[Ah]$

V_B = Normal battery Voltage $[V]$

A storage battery with a capacity of 200 Ah and a rated voltage of 12 V, can store 2400 *Wh* of electric energy.

The amount of energy recovered, P_d from a battery during discharging process.

$$P_d = V_d\, I_d\, t_d\ [Wh]$$

where V_d = Discharge voltage [V]

I_d = Discharge current [A]
t_d = Discharge duration [H]

In order to get highly reliable power supply, a diesel engine should also be used as back-up unit in addition to storage battery.

2. *Pumped Hydro Storage*: This method is most suitable for larger power plants. The surplus energy is used to pump water into high reservoirs during sunny periods or periods of low demands and extractions of power during evening or cloudy periods or periods of higher demands by running the stored water through water turbines.

The main limitation of this system is to find site with suitable topography near solar power plants. Such power plants are mostly located in desert like flat terrains.

3. *Cryogenic Storage*: The electric energy is directly stored in large underground electrical coils at liquid-helium temperatures of 4K. The electrical resistivity is almost zero.

4. *Flywheel*: The electric energy is stored as kinetic energy into the flywheel and can be recovered using the inertia of the flywheel disc.

5. *Hydrogen*: The electrical energy can be used to produce hydrogen by splitting water through an electrolyser. The hydron can be stored and used to generate electricity, using a fuel cell or proper internal-combustion engines.

2.13 DESIGN OF A SOLAR POWER PLANT

An autonomous solar power plant consists of the following:

1. Solar array or generator
2. Storage battery
3. Charge control unit
4. Inverter
5. Back-up diesel generator
6. Electricity consumer network
7. Support structures and control systems

The power balance equation for the period of utilization of plants can be written as:

$$(P_G + P_B + P_D) = P_{1L} = P_L \text{ [Wh]}$$

where P_G = Electrical energy supplied from solar generator
P_B = Electrical energy supplied from battery
P_D = Electrical energy supplied from diesel engine
P_{1L} = Internal energy losses and system consumptions
P_L = Energy requirement of consumer network.

The energy supplied by solar generator over a given time duration

$$P_G = \int A_G S \eta_g dt [Wh]$$

where A_G = Total solar-cell surface area (m^2)
S = Mean solar radiation (W/m^2)
η_G = Average solar generator efficiency
t = Time duration (h).

2.13.1 Size of Solar Array

The following input data is required for the design:

1. Daily solar radiation at site
2. Ambient temperature
3. Network load and voltage
4. Specification of solar generator and its efficiency
5. Specification of storage battery

The daily electrical load is calculated as follows:

$$P_L = \sum_i n_i P_i t_i$$

where n = Number of power consumers of one type
P = Power requirement of consumers of one type [W]
t = Daily consumption hours (h)

Total area of solar array,

$$A_G = \frac{P_L}{S\eta_G} (m^2)$$

where S = Daily amount of solar energy incident on 1 m^2 of solar array [W/m^2/day]

Maximum peak power output of the generator.

$$P_{\text{max.}} = A_G\, S\, \eta_G\ [W]$$

$$S = 1000\ \text{w/m}^2$$

Number of solar panels (modules) required,

$$N_{\text{mod.}} = \frac{P_{\text{max.}}}{P_{\text{mod.}}}$$

where $P_{\text{mod.}}$ = Maximum power output of a module [W]

2.13.2 Solar Panel Tilt

The tilt angle θ of a solar panel is selected so that generator receives maximum solar radiation at the time of maximum load.

$$\theta = \phi \pm 15^\circ$$

where ϕ = Latitude of site in degrees.

2.13.3 Storage Battery Capacity

The performance parameters of a storage battery are:

1. Capacity [Ah]
2. Rated voltage [V]
3. Rated current [A]
4. Efficiency. The battery efficiency is the energy recovered to energy charged. The usual value of efficiency is 75 to 90%.

The capacity of a storage battery, C can be calculated as follows:

$$C = \frac{FP_L N_D}{V_B D_{\max}\eta_B}|Ah|$$

where F = Reserve factor = 1.2

P_L = Daily power load (wh/day)

ND = Number of required storage days

$D_{\max}$ = Maximum allowable depth of battery discharge = 0.8

V_B = Rated battery voltage (V)

η_B = Battery efficiency

For large power storage, batteries are connected in series and parallel in a storage bank.

The number of batteries to be connected in parallel is the ratio of total energy capacity and energy capacity of each battery.

The number of batteries to be connected in series is the rated voltage of the network load divided by the rated voltage of a battery.

The total number of batteries is the product of batteries in parallel and batteries in series.

Example 2.3: *An autonomous solar power plant is to be designed to supply power to a village school. The power supply is at 12 V dc. The building loads are:*

1. *LED bulbs = 30 × 8 W for 4.5 hrs/day*
2. *Radio with cassette player = 2 × 25 W for 3 hrs/day*
3. *Colour TV sets = 2 × 80 W for 4 hrs/day*
4. *Computers = 4 × 24 W for 7 hrs/day*

The daily solar radiation is 5.4 kWh/m^2/day and the average efficiency is 11%. Solar panels are available with peak power rating of 160 W. Determine:

1. *Daily power requirement*
2. *Solar panel area*
3. *Total peak power output*
4. *Number of solar panels needed*

Solution:

1. Daily load,

$$P_L = \sum_i (n_i P_i t_i)$$

$$= 30 \times 8 \times 4.5 + 2 \times 25 \times 3 + 2 \times 80 \times 4 + 4 \times 24 \times 7$$

$$= 2542 \text{ Wh/day}$$

2. Solar panel area required,

$$A_G = \frac{P_L}{S\eta_G}$$

$$= \frac{2542}{5.4 \times 1000 \times 0.11} = 4.28\,\mathrm{m}^2$$

3. Total peak power output,

$$P_{\max} = A_G \times S \times \eta_G = 4.28 \times 1600 \times 0.11$$
$$= 470.8\text{ W.}$$

4. Number of solar panels needed $= \frac{470.8}{160} = 2.94 = 3.$

Example 2.4: *An acid-lead battery bank is required for a solar generator serving a building with a load of 2542 Wh/day for 3 days. The rated voltage of battery is 12 V.*

Determine the battery storage capacity for battery efficiency of 83%, maximum depth of discharge 0.8 and reserve factor of 1.2. Also calculate the number of batteries connected in parallel if the capacity of a single battery is 180 Ah.

Solution:

1. Battery bank capacity

$$C = \frac{FP_L N_D}{V_B D_{\max} \eta_B}$$

$$C = \frac{1.2 \times 2542 \times 3}{12 \times 0.8 \times 0.83} = 1148.5\,\mathrm{Ah.}$$

2. Number of batteries to be connected in parallel,

$$= \frac{C}{C_1} = \frac{1148.5}{180} = 6.38 = 7.$$

2.14 APPLICATIONS OF SOLAR PHOTOVOLTAIC SYSTEMS

The solar photovoltaic systems are classified as per field of application, type of system, rated capacity, and so on. The main field of applications are as follows:

1. Autonomous-power generation systems
2. Solar water pumps
3. Central power generation

4. Space satellite power stations
5. Transportation, like cars, airplanes.

2.14.1 Autonomous Power Systems

The main applications of such power systems are as follows:

1. Amorphous silicon solar cells of very small capacity are used in watches, pocket calculators, etc.
2. Small capacity solar systems from 50 W to 50 kW capacity are used for remote houses and villages for lighting for domestic use, street lighting, telecommunications, community development, water pumping, etc.
3. Roof-mounted solar systems of 1 kW to 5 kW can be used for residential houses.
4. In developing countries solar systems can find applications for drinking water supply, irrigation, vaccine refrigeration, milk cooling, and rural power supply.
5. In developed countries, solar generators can be used for lighting, recreation centers, radios, TVs, small refrigerators, etc.
6. Solar generators can be used for boats, lighting towers, radio buoys, traffic signals, and parking lights.
7. Developing countries have high solar energy potential and solar generators are used for water pumping, domestic power supply, hospitals, schools, and farmhouses.
8. Other applications can be for cathodic protection of oil pipelines, weather monitoring, railway signaling, and battery charging.

2.14.2 Central Power Generation

A solar photovoltaic power plant of 16 MW has been developed to supply electricity to 2300 households. Solar power plants with a total capacity of 100 MW are planned for future installation.

2.14.3 Solar Water Pumps

The major applications of photovoltaic systems lie in water pumping for drinking water, irrigation in rural areas, and cattle stock water. The solar generators required for this purpose should have a power capacity from 10 W to 10 kW. The water discharge from pumps ranges between 1 to 40 m^3/h with delivery head from 2.5 m to 120 m. These generators usually work without storage battery.

The specifications of solar photovoltaic water pumping systems standardized by Central Electronics Ltd. (U.P.) are as follows:

1. Solar panel : 300 W (peak)
   2.4 m × 2.5 m (size)
   System voltage : 600 V dc normal
2. Motor-pump set : DC motor-centrifugal pumps of monoblock configuration.
   Peak water output : 1.5 to 2.0 litres/sec.
   Average water output at 5 m head : 30 to 40 m^3 per day
   Maximum suction head : 6 m
   Maximum total head : 10 m

The solar array consists of five rows of four modules each. Each module consists of 36 cells, each of 76 mm diameter connected in series to generate about 16 peak watts of power at incident radiation of 10^6 mW/cm^2 at 28°C. Four such modules are connected in series and five such series connected module chains are kept in parallel. The complete array is mounted on an angle iron structure which can be provided with storage batteries and power conditioning equipment.

2.14.4 Space Satellite Power Station (SSPS)

The following system has been conceived as the future solar power supply system: A large surface area of photovoltaic panel will be mounted on a space satellite which will be synchronically moving with the earth orbit so that it will look stationary from every point on the earth. The energy generated will be converted into microwave energy and transmitted to the earth. It will be collected with antennas of a few square kilometer area and then converted into commercial frequency electric power.

Satellite-mounted solar power plants can be designed for power outputs from 3 to 20 gW. The plant will require solar battery of 20 km^2 total area. The transmitting antenna will be 1 km diameter and receiving antenna of 7 to 10 km diameter. The overall efficiency is expected to be 77%.

2.15 ADVANTAGES OF PHOTOVOLTAIC SOLAR SYSTEMS

Photovoltaic solar systems have the following advantages:

1. Absence of moving parts.
2. Direct conversion of light into electricity at room temperature.
3. Can function unattended for long periods.
4. Modular design and voltage and power outputs can be manipulated by integration.
5. Low maintenance cost.
6. No environmental pollution during operation.
7. Very long life.
8. High reliability.
9. Solar energy is free as no fuel is required.
10. Can be started easily and quickly and no starting time is involved.
11. Solar cells can be made from microwatts to megawatts. There can be used to feed the utility grid.
12. Easy to fabricate.
13. These have high power-to-weight ratio, therefore they are very useful for space applications.
14. Decentralized or dispersed power generation at the point of power consumption can save power transmission and distribution costs.
15. These can be used with or without sun tracking.

2.16 LIMITATIONS OF PHOTOVOLTAIC SOLAR SYSTEMS

The main limitations of photovoltaic solar systems are:

1. Manufacture of silicon crystals is labor- and energy-intensive.
2. The principal limitation is high cost, which is being reduced through various technological innovations.

3. The solar insolation is unreliable and therefore costly storage batteries are needed. Good storage batteries are not available.
4. Solar power plants require very large land areas.
5. Electrical generation cost is very high.
6. The energy spent in the manufacture of solar cells is very high. The plant operation period during which photovoltaic plant recovers the spent energy varies from four to seven years.
7. The initial cost of the plant is very high and requires a long gestation period.

EXERCISES

1. What is photon energy? Explain Plank's Law.
2. Explain photon flux. How can this be calculated?
3. Discuss the basic solid-state phenomenon and principles that are important in the photovoltaic energy conversion.
4. Explain Band Theory and *p*-*n* junction.
5. Discuss various types of semiconductors.
6. Describe the construction and operation of a solar cell. What are its performance characteristics?
7. Explain various losses in silicon photovoltaic conversion array. What are achievable efficiencies?
8. What methods can be adopted for increasing the solar-cell efficiency?
9. Derive expressions for maximum power output and efficiency of a solar cell.
10. Write a detailed note on solar-cell materials.
11. How are solar modules and solar arrays designed and assembled?
12. With the aid of suitable block diagrams, explain the following:

(*a*) Autonomous solar power plant.
(*b*) Combined solar power plant.

13. Detail the various energy storage schemes used with solar power plants.

14. Give a step-by-step procedure for the design of a solar photovoltaic power plant.

15. What are the main applications of solar photovoltaic systems? Discuss the same under the following heads:
(*a*) Autonomous power systems
(*b*) Central power generation
(*c*) Solar water pumps
(*d*) Space satellite power stations.

16. List the advantages and limitations of photovoltaic solar systems.

17. Discuss the environmental effects of space satellite power stations.

18. Name the important photovoltaic solar devices developed in India. Name some institutions of India connected with the development of solar cells.

19. Determine the configuration for cells of a PV module to provide 130 W at 12 V. The cell's maximum voltage and current are 0.5 V and 5.2 A, respectively. (ans. 2 rows of 25 cells, in parallel).

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CHAPTER 3

FUEL CELLS

3.1 INTRODUCTION

If an electric current is passed through a dilute solution, an acid, or an alkali by means of two platinum electrodes, hydrogen is produced at the anode and oxygen is evolved at the cathode. If this process is reversed by removing the power supply and connecting the two electrodes through a suitable load/resistance, the presence of hydrogen at one electrode and oxygen at the other will produce a small current in the external circuit and water being produced as a by-product. The reverse process of electrolysis is the essence of the fuel-cell technology as chemical energy stored in hydrogen and oxygen has been combined to produce electricity.

Unlike other heat engines, fuel cells do not have moving parts. Therefore, the fuel cell will be much quieter and require less maintenance and attention, when in normal operation. The conversion efficiency can be much higher; they may be cheaper to operate if manufacturing and operation and maintenance (O&M) costs are justified, and there will be less heat produced resulting in small radiator and exhaust systems.

Although much of the interest in the fuel cells is due to their efficient use of fuel, there are considerable pollution control advantages to be gained as well. Because the fuel reacts electrochemically rather than by combustion with air, no nitrogen oxides are formed. For the same reason, emission of unburned and partly burned gaseous and particulate products are essentially nil. There is relatively little thermal pollution because less heat is lost as waste. Energy conversion via fuel cells, therefore, represents one of the best ways to achieve this goal, because it is possible, simultaneously, to obtain more work and less pollution from used fuel with a fuel cell than any other energy conversion device. Fuel cells have good potential to produce green energy, when fuel supply, manufacturing, and O&M costs are justified.

With this impressive list of advantages, it is perhaps surprising that fuel cells have not been more readily accepted. Cheap, practical, and long-lasting devices are still not available in the market. Fuel cells have not been widely used or developed as terrestrial energy sources because of their high costs (partly due to expensive catalysts and maintenance) and short operating lifetime (due to primarily degradation of electrode material). The only development of fuel cells for electrical power generation was overshadowed by the steam turbine generation and for mobile application, it could not compete with internal combustion energies. The biggest boost to fuel-cell development has been space-power application where high-power density and low weight are important. Fuel cells have been an integral part of the Gemini, Apollo, and space Shuttle vehicles systems. It is only recently that source of the problems of high cost and short lifetime may be overcome, and fuel-cell batteries may be commercially viable within a short period.

Hydrogen and oxygen were selected as reactants for the fuel cells used for space-craft power supplies because of relatively high reactivity of hydrogen. Presently hydrogen is a relatively expensive fuel, about $14 per kg. The reactants for commercial fuel cells should be as cheap and readily available as possible, for example, air as oxidant and natural gas or petroleum derivatives as fuel. The output of fuel cells is low-voltage direct-current (D.C.) power. Hence cells may be connected in various series and parallel arrangements to get whatever voltage and power are desired and highly efficient inverters are available for conversion of the direct-current electrical power into alternative current (A.C.).

Fuel cells have been proven as practical power sources in certain specific applications, such as space missions and remote-site operations. The development of fuel cells for widespread commercial applications is now underway. Although advantages of fuel cells over other heat energies could swing the balance in favor of fuel cells, the relatively high development costs involved means that substantial markets must be sought by finding new applications.

3.2 H_2—O_2 FUEL CELL

Although hydrogen and oxygen are main fuels that are required for electrochemical reactions in a fuel cell, but they can be extracted, through proper process, from hydrocarbons like methanol, natural gas for hydrogen and readily available atmospheric air for oxygen. Also, water is suggested as a source for both hydrogen and oxygen, obtained through electrolysis process. In the following sections, we consider having pure hydrogen and oxygen as fuels for the purpose of related calculations.

3.2.1 Principle of Operation

The following three stages of energy conversion are required in a steam power plant:

1. Conversion of chemical energy of fuel into thermal energy by combustion and heat transfer in a boiler.
2. Conversion of thermal energy into mechanical energy of rotation in a steam turbine.
3. Conversion of mechanical energy into electrical energy in an electric generator.

Fuel cells convert the chemical energy of fuel directly into electrical energy by an electrochemical process. Low-voltage D.C. power is produced by using hydrogen. The schematic diagram of a H_2–O_2 fuel cell is shown in Figure 3.1.

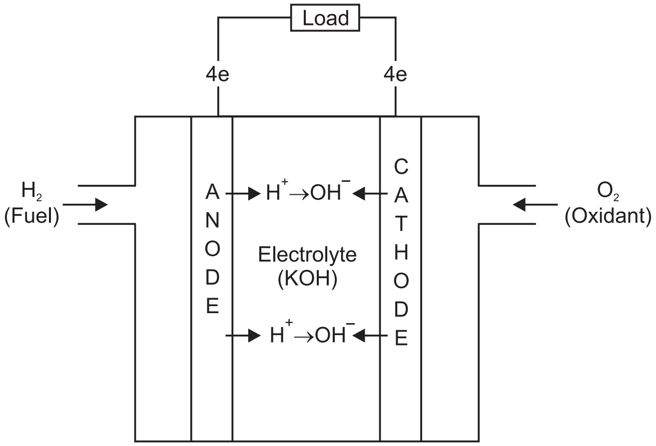

FIGURE 3.1 Hydrogen-oxygen fuel cell.

The working of a fuel cell may be explained with reference to the hydrogen-oxygen fuel cells using aqueous electrolyte. It consists of two porous metal electrodes with the electrolyte between their inner faces kept stirred by circulation. The porous electrodes have a matrix of coarse pores, coated on electrolyte side with a layer of material having finer pores. The reactant gases are supplied to the electrodes as shown in Figure 3.1. The pressure difference between the gases and the electrolyte is enough to displace the liquid from the coarse pores, but not from the fine pores. In order to obtain a large area of electrode–electrolyte interface (at which electron transfer takes place), the gases must either diffuse through a layer of electrolyte on the surface of the electrodes or migrate along the surface beneath the electrolyte. Similarly, the ions must diffuse through the electrolyte trapped in the fine pore layer, which is not stirred by recirculation.

Platinum and other precious metals are used as electrodes in the fuel cells for military and space applications. Platinum being expensive, porous nickel electrodes and porous carbon electrodes are generally used in fuel cells for commercial applications. A catalyst is included in the electrode to expedite the reactions. The best electro-chemical catalysts are finely divided platinum deposited on electrode material. Other cheaper catalysts like nickel for hydrogen and silver for oxygen are used whenever possible.

The chemical reactions taking place at the two electrodes are as follows:

(*i*) Hydrogen electrode (anode)

$$2H_2 = 4H^+ + 4e^-$$

$$4H^+ + 4OH^- = 4H_2O + 4e^-$$

(*ii*) Oxygen electrode (cathode)

$$O_2 = 2O^-$$

$$2O^- + 2H_2O + 4e^- = 4OH^-$$

(*iii*) Overall cell reaction

$$2H_2 + O_2 = 2H_2O$$

The H_2 molecules break into H^+ ions at the anode. These H^+ ions combine with OH^- ions to form water and release electrons at the anode. The electrons travel to the cathode through external circuit. At the cathode, the two oxygen atoms combine with the four electrons arriving by the external circuit and two molecules of water (out of the four molecules produced at the anode) to four $4OH^-$ ions migrate towards the anode and are consumed there. The electrolyte remains invariant. This invariance is a critical feature of the fuel-cell electrolyte and requires that the composition of the electrolyte must not change appreciably as the cell operates. In other words, ions removed by the reaction at the electrode must be replaced one for one at the other electrode.

The most difficult problem in the design of a fuel cell is to obtain enough fuel electrode-electrode reactions site in a given volume. A large effective surface is achieved by a porous electrode structure and surface-tension forces are utilized to get reasonable contact stability. Also, the electrochemical reaction rate is boosted by using some catalyst, like platinum.

3.2.2 Performance Analysis

The theoretical maximum electromotive force (EMF) developed in a fuel cell can be calculated with the help of Gibbs free energy as follows:

$$E = \frac{-\Delta G}{nF}, \ [V]$$

where ΔG = Change in Gibbs free energy reaction [J/mol]

n = No. of electrons per mole of fuel which take part in the reaction (for hydrogen, $n = 2$)

F = Faraday's constant

= 96487 Coulombs/mole.

The change in the Gibbs free energy in a chemical reaction is given by

$$\Delta G = \Delta H - T\Delta S, \ [\text{J/mol}]$$

where ΔH = Change of enthalpy of total reactions, [J/mol]

$T\Delta S$ = Amount of heat absorbed during a reversible process at constant temperature, [J/mol]

The voltage of fuel cells depends upon temperature and pressure. For a $H_2 - O_2$ fuel cell at a pressure of atmosphere, the value of E at 25°C is 1.23 V and only 1.15 V at 200°C. If pressure increases, the fuel cell's voltage also increases.

The maximum efficiency is achieved in a reversible fuel cell

$$\eta_{th} = \frac{\Delta G}{\Delta H} = 1 - T\frac{\Delta S}{\Delta H}$$

where ΔG = Change in Gibbs free energy
= –237.14 [kJ/mol].

ΔH = change in enthalpy by formation of 1 mole of liquid water from H_2 and O_2 at 1 atmosphere and 25°C.

= –285.83 kJ/mol.

Therefore, $\eta_{th} = 83\%$.

The maximum work per mole of H_2 (reactant) or per mole of H_2O (product) is given as:

$$W_{max} = \Delta G_R - \Delta G_{H_2O} \text{ [kJ/mol]}$$

$\Delta G_R = 0$ kJ/need for reactants, basic elements.

The electromotive force (EMF) is given by

$$EMF = E_{rev} = \frac{W_{max}}{n.F} \ [V]$$

The overall efficiency of fuel cell is its thermal efficiency and performance factor.

$$\eta_{overall} = \eta_{th} \times (\text{Loss factor})$$

The power output of a reversible fuel cell

$$P_{rev} = \frac{\Delta G \times \dot{m}}{M_{H_2}}, [W]$$

where $\dot{m}$ = Mass flow rate of hydrogen [kg/s]

M_{H_2} = 2.016 kg/mol
= Molar mass of hydrogen

The actual electrical power output

$$P = P_{rev} \times \eta_{overall}, [W].$$

The rate of heat released which can be utilized,

$$Q = P_{rev} - P, [W].$$

3.2.3 Performance Characteristics

The Carnot efficiency of any heat engine increases with the source temperature for a given sink temperature:

$$\eta_c = \frac{T_1 - T_0}{T_1}$$

The heat source temperature T_1 if varied from 400 K to 1400 K, the performance curve is plotted in Figure 3.2. The heat sink temperature is $T_0 = 300$ K. If the fuel-cell temperature is equal to source temperature, the efficiency decreases linearly with temperature. The theoretical efficiency of $H_2 - O_2$ fuel cell as a function of temperature is plotted in Figure 3.2.

The relationships between current and voltage and power density for $H_2 - O_2$ fuel cell are plotted in Figure 3.3, along with power per unit area (power density).

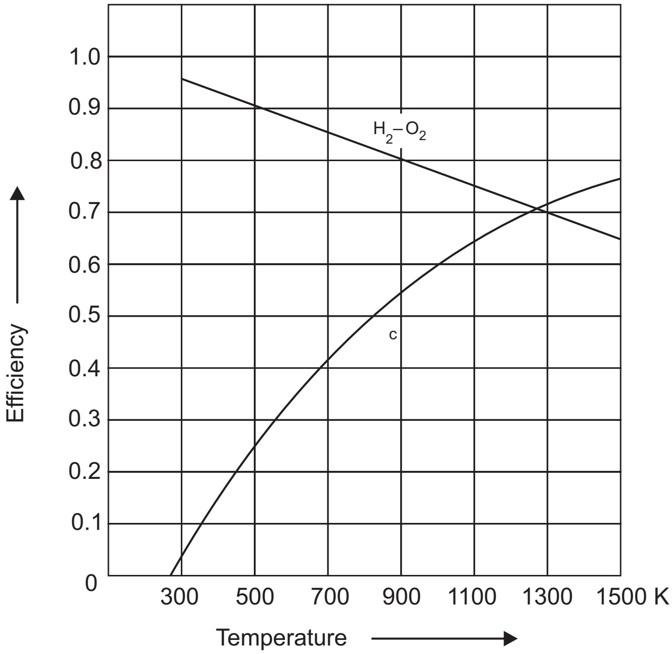

FIGURE 3.2 Fuel-cell and Carnot efficiency as function of temperature.

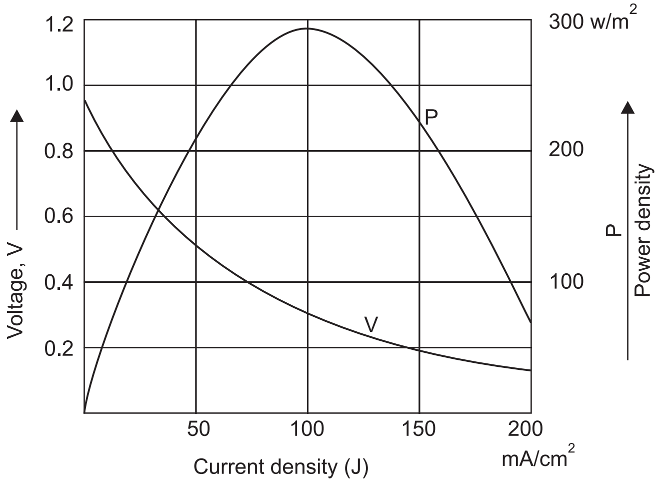

FIGURE 3.3 Current-voltage-power characteristic of $H_2 - O_2$ fuel cells.

3.2.4 Polarization in Fuel Cells

There is a significant drop in the voltage in a fuel cell with increase of current density. This energy loss is called polarization or over potentials.

There are three types of polarization as shown in Figure 3.4. (identified by regions I/activation, II/resistance, and III/concentration).

1. Activation Polarization

This is related to the activation energy barrier for the electron transfer process at the electrode. A drop of potential at the electrode gives a greater driving force to overcome this energy barrier and thus allows current to flow. The polarization may be reduced by:

(*i*) using better electrode catalysts
(*ii*) increasing surface area of electrodes, or decreasing contact resistance
(*iii*) raising the operating temperature.

2. Resistance (Ohmic) Polarization

The internal resistance of a fuel cell consists of:

1. electrode resistance
2. bulk electrolyte temperature
3. interface contact resistance between electrode and electrolyte.

The reduction in internal resistance is the main design criterion for low resistance polarization. This can be reduced by:

(*i*) using more concentrated electrolyte
(*ii*) closer spacing of electrodes, by mechanical compression
(*iii*) increase of operating temperature.

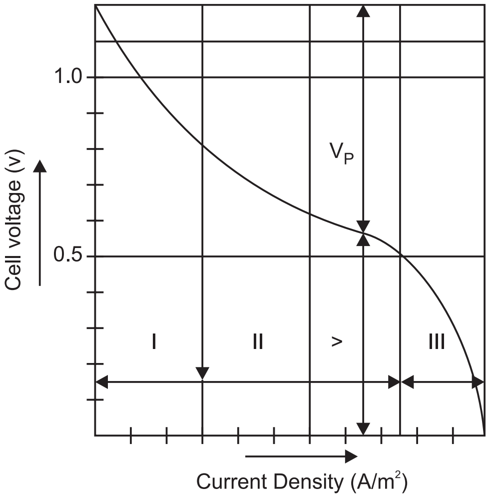

FIGURE 3.4 Polarization in a fuel cell.

3. Concentration Polarization

This can be divided into two parts:

1. Electrolyte side polarization: This is due to slow diffusion of ions into the electrolyte.
2. Gas side polarization: This is due to slow diffusion of reactants into the porous electrode.

These losses can be reduced by increasing temperature.

The no-load or open circuit voltage (Voc)

$$E = V + V_P$$

where V = Operating voltage at a given current density
V_P = Polarization loss.

All the losses in a fuel cell may be included under voltage efficiency,

$$\eta_v = \frac{V}{E}$$

For an ideal cell, $\eta_v = 100\%$

Most of the energy converters convert heat energy into electricity. The efficiency is defined as the ratio of work output and heat input.

The work output of energy converter operating at the thermodynamic reversible potential of the cell is the free energy of the cell.

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

The heat input is the enthalpy change of the reaction = ΔH.

The ideal efficiency of a fuel cell,

$$\eta_{\text{ideal}} = \frac{\Delta G}{\Delta H} = \frac{nFE}{\Delta H}$$

Example 3.1: *Find the reversible voltage for hydrogen-oxygen fuel cell, having the following reaction:*

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

Given $(\Delta G°)_{25} = -237.3 \times 10^3$ *J/g mol of* H_2.

Solution: $$E = -\frac{\Delta G}{nF}$$

where n = Electrons for mole of H_2

$= 2$

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

Example 3.2: *Calculate the following for a hydrogen-oxygen fuel cell.*

(a) *The voltage output of the fuel cell.*
(b) *The cell efficiency.*
(c) *The electrical work output per mole of* H_2 *consumed and per mole of* H_2O *produced.*
(d) *The heat transfer to the surroundings.*

The following reactions take place:

At the anode:

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

At the cathode:

$$2\,\bar{e} + \frac{1}{2}O_2 + H_2O = 2OH^-$$

The cell operates at 25°C. Take the following data.

$$\Delta H^0_{298\,k} = -286 \times 10^3 \text{ kJ/kg mol.}$$

$$\Delta G^0_{298\,k} = -237.3 \times 10^3 \text{ kJ/kg mol.}$$

Solution: $n = 2$

(*a*) $$E = -\frac{\Delta G}{nF} = \frac{237.3 \times 10^3}{2 \times 96,500} = 1.23 \text{ V}$$

(*b*) $$\rightarrow \eta_{\max} = \frac{\Delta W_{\max}}{-(\Delta H)_{298k}} = \frac{-(\Delta G^0)_{298\,k}}{-(\Delta H^0)_{298\,k}}$$

$$= \frac{237.3 \times 10^3}{286 \times 10^3} \times 10 = 83\%$$

(*c*) The electrical work output per mole

$$\Delta W_r = n\,F\,E$$
$$= 2 \times 96500 \times 1.23$$
$$= 237.4 \times 10^3 \text{ kJ/kg mol of } H_2.$$

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

i.e., one mole of H_2O is produced for each mole of H_2.

∴ ΔW_r per mole of water = 237.4×10^3 kJ/kg mol of H_2O.

(*d*) The heat transfer to surrounding

$$Q = T\Delta S = \Delta H^0_{298\,k} - \Delta G^0_{298\,k}$$
$$= (-286 + 237.3) \times 10^3$$
$$= -48.7 \times 10^3 \text{ kJ/mol.}$$

The negative sign shows that the heat is rejected from the cell to the surroundings.

Example 3.3: *A hydrogen-oxygen fuel cell operates at 25°C. Calculate the voltage output of the cell, the efficiency and the electrical work output per mole of* H_2 *consumed and per mole of* H_2O *produced if*

$$\Delta H^{\circ}_{298\,k} = -285838 \text{ kJ/kg mol}$$

and $$\Delta G^{\circ}_{298\,k} = -237191 \text{ kJ/kg mol.}$$

Also compute the heat rejected by the cell.

Solution:

$$H_2 + 2OH^- = 2H_2O + 2e^-$$

$$\therefore \qquad n = 2.$$

The cell voltage,

$$E = \frac{\Delta G^{\circ}{}_{298\,k}}{nF}$$

$$= \frac{237.191 \times 10^3}{2 \times 96,500} = 1.229 \text{ V.}$$

$$\eta_{\max} = \frac{\Delta G^0_{298\,k}}{\Delta H^0_{298\,k}} = \frac{-237.191 \times 10^3}{-285.838 \times 10^3} \times 100 = 83\%$$

The electrical work,

$$W_e = -\Delta G^{\circ}$$

$$= -237.191 \text{ kJ/kg mol } H_2$$

$$= -237.191 \text{ kJ/kg mol of } H_2O.$$

There is one mole of H_2O produced per mole of H_2 consumed.

Heat rejected by the cell,

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

$$= \Delta H^0_{298\,k} - \Delta G^0_{298\,k}$$

$$= -285.838 + 237.191$$

$$= -486.5 \text{ kJ/kg mol.}$$

Example 3.4: *Calculate the open-circuit voltage, the maximum work and thermal efficiency of a* $H_2 - O_2$ *fuel cell operating at 25°C and 1.1013 bar. The product* H_2O *is in liquid state.*

Determine the power output in reversible and actual processes and overall cell efficiency when performance factor is 0.7. The hourly hydrogen consumption is 1.3 kg/hr.

Solution:

The Gibbs free energy change and production enthalpy of H_2O (liquid) at 1.013 bar and 25°C are

$$\Delta G_{H_2O} = -237.14 \text{ kJ/mol}$$

$$\Delta H_{H_2O} = -285.83 \text{ kJ/mol.}$$

The free energy change and production enthalpy for the reactants are zero.

For reactants,

$$\Delta H = \Delta G = 0 \text{ kJ/mol}$$

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

$$= 237.14 \text{ kJ/mol}$$

$$E = \frac{W_{\max}}{nF}$$

$$= \frac{237.14 \times 10^3}{2 \times 96,500} = 1.229 \text{ V.}$$

$$\eta_{th} = \frac{\Delta G}{\Delta H} = \frac{237.14 \times 10^3}{283.83 \times 10^3} \times 100 = 83\%$$

$$\eta_{overall} = \eta_{th} \times \eta_{per}$$

$$= 0.83 \times 0.7 = 0.58$$

$$= 58\%$$

Maximum power,

$$P_{\max} = \frac{\Delta G \times m}{M_{H_2}} \times \frac{\frac{237.14 \times 1.3}{3600}}{2.016} = 42.48 \text{ W}$$

$$M_{H_2} = 2.016 \text{ kg/mol.}$$

$$M = \frac{1.3}{3600} \text{ kg/sec.}$$

Actual power output,

$$P = P_{\max} \times \eta_{\text{overall}}$$
$$= 42.48 \times 6.58 = 24.64 \text{ W.}$$

Heat rejected, $Q = P_{\max} - P$

$$= 42.48 - 24.64 = 17.84 \text{ W.}$$

3.3 TYPES OF FUEL CELLS

Many types of fuel cells have been developed for different applications. A general classification of fuel cells is shown in Figure 3.5. Various technical specifications of fuel cells are given in Table 3.1. A similar table is provided by DOE (office of Energy Efficiency & Renewable Energy) at *https://www.energy.gov/eere/fuelcells/comparison-fuel-cell-technologies*

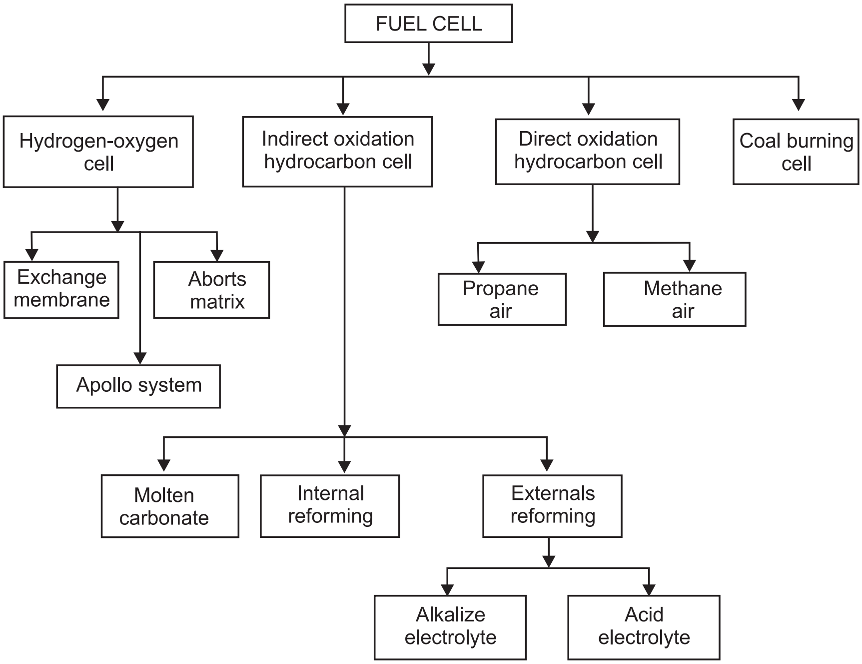

FIGURE 3.5 Classification of fuel cells.

Table 3.1 Technical Specifications and Applications of Fuel Cells

No.	Type of Fuel Cell	Fuel	Electrolyte	Capacity [kW_e]	Efficiency [%]	Working Temperature [°C]	Applications	Remarks
1.	Proton Exchange Membrane (PEM) or solid polymer	H_2, CH_4, CH_3OH	Polymer Membrane	up to 250	60 (H_2) 40 (CH_4)	60 – 80	Cars, buses, houses, CG plants	H_2 is produced in a reformer CO sensitive
2.	Solid Oxide (SoFC)	H_2, CH_4 coal gas	Zr (y) O_2	10–25	50–65	800–1000	Domestic small plants, CG plants	No reforming needed
3.	Alkaline (AFC)	Pure H_2	KOH	20	60	60–90	Space-crafts boats	CO_2 sensitive
4.	Molten carbonate (MCFC)	H_2, CH_4 coal gas	Molten carbonate of Li, Na and K	2200 (max.)	48–60	650	Small plants, CG plants	CO_2 must be circulated
5.	Direct Methanol (DMFC)	CH_3OH	Polymer membrane	N.A.	40	60–130	Small domestic plants, CG plants	No H_2 production needed
6.	Phosphoric Acid (PAFC)	H_2, CH_4	H_3PO_4	1100 max	40	130–220	Small power plants, CG plants	CO sensitive
7.	Regenerative (RFC)	H_2	N.A.	N.A.	N.A.	upto 120	Domestic, CG plants	Low cost of material

Note: CG-Cogeneration.

The power conversion rates depend upon the type of fuel and fuel cell. Some typical values are given in Table 3.2.

Table 3.2 Heat Rate of Fuel Cells

No.	Fuel	Fuel cell	Fuel to A.C. power heat rate (kJ/kWh)
1.	Hydrogen	Alkaline	6500
2.	Impure hydrogen	Acid	7750
3.	Syngas	Molten carbonate	8200
4.	Methanol	Acid	6500
5.	SNG	Molten carbonate/acid	7500
6.	Naphtha	Molten carbonate/acid	7500

3.3.1 Proton Exchange Membrane Fuel Cells (PEMFC)

These fuel cells use thin polymer film as electrolyte and porous carbon with platinum catalyst as electrodes.

The reaction at the anode:

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

The polymer membrane allows protons (H^+) to pass through. The free electrons (e^-) pass through the external circuit and reach cathode.

The reaction at the cathode:

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

Water is produced.

The total reaction:

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

The PEM fuel cells operate at about 80-95°C and have high power density. The output can be varied very quickly. These are very suitable for transportation applications. The main applications are:

1. Light duty vehicles;
2. Cogeneration (CHP) plants;
3. Power supply for buildings; and
4. Rechargeable batteries for video cameras.

Examples of Fuel Cell Vehicles

1. Bus developed by Ballard Power System, Canada
2. XC ELLSTS Fuel Engines Inc. (USA), 1998
3. Honda FCX Clarity
4. Mercedes-Benz F-Cell
5. Toyota Mirai
6. Hyundai NEXO

3.3.2 Solid Oxide Fuel Cells (SOFC)

In these cells, the electrolyte used is ceramic membrane with yttruim stabilized zinconium (YSZ). The electrodes are made of porous metal-ceramic. These cells operate at high temperature of 800-1000°C. No catalyst is needed.

The anode reaction,

$$H_2 + O^{2-} \rightarrow H_2O + 2e^-$$

or,

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

The cathode reaction,

$$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$$

The total reaction,

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

or

$$CO + \frac{1}{2}O_2 \rightarrow CO_2.$$

Fuel cells of capacity up to 250 kW_e are used in cogeneration plants with natural gas as fuel. These are also used for industrial power plants. Efficiencies up to 60% can be attained.

3.3.3 Alkaline Fuel Cells (AFC)

These fuel cells have low weight, low operating temperature (90°C), and high efficiency (60%). These are very attractive for space and military applications. The main drawbacks are an extremely high cost per unit of power produced.

3.3.4 Molten Carbonate Fuel Cells (MCFC)

These cells use a liquid solution of lithium and sodium/potassium carbonate soaked in matrix as electrolyte. The operating temperature is 650°C and attainable efficiency of 60%. Fuel utilization factor is 85% in cogeneration plants. Power plants of 2 MW capacity have been tested with hydrogen, natural gas, and other gaseous fuels.

Anode reaction,

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

Cathode reaction,

$$\frac{1}{2}\,O_2 + CO_2 + 2e^- = CO_3^{2-}$$

Total reaction,

$$H_2 + \frac{1}{2}O_2 + CO_2 = H_2O + CO_2$$

3.3.5 Direct Methanol Fuel Cell (DMFC)

A polymer membrane is used as electrolyte in this type of fuel cell.

Anode reaction,

$$CH_3\,OH + H_2O \rightarrow CO_2 + 6\,H^+ + 6e^-$$

Cathode reaction,

$$6H^+ + 6e^- + 1.5\,O_2 \rightarrow 3\,H_2O$$

Total cell reaction,

$$CH_3\,OH + 1.5\,O_2 \rightarrow CO_2 + 2\,H_2O$$

The cell efficiency can be 40% at operating temperature of 50°C to 90°C. The anode catalyst can draw hydrogen directly from liquid methanol without reforming.

3.3.6 Phosphoric Acid Fuel Cell (PAFC)

These are commercially, most developed fuel cells. These operate at 160°C to 220°C. The efficiency is above 40% for electricity production, but when used in cogeneration plants the efficiency can increase to 85%.

These cells are suitable for autonomous power plants as well as for cogeneration plants in the capacity range from a few kilowatts to 10 MW. These can be employed for residential, commercial, institutional buildings, and small factories. These have been also successfully used for hospitals, nursing homes, hotels, office buildings, schools, and central power plants in the United States.

The capital cost of phosphoric acid fuel cells in the power range of 200 kW is 4500 DM/kW when operated on natural gas.

For widespread use of this fuel cell, the cost must be reduced to 1300 DM/kW and life span has to be increased from the present 15000 hours to 40,000 hours.

3.3.7 Regenerative Fuel Cells (RFC)

Water can be split into hydrogen and oxygen using solar energy. The gases H_2 and O_2 can be used as fuel and oxidant for producing electricity. Water produced is recirculated for electrolytes. These fuel cells can also be used for energy storage.

Example 3.5: *A galvanic cell has the following reaction:*

$$Ag(s) + HgCl(s) = AgCl(s) + Hg(l)$$

$$\text{Take } E^\circ_{25^\circ C} = 0.0455 \text{ V}$$

$$\frac{dE^\circ}{dT} = 0.000338 \text{ V/K.}$$

Calculate ΔG°, ΔS° and ΔH°.

Solution:

$$\begin{aligned} \Delta G^\circ &= -n\,F\,E \\ &= -(1 \times 96{,}500 \times 0.0455) \\ &= -4400 \text{ J.} \end{aligned}$$

$$\Delta S^\circ = nF\left[\frac{dE}{dT}\right]_p$$

$$= 1 \times 96{,}500 \times 0.000338$$

$$= 32.6 \text{ J/K}$$

$$\Delta H^\circ = nF\left[+\frac{dE}{dT} - E\right]$$

$$= 1 \times 96{,}500\ [298 \times 0.000338 - 0.0455]$$

$$= 5300 \text{ J}$$

Example 3.6: *Prove that maximum efficiency of a methane fuel cell is 92% and ideal cell voltage is 1.15 V. Calculate the quantity of methane to produce 100 kWh. How much heat will be generated?*

given that $\Delta G^\circ_{25°C} = -195{,}500$ *cal/gmol.*

$\Delta H^\circ_{25°C} = -212{,}800$ *cal/gmol.*

Solution: The fuel-cell reaction is as follows:

$$CH_4 + 2\ H_2O \rightarrow CO_2 + 8H^+ + 8e^-$$

$$\therefore \quad n = 8$$

$$E^\circ_{25°C} = \frac{-\Delta G^\circ_{25°C}}{nF}$$

$$\therefore \quad E^\circ_{25°C} = \frac{195500 \times 4.186}{8 \times 96{,}500} = 1.060 \text{ V.}$$

$$\eta_{max} = \frac{\Delta W_{max}}{-(\Delta H^\circ)} = \frac{\Delta G^\circ}{\Delta H^\circ}$$

$$= \frac{195{,}500}{212{,}800} = 0.92$$

$$\eta_v = \frac{\text{Operating voltage}}{\text{Open circuit voltage}} = \frac{V}{V_0}$$

$$V_0 = \frac{V}{\eta_V} = \frac{1.060}{0.92} = 1.15 \text{ V.}$$

$$P = 100 \text{ kW}$$

Quantity of methane required,

$$\dot{m} = \frac{100 \times 10^3 \times 3600 \times 36}{195,502 \times 4.186} = 6.547 \text{ kg/hr}$$

$$M_{CH_4} = 36$$

Quantity of heat generated,

$$\begin{aligned} Q &= T\Delta S \\ &= \Delta H + \Delta W \\ &= \Delta H^\circ_{25^\circ\text{C}} - \Delta G^\circ_{25^\circ\text{C}} \\ &= -212,800 - (-195,500) \\ &= -116,700 \text{ kcal/kg mol.} \end{aligned}$$

3.4 APPLICATIONS OF FUEL CELLS

The applications of fuel cells may be discussed under the following groups:

1. Central power generation
2. Cogeneration plants
3. Automotive vehicles
4. Domestic power units
5. Special applications

3.4.1 Central Power Generation

The fuel cell converts chemical energy of fuel directly into electrical energy. Therefore, power generation is the most natural application of fuel cells. For this application, fuel cells must compete with steam turbine, which are remarkably efficient devices with efficiency approaching 40% at rated load. However, demand for electrical energy is far from constant. Over the course of a year, the actual output of a power plant may vary by a factor of four and the daily variation in load can be almost a factor of three. To adjust to the changing demand, either the large base load plants must sometimes operate at part load, or smaller cycling or weaker units must be used during periods of high demand. Either way, efficiency suffers and pollution increases. However, the fuel-cell system not only has a greater efficiency at full load, but this efficiency is retained and even increases as load diminishes, so that inefficient packing/standby generator may not be needed.

A fuel-cell system, unlike a steam turbine need not be big to be efficient, since it is scalable. This characteristic, takes together with two others, low emission and capability of operation on a variety of fuels, allows fuel-cell system to be operated almost anywhere. A small power plant for a community can be operated on the optimum fuel available locally with nearly the same efficiency achieved by a large central power plant. An electric supply company of a large metropolis can dispense a number of generators throughout its area and match capacity to local demand, substantially reducing the expenses and other problems associated with transmission and distribution of electrical energy. Costs and other problems involved with local distribution of electrical energy are likely to be greater with the adoption of underground lines in urban areas.

The flow diagram of a hydrocarbon fuel cell for power generation is shown in Figure 3.6.

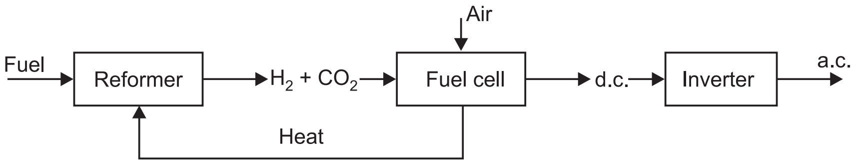

FIGURE 3.6 Hydrocarbon fuel cell power unit.

The following characteristics of a power circuit are discussed below:

1. Efficiency
2. Pollution
3. Scale
4. Modularity
5. Versatility.

1. Efficiency

Fuel cells have high-conversion efficiency especially at low power levels as they are not subject to Carnot limitations on efficiency. It is a one-step process without moving parts and both mechanical and heat losses are absent. This indicates that these systems have the potential for very high efficiency and silent and unattended operation, at least for some types of fuel cells.

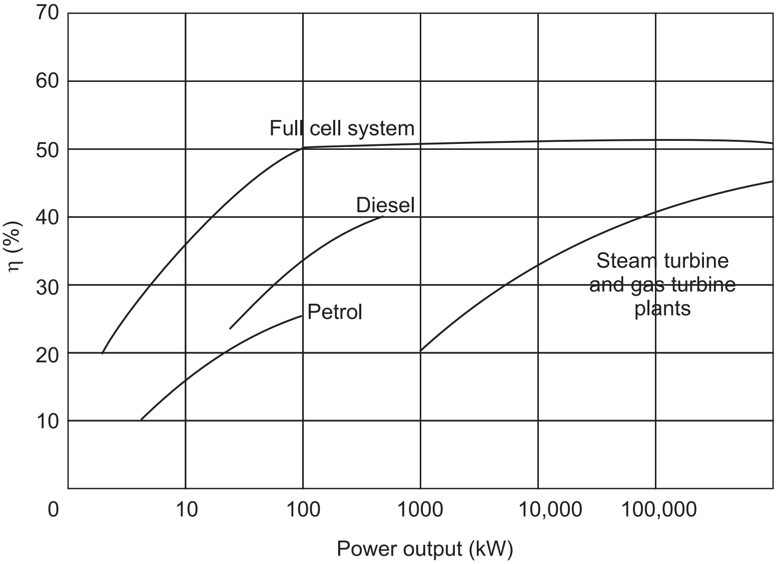

FIGURE 3.7 Thermal efficiency of power nits.

The hydrocarbon fuel cells operate at much the efficiency in the 100 kW range as large multi-megawatt units, see Figure 3.7.

Efficiency may be further improved to about 55% if pure hydrogen is used in place of processed fossil fuels and again to 60% when oxygen is additionally substituted for air. The efficiency of the fuel cell increases as the power level is decreased to about 40% load.

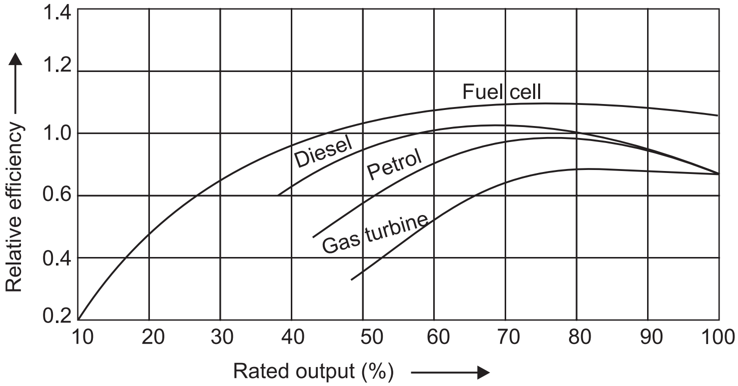

FIGURE 3.8 Part load efficiency of power units.

2. Pollution

In conventional power plants, a considerable amount of NO_X, SO_2, CO_2, and particulates are emitted due to combustion of fuel. Fuel cells emit mostly nontoxic and harmless air, CO_2, water vapor, and small heat as exhaust. Thermal pollution of waterways is not a problem because fuel cells are air cooled and are not dependent on a source of water supply. There are few restrictions on site locations. Air pollutants are reduced by a factor of more than ten over conventional systems. The environmental impact of fuel cells is compared with code requirements of conventional systems in Table 3.3. However, pollution for manufacturing the fuel-cell parts should be considered in a comprehensive study/comparison.

Table 3.3 Environmental Impact of Fuel Cells (Kilogram of Pollutants per Million kJ Heat Input) (USA Federal Standards)

Emissions	Gas-Fired Central Stations	Oil-Fired Central Stations	Coal-Fired Central Stations	Fuel Cell
Particulates	0.05	0.05	0.05	0.0000015
NO_X	0.10	0.15	0.35	0.006–0.009
SO_2	Not required	0.40	0.60	0.000012
Smoke	20% opacity	20% opacity	20% opacity	Negligible

3. Scale

Fuel-cell efficiency is insensitive to size. Scale-up in power output is accompanied by interconnecting fuel stacks (modules) due to a limit to the size of the thin electrodes. There is a saving in cost due to mass production of identical components for scale up.

The fuel cell is relatively a simple device in terms of number of parts with no moving parts except a few fuel and coolant pumps. The fuel-cell stack can be assembled to achieve desired power with required voltage.

4. Modularity

Fuel-cell units can be added to a power plant system, incrementally over a period of time and built rapidly. There is no need to tie up considerable capital in unused initial capacity which is a very serious drawback of large power plants with long construction periods.

5. Versatility

Fuel cells have inherent adaptability towards a broad range of applications. The direct nature of electrochemical process minimizes the effect of both scale and load level on operating characteristics. The power plant modular construction and ease with which units can be linked permits matching of capacity to demand. Increased capacity can be added quickly and simply. Because the power plant is air cooled, it is not dependent on cooling water availability and thus has few location destructions. It has the ability to operate on a variety of fuels as given in Table 3.2.

Small-scale fuel-cell power units can be used with advantage for planning the complete power requirements of a city. The individual houses, apartments, commercial buildings, and industrial sites, independent onsite power units could meet power demand from a kW to several kilowatts. They can be integrated into total energy packages that not only generate electricity, but provide control of temperature, humidity and cleanliness. They can also decentralize the generation of electricity and trim the expenses of transmission over networks by saving as substations. Fuels can be processed on site or supplied to individual power units through underground pipelines.

3.4.2 Cogeneration Units

Cogeneration presents an efficient way of utilizing our limited energy resources because the same fuel source is used simultaneously to produce two forms of useful energy including electricity and heat. Cogeneration applications are process and site specific for a given industry or a commercial building. The cogeneration potential is illustrated in Figure 3.9.

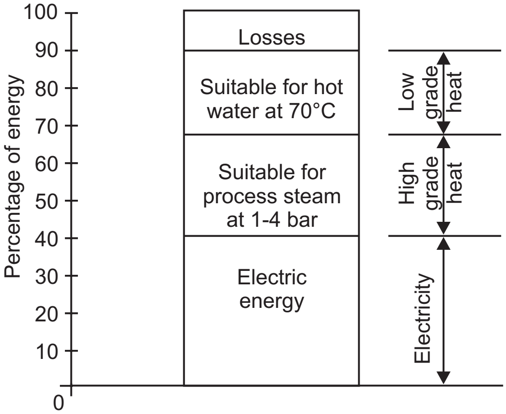

FIGURE 3.9 Cogeneration potential.

The phosphoric acid fuel cell can be used for cogeneration system. The block diagram for such a plant is shown in Figure 3.10.

It is capable of operating on a variety of fuels, including natural gas, light distillate, propane and coal-derived synthetic fuels. Synthetic fuels include hydrogen/carbon monoxide/methane mixture and methanol that can be refined, reformed, and/or shifted to produce hydrogen.

The cogeneration system incorporates fuel-cell stacks, turbo-compressor for supply of pressurized air to the cell cathodes, and for recovery of pressure and heat energy from the cell exhaust streams, desulfurized for removal of sulphur from raw fuel, a steam reformer for conversion of hydrocarbon fuel to hydrogen and carbon monoxide, shift converters for reaction of carbon monoxide and water to produce hydrogen and carbon dioxide, and a heat recovery system for generation of process steam for industry and reformer steam from waste heat transferred from the cell.

The overall process in the fuel cell consists of the continuous electrochemical reaction of hydrogen in the fuel stream and oxygen from air to produce electric power and by-product hot water and heat. Electric efficiency of the system, after parasitic power, is in the range of 38% to 41%. If process steam generated at 6 bar is not sufficient for the industry, supplementary firing may be used.

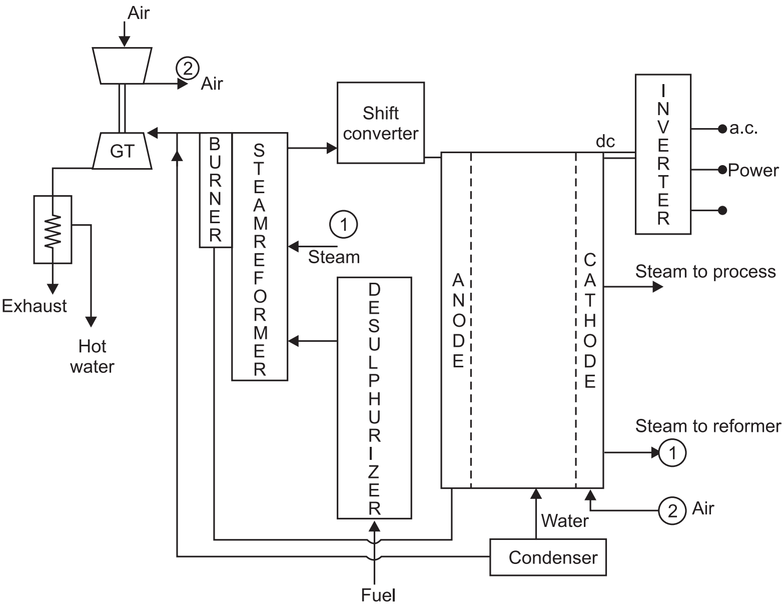

FIGURE 3.10 Phosphoric acid fuel cell cogeneration plant.

3.4.3 Mobile Units for Automotive Vehicles

Fuel cells may provide practical low-pollution vehicles with useful performance and range. Batteries, fuel cells and combination of both have been tried for electrically powered vehicles. The most practical system will probably be hybrid power plants in which batteries provide peak power and the fuel cells act as charging units during low power period.

In the transport industry, high efficiency and low pollution make the fuel cell attractive. Fuel cells are expected to meet the requirements of high-energy density handily since the amount of energy available is determined by the fuel tank. A fuel-cell powered vehicle can have a good range without refuelling, and can be refuelled rapidly, the same as present-day internal combustion engines.

Fuel-cell systems of adequate performance can be built to propel local trains for the city. It would be very smooth and quiet, virtually pollution-free, and could operate on conventional fuels. The fuel cell could replace the conventional diesel engine/generator set directly or small fuel cells with a motor be fitted to each wheel.

It is possible to meet the high-power density criteria for large buses and trucks—ro propel a vehicle of weight comparable to an intermediate car with speeds and accelerations usable in present traffic conditions. With almost instant starting characteristics and very intermittent use, it is probably necessary to achieve a power density of about 220 W/kg, which is equivalent to 6 kg/hp. It can be possible to meet that goal by hybridizing a fuel battery with one of several high-power storage devices such as new generation flywheels.

The criteria of high-power density are more difficult to achieve for small personal cars. Changed driving patterns of decreased speed and acceleration requirements can help to introduce low power vehicles. In the case of a new city, multilane roads and unlevelled road crossing can be planned to mitigate the necessity for high power densities.

3.5 ADVANTAGES AND LIMITATIONS OF FUEL CELLS

3.5.1 Advantages

Fuel cells have the following advantages:

1. These cells have high efficiency (> 50%) in full-load and part load operation. These are potentially ideal sources of power generation. Efficiencies

of the order of 40% have already been achieved. An overall efficiency of more than 80% can be achieved in cogeneration plants if heat generated in the fuel cell can also be utilized in addition to electricity.

2. No pollution emissions. When fuel cells are used for power generation and transport sectors, NOx will be reduced by 50% to 90% and CO_2 by 50% in comparison to present conventional technologies.
3. Water is a by-product of reaction. This is a useful product in space and remote applications.
4. There is no moving part and operation of a fuel cell is noiseless. This can be a great advantage for military and other strategic applications.

3.5.2 Limitations

The main limitations hindering the growth of fuel cells are:

1. High capital cost of fuel cells is the main limitation against commercialization. This limitation can be overcome by new material development as the present materials being used are very costly. Search for new applications and markets can help to reduce the costs by taking advantage of scale of production.
2. Low life-span of fuel cells due to heavy corrosion of electrodes. This can be overcome again by new material technologies.
3. Maintenance of parts mainly the electrode assembly and supply of fuel.

EXERCISES

1. What is a fuel cell? Describe the principle of working of a fuel cell with reference to H_2–O_2 cell.
2. Derive an expression for e.m.f., free energy, potential, power output, and efficiency of a fuel cell.
3. What are the advantages and limitations of a fuel cell?
4. How can an energy efficient city be designed with the help of fuel cells?

5. Explain the performance characteristics of a fuel cell.
6. What are the various types of fuel cells? Define their technical specifications and explain their applications.
7. Compare the performance of a fuel-cell power plant with a conventional power plant.
8. Design a cogeneration plant with the help of a phosphoric acid fuel cell.
9. Write a detailed note on application of fuel cell for automotive vehicles.
10. What is an "ideal fuel cell"? Explain various polarizations in an actual fuel cell.

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CHAPTER 4

MAGNETO-HYDRODYNAMIC POWER GENERATION

4.1 INTRODUCTION

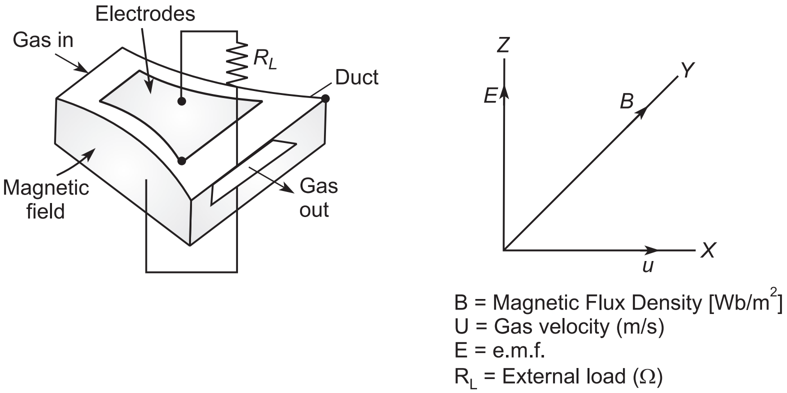
Magneto-hydrodynamic (MHD) is a direct heat to electricity conversion technology based on Faraday's law. This law states that when an electric conductor moves across a magnetic field, a voltage is induced in it which produces an electric current. Here the conductor is an ionized gas or plasma which is passed at high velocity through a powerful magnetic field, perpendicular to the gas flow direction. Hence a current is generated and can be extracted by placing electrodes in a suitable position (mutually perpendicular to the magnetic field and gas flow direction) in the stream. As the result the system produces D.C. power, directly which can be con be converted to A.C. using an inverter. MHD power generation is a promising direct energy conversion technique where the mechanical link can be avoided. It can overcome some of the limitations of conventional power generation by improving the efficiency from 40% to 55%, when combined with other power cycles like Brayton and thus better utilizing the fuel resources and reducing the environmental pollution. MHD power generation layout could be divided into open and closed systems, as described in this YouTube clip: *https://www.youtube.com/watch?v=e9LvM8EThyk*.

MHD power generation has great potential for power production in excess of 1000 MW. It can be used as topper for a coal fired thermal power plant. This will increase the thermal plant efficiency by affecting direct conversion of heat to electricity. In addition to fuel economy and reduced environmental pollution the capital cost of the power plant will also be reduced.

4.2 PRINCIPLE OF OPERATIONS

The arrangement of an MHD power generator is shown in Figure 4.1. The ionized gas (usually air or argon) working as an electrical conductor experiences a braking force due to electromagnetic interaction. The degree of ionization required in practice is very small of the order of 0.1%; the gas is still composed of neutral particles which carry nearly all the kinetic energy of steam and they are unaffected by magnetic forces.

The retarding force is a complex function of collision, cross-section and magnetic flux density. The applied magnetic field manifests itself through the force that is exerted on the electrons in the gas. The force is then coupled to the neutral particles by the electron-ion Coulomb force and ion-neutron collisions.



B = Magnetic Flux Density [Wb/m^2]
U = Gas velocity (m/s)
E = e.m.f.
R_L = External load (Ω)

FIGURE 4.1 MHD power generator.

In order to achieve a large power output, the gas velocity should be high (10^3 m/s) and the applied magnetic flux density must be as large as possible. There should be adequate gas electrical conductivity (more than 10 S/m^3 or mhos/m^3). To achieve equilibrium conditions in pure gas by thermal ionization, temperatures of tens of thousands of degrees are required. By seeding the gas with elements which have low ionization potential such as alkali metals, cesium and potassium, it is possible to achieve reasonable conductivity at temperature in the region of 2000°C. The temperature is within the limits of material technology of MHD.

The electrical power is proportional to magnetic flux density (B) and gas velocity (U) and gas electrical conductivity (σ).

If a particle with positive charge q is moving in a duct with plate walls P_1 and P_2 with a velocity v', the magnetic flux density B pointing into the paper will apply a magnetic force F on the particle. The force, magnetic field and velocity are vector quantities.

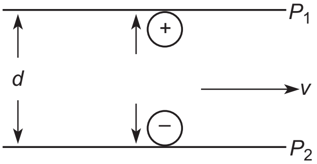


FIGURE 4.2 Force on charge particle.

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

The positive charged particle moves upward and a negatively charged particle moves downward. If P_1 and P_2 are externally connected through a resistance/load, a current will flow and hence mechanical energy (kinetic energy) of gas is converted into electrical energy. If an electrical field of strength E is also applied the total force is obtained from the Lorentz force law in a constant magnetic field (force created due to the combination of the magnetic and electric fields).

$$\begin{aligned} \vec{F} &= q\vec{E} + q(\vec{v}' \times \vec{B}) \\ &= q(\vec{E} + \vec{v}' \times \vec{B}) \end{aligned}$$

where E is the electromagnetic field (e.m.f) applied opposite to the direction of the current.

Note that the electric field by an electric charge may create positive or negative forces on other charges, attracting or repelling them.

Now $\vec{v}' = \vec{U} + \vec{v}$

where $\vec{U}$ = gas velocity

$\vec{v}$ = drift velocity driven by e.m.f.

$$\begin{aligned} \vec{F} &= q\vec{E} + (q\vec{U} \times \vec{B}) + (q\vec{v} \times \vec{B}) \\ &= q(\vec{E} + \vec{U} \times \vec{B} + \vec{v} \times \vec{B}) \\ &= q\vec{E}' + q(\vec{v} \times \vec{B}) \end{aligned}$$

where $E' = E + \vec{U} \times \vec{B}$

The drift velocity is related to the force on the particles through the mobility, μ

$$F = \frac{qv}{\mu}$$

Note: The mobility equation relates the particle drift speed through the gas exposed to an electric field. The mobility constant depends on the particle characteristics and medium properties.

$$\vec{v} = \mu\vec{E} + \mu(\vec{U} \times \vec{B}) + \mu(\vec{v} \times \vec{B})$$

This is the general equation in the vector form.

If the gas flows in x direction and magnetic field, $\vec{B}$ is applied in the + y direction, then

$$U_x = U$$
$$U_y = U_z = 0$$
$$\vec{B}_y = B$$
$$B_x = B_z = 0$$

Put $\mu B = \beta$

$$\therefore \quad v_x = \mu E_x - \beta v_z$$
$$v_y = \mu E_y$$
$$v_z = \mu E_z + \beta U + \beta v_x$$

These are the scalar equations and can be solved for v_x and v_y. There will be no force acting in the y direction.

$$\therefore \quad v_x = \frac{\mu E_x - \beta^2 U}{1 + \beta^2}$$

$$v_y = \frac{\mu E_z + \beta U + \beta \mu E_x}{1 + \beta^2}$$

The current density,

$$J = \frac{\sigma v}{\mu}$$

where v = Drift velocity

μ = Mobility

σ = Gas electrical conductivity

$$J_x = \sigma \frac{E_x - \beta BU}{1+\beta^2}$$

$$J_z = \sigma \frac{E_z + BU + \beta E_x}{1+\beta^2}$$

These are the basic equations for the analysis of MHD generator. Both J_x and J_z can be extracted. In a Faraday MHD generator, the current J_z is extracted and in a Hall MHD generator, J_x is extracted. The flow of current *cn* in the *x* direction is called Hall effect.

4.3 DESIGN PROBLEMS

The design problems are discussed under the following headings:

1. Gas Velocity
2. Magnetic Flux Density
3. Gas electrical Conductivity
4. MHD Duct

4.3.1 Gas Velocity

The power is proportional to the square of gas velocity, the latter should be as high as possible. This can be achieved by converting thermal energy of gas emerging from the furnace into directed kinetic energy in a nozzle. This kinetic energy and thermal energy are then converted into electrical energy by the MHD process.

The conversion of thermal energy into directed kinetic energy can be brought about by conventional nozzle-expansion technologies, and velocities of the order of 10^3 m/s (about Mach number of 3) can be obtained. For sealed inlet gas, the duct is designed to give a constant optimum Mack Number of 0.5 which ensures that maximum density of power is extracted at each section of the duct. The temperature pressure and velocity will fall in such a way as to keep the optimum Mack number constant. However, as the mass flow rate through the duct must remain constant, the area of the duct will vary with velocity. The area of the duct will increase, and velocity will decrease with the gas flow.

4.3.2 Magnetic Flux Density

The power is proportional to magnetic flux density (B) which should be as strong as possible. This can be achieved by passing a heavy current through the coils. The energy dissipated in the magnet is proportional to the length of the duct, but is independent of its cross-sectional area. It is also proportioned to the resistivity of the winding material. The capital cost of the magnet is proportional to the bulk cost of the winding material.

Magnets constructed with copper windings on a soft core can carry flux density up to 3 Wb/m^2. Water cooling must be used to remove the heat generated in the windings by joule effect. For a 100 MW MHD plant, heat dissipated is about 12 MW.

The resistivity of certain materials falls very fast with the decrease of temperature. The decrease in the power needed to generate magnetic field is much greater than additional power needed for the refrigeration equipment. The decrease in running cost is produced at the expense of capital cost of the refrigeration equipment. Magnets made of superconductivity materials (NbZr, Nb_3 Sb) can reduce power dissipation in the windings to nearly zero, but a refrigeration plant would be required to keep the windings at liquid-helium temperature.

4.3.3 Gas Electrical Conductivity

It is a difficult task to attain reasonable (10 to 100 mhos/m) conductivity in a gas. The gas must be made a conductor by ionizing some fraction of it. Thus, gas in the MHD generator can be called plasma, that is, an ionized gas in which positive ions and electrons are present in equal number. In order to attain a reasonable high-temperature plasma, it is necessary to have fuel gas with a calorific value of at least 8500 kJ/Nm^3. At 3000°C, a small degree of ionization equal to 0.1% is obtained, which gives a conductivity of 50%. By increasing the degree of ionization to 1%, the conductivity can be raised to 80%. Hence, a high degree of ionization is not needed for practical purposes. However, it is difficult to find suitable structural material for a combustion chamber, ducts, and nozzles to withstand flow of ionized gases at 3000°C.

One way of increasing the gas electrical conductivity without the need of exceedingly high temperatures is to introduce seeding agents which will ionize more readily than the gas itself and will enhance the electrical conductivity. The best seeding material is metal cesium which has ionization potential of 3.89 eV. Cesium is very expensive and the next seeding material being used is potassium with ionization potential of 4.34 eV. In this case, conductivity of 10 to 100 mhos/m can be achieved at temperatures of 2000°C to 2400°C which are within the range of material technology. However, material selection must take care of enhanced corrosiveness of plasma due to presence of seeding material.

4.3.4 MHD Duct

The main difficulty encountered in the design of MHD power generator is finding suitable material of constructions for the duct to handle highly corrosive and high-temperature gases and seeding materials. The development of a long-lived duct is one of the prime requirements for MHD generator, Ceramics were initially used. If uncooled walls are cooled, severe ablation and erosion takes place and extremely high thermal stresses are set up which leads to rapid disintegration of material. Temperature gradients of 10,000°C/cm can be obtained.

A more promising mode of construction is the use of water-cooled metal walls. A ceramic material, such as zirconia or alumina is sandwiched between water-cooled metal segments. This makes the wall electrically nonconducting. This results in large pressure drops due to rough surface on gas flow side. Water cooled peg wall or modular construction have been used successfully. But smooth walls of ceramic construction give better flow conditions and greater efficiency. The most important insulating materials are magnesia, alumina, calcium zirconate, and strontium zirconate. For electrodes, graphite and water-cooled copper electrodes have been used.

4.4 THERMODYNAMIC PERFORMANCE ANALYSIS

A schematic diagram of MHD power cycle along with its T-S diagram are shown in Figure 4.3 and Figure 4.4 respectively:

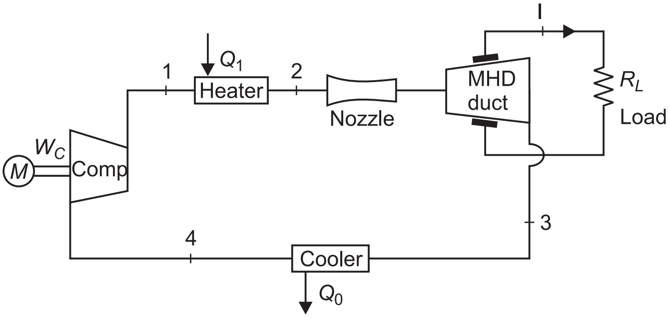


FIGURE 4.3 MHD power cycle.

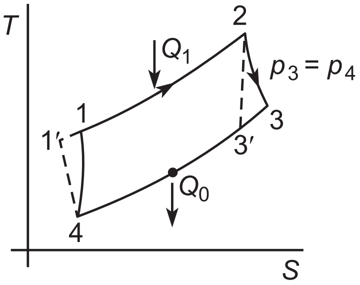


FIGURE 4.4 T-S diagram of MHD cycle.

The total current,

$$I = \sigma\,(E + U \times B)$$

where, σ = Gas electrical conductivity [$m$hos/(m)]
E = Applied electrical field [V]
U = Gas velocity [m/s]
B = Magnetic flux density [W/m^2]

$$\text{The work output} = W_{\text{MHD}} - W_{\text{Comp}}$$

$$\text{Heat input} = Q_1$$

$$W_{\text{MHD}} = h_2^* - h_3^*$$

$$W_{\text{Comp}} = h_2^* - h_1^*$$

where ∗ indicates enthalpy at stagnation values which consider kinetic energy of flow,

$$h^* = h + \frac{u^2}{r}$$

$$\text{The thermal efficiency} = \frac{(h_2^* - h_3^*) - (h_1^* - h_3^*)}{(h_2^* - h_1^*)}$$

The following factors can adversely affect the thermal efficiency:

1. Dissipation of energy in the internal resistance of ionized gas.
2. A space charge barrier at the electrode surface.
3. Heat loss through the electrode and insulator walls.
4. Losses associated with fluid friction.
5. Hall-effect losses due to current induction in the direction of flow of gas.

4.5 ELECTRICAL ANALYSIS

When a current I flows across load resistance R_L with voltage V across the load, the electrical intensity across the electrode plates will be,

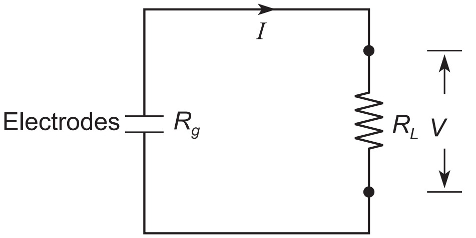


FIGURE 4.5 Electrical circuit of an MHD generator.

$$E = \frac{v}{d}$$

when d = Distance between the electrodes.

The open circuit voltage,

$$E_0 = BUd = IR_g$$

where R_g is the internal resistance of the generator

$$R_g = \frac{d}{\sigma A}$$

where σ = Gas conductivity ($mhos/m$)

A = Electrode plate area (m^2)

Maximum power output is obtained when

$$R_g = R_L$$

$$W_{\max} = E_0 I = (IR_g)\, I = I^2 R_g.$$

$$= \left[\frac{E_0}{R_L + R_g}\right]^2 R_g$$

$$W_{\max} = \frac{E_0^2}{4\,R_g} = \frac{B^2U^2d^2}{4R_g} \qquad [\sigma E_0 = BUd]$$

Now, $R_g = \dfrac{d}{\sigma A}$

$$\therefore \qquad W_{\max} = \frac{B^2U^2d^2}{4d}\sigma A = \frac{1}{4}\sigma U^2 B^2 dA$$

Maximum power per unit volume,

$$\frac{W_{\max}}{dA} = \frac{1}{4}\sigma\, U^2 B^2 .$$

Example 4.1: *Calculate the open circuit voltage and maximum power output for the following MHD generator:*

Plate area $= 0.25\ m^2$
Distance between plates $= 0.50\ m$
Magnetic flux density $= 2\ Wb/m^2$
Average gas velocity $= 10^3\ m/s$
Gas electrical conductivity $= 10$ *mhos/m.*

Solution: Open circuit voltage $E_0 = BUd$

$$= 2 \times 1000 \times 0.5$$

$$= 1000 \text{ V}$$

Generator resistance, $R_g = \dfrac{d}{\sigma A} = \dfrac{0.50}{10 \times 0.25}$

$$= 0.20\ \Omega$$

Maximum power, $W_{\max} = \dfrac{E_0^2}{4R_g} = \dfrac{(1000)^2}{4 \times 0.20}$

$$= 1250 \times 10^3 \text{ W}$$

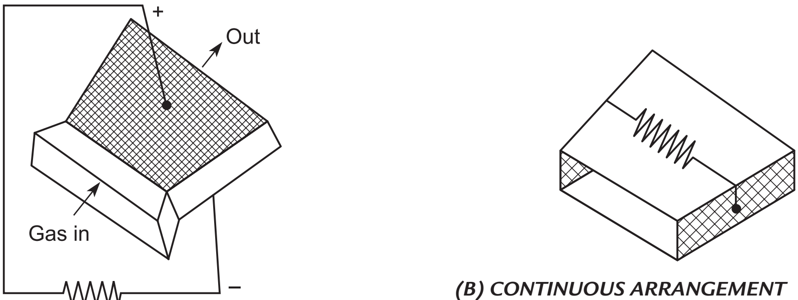
$$= 1250 \text{ kW.}$$

4.6 MHD GENERATOR EFFICIENCY

Possible arrangements of an MHD generator are shown in Figure 4.6.

The current generated in a Faraday generator at the maximum power output,

$$I_{\max} = UB = UB\frac{A}{\rho}[A]$$



(A) PRINCIPLE OF MHD GENERATION OPERATION

(B) CONTINUOUS ARRANGEMENT IN A FARADAY GENERATOR

(C) SEGMENTAL ELECTRODES IN A FARADAY GENERATOR

(D) HALL GENERATOR

FIGURE 4.6 Electrode arrangements.

where U = Flow velocity [m/s]

B = Magnetic flux density [Wb/m]

A = Electrode surface area (m^2)

ρ = Specific resistance of ionized gas (Ω m)

The voltage at maximum power output of above generator,

$$V_{\max} = d\left(UB - I_{\max}\frac{\rho}{A}\right)[V]$$

where d = Distance between the electrodes (m)

The maximum power output,

$$W_{\max} = V_{\max} \,.\, I_{\max}\ [W].$$

The efficiency of energy conversion of MHD generator is defined as the ratio of useful electrical power output and the power required to transport the plasma through the MHD duct.

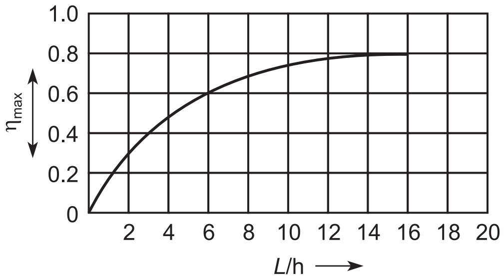


FIGURE 4.7 η v/s L/h.

$$\eta_{\text{MHD}} = \frac{W_{\text{net}}}{W_{\max}}.$$

The efficiency of MHD generator can also be expressed as,

$$\eta_{\text{MHD}} = \frac{V_{\max}}{(UB)}$$

This can be approximated to,

$$\eta_{\text{MHD}} = \frac{R_L}{R_L + R_g}$$

where R_L = External load (Ω)
R_g = Internal resistance of ionized gas (Ω).

The variation of η_{MHD} as a function of L/h is shown in Figure 4.7 when L is the length of the duct and h is the height of duct. Maximum efficiency of 0.5 can be achieved with optimum design.

Example 4.2: *For an MHD Faraday generator, the specific resistance is 0.08 Ωm and magnetic field density is 3.8 Wb/m^2. The electrode area is 1.2 m^2, plasma velocity is 950 m/s and the distance between the electrodes is 0.9 m. Determine the net power output and conversion efficiency.*

Solution: The open circuit voltage,

$$\begin{aligned} E_0 &= BUd \\ &= 3.8 \times 950 \times 0.9 \\ &= 3249 \text{ V} \end{aligned}$$

The short circuit current,

$$I_{\text{SC}} = \frac{AUB}{\rho}$$

$$= \frac{1.2 \times 950 \times 3.8}{0.08}$$

$$= 54150 \text{ A}$$

The current for maximum power output

$$I_{\max} = \frac{UBA}{2\rho} = \frac{950 \times 3.8 \times 1.2}{2 \times 0.08}$$

$$= 27075 \text{ A}$$

$$V_{\max} = UBd - \left(I_{\max} \rho \frac{d}{A} \right)$$

$$V_{\max} = 950 \times 3.8 \times 0.9 - \frac{27073 \times 0.08}{1.2}$$

$$= 1624.5 \text{ V.}$$

The maximum power output

$$W_{\max} = I_{\max} \times V_{\max}$$

$$= 27075 \times 1624.5$$

$$= 44 \text{ MW}$$

The conversion efficiency,

$$\eta_{\text{MHD}} = \frac{V_{\max}}{UB} = \frac{1624.5}{950 \times 3.8} \times 100$$

$$= 45\%$$

4.7 OPEN CYCLE MHD POWER GENERATION SYSTEM

An open cycle MHD power generation system is shown in Figure 4.8.

The system consists of the following units:

1. Combustion chamber
2. Nozzle
3. MHD duct
4. Preheater
5. Seed recovery unit
6. Hot gas

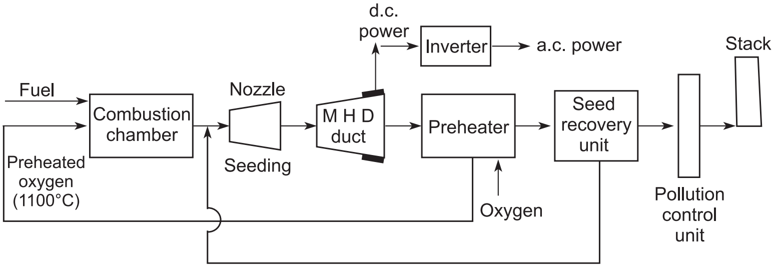


FIGURE 4.8 Open cycle MHD generator.

1. Combustion Chamber: The fuel (coal, oil, or natural gas) is burnt with preheated oxygen (or air) at 1100°C. The hot, pressurized working fluid at 2300°C to 2700°C is seeded with potassium carbonate (or cesium) to ionize the gas.
2. Nozzle: A convergent-divergent nozzle is used to increase the velocity of gas to 10^3 m/s to get directed mass motion energy.
3. MHD Duct: It is a divergent channel made of heat resistant material, externally water cooled. The magnetic field acts perpendicular to the direction of gas motion. The electrode pair may be connected in different ways as per Figure 4.6 to reduce losses. The D.C. power produced is converted into A.C. power with the help of an inverter.
4. Preheater: The gas at 1900°C enters the gas preheater where oxygen or oxygen enriched air or compressed air is heated to a temperature of 1100°C. The preheated gas helps to produce working fluid at 2300°C to 2700°C.
5. Seed Recovery Unit: The seed material is removed for successive use for seeding of hot working fluid in the combustion chamber. The original potassium carbonate seed is converted into potassium sulphate due to presence of sulphur in the fuel. The potassium sulphate is converted back to potassium carbonate chemically in the seed recovery unit.
6. Hot Gas: The hot gases are passed through a pollution control device to remove sulphur and nitrogen oxides before exhausting through a chimney.

4.8 CLOSED CYCLE MHD POWER GENERATION SYSTEM

In a closed system, helium or argon is used as working fluid which is heated in a heat exchanger. Higher temperature and better thermal efficiency are possible. However, seeding is required to attain reasonable gas electrical conductivity at temperatures workable with available structural materials. Instead of seeding with cesiums or potassium carbonate, a liquid metal is mixed with an inert gas to form the working fluid. The liquid metal provides the conductivity.

The following systems are discussed below:

1. Seeded insert gas system
2. Liquid metal system

4.8.1 Seeded Insert Gas System

The main components of a closed cycle seeded insert gas MHD system are shown in Figure 4.9.

1. Combustor and heater: The carrier gas (argon or helium) is heated by the combustion of fuel gas to 1900°C and seeded by cesium injection.
2. MHD generator: The seeded hot working fluid is passed through the MHD generator at high speed. The D.C. power from MHD generator is converted to A.C. power by the inverter. The working fluid is slowed down in the diffuser and precooled.
3. Compressor: The precooled gas is compressed for heating.

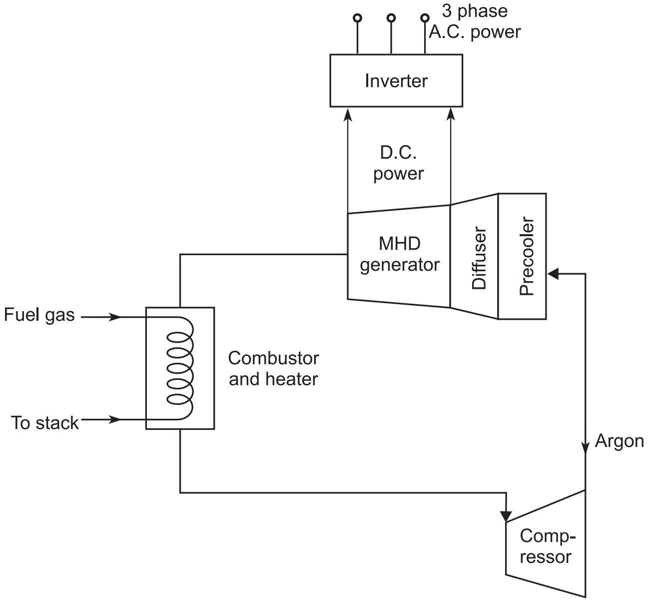


FIGURE 4.9 Closed cycle MHD system.

4.8.2 Liquid Metal System

The carrier gas (argon or helium) is pressurized and heated in a heat exchange within the combustion chamber. The hot gas is incorporated into the liquid metal (hot sodium) to form the working fluid. The schematic diagram is shown in Figure 4.10.

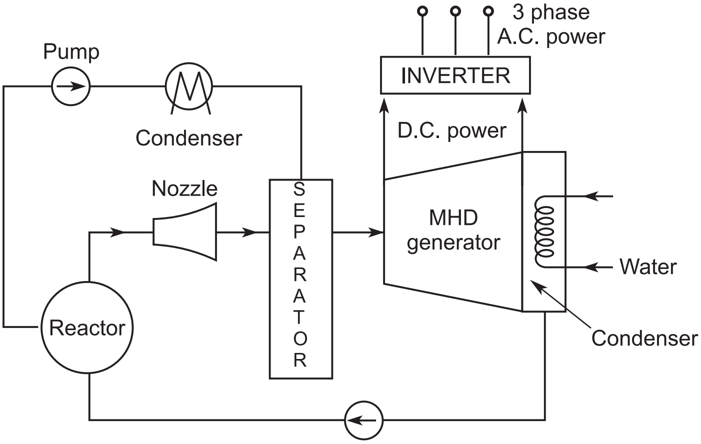


FIGURE 4.10 Liquid metal closed cycle MHD system.

1. MHD generator: The working fluid consisting of gas bubbles uniformly dispersed in an equal volume of liquid sodium is passed through an MHD generator with high directed velocity.
2. Breeder reactor: The exhaust from an MHD duct is passed through a condenser where potassium liquid is formed and pumped to a breeder reactor. The liquid potassium is heated in vapor form and accelerated through a nozzle.
3. Separator: The vapors are separated, condensed, and pumped to a breeder reactor.

4.9 HYBRIDIZATION OF MHD POWER GENERATOR

The overall energy utilization can be improved by employing combined cycle power plant consisting of MHD generator as topping plant and a gas or steam turbine as its bottoming plant. The overall efficiency of about 60%

can be achieved in the combined cycle. The schematic diagram is shown in Figure 4.11.

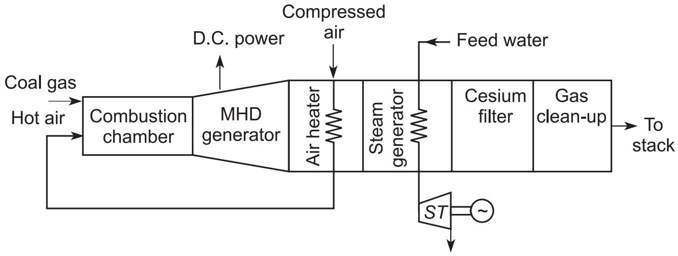


FIGURE 4.11 MHD generator—steam turbine combined cycle plant.

If the gas entering the MHD duct at about 3000°C could be expanded to the ambient temperature of 30°C, the Carnot efficiency would have reached 90%. Unfortunately, the MHD power output is restricted because by the time the gas temperature falls to 2000°C, the electrical conductivity becomes very low with the electrons combining with ions to form neutral atoms and the generator then ceases to operate satisfactorily. Therefore, the MHD generator is used as a topping plant and the MHD exhaust at about 2000°C is utilized in raising steam to drive turbine and generate electricity in a conventional steam power plant. If the fraction Z of the fuel energy is directly converted to electricity in the MHD generator, the remaining (1 – Z) is converted with an efficiency η′ in the bottoming plant so that overall efficiency is

$$\eta = Z + \eta' (1 - Z)$$

If $Z = 0.3$ and $\eta' = 0.4$, then $\eta = 0.58$ which is a good power plant efficiency. MHD topped steam plants can operate either in an open cycle or in a closed cycle. A gas turbine plant can also be used as a bottoming plant. Since, the combined cycle plant operates over a larger temperature difference, the efficiency will obviously be higher.

Example 4.3: *Determine the overall efficiency of a combined cycle power plant which consists of an MHD generator with an efficiency of 40% and a steam power plant with an efficiency of 38%.*

Solution: The overall efficiency,

$$\begin{aligned}\eta &= \eta_{\text{MHD}} + \eta_{\text{ST}} - \eta_{\text{HMD}} \times \eta_{\text{ST}} \\ &= 0.4 + 0.38 - 0.4 \times 0.38 \\ &= 0.628 = 62.8\%\end{aligned}$$

4.10 INDIAN EXPERIENCE

Many countries world over are working on the development of MHD technology. The specifications of a Japanese pilot plant (Tokyo) are given below:

Thermal input = 24 MW
Electrical power output = 1 MW
Mass flow of gas = 2.8 kg/s
Flow velocity = 900 m/s
Gas temperature = 2900 K
Duct length = 1.2 m
Inlet = 8 × 10 cm
Outlet = 8 × 25 cm
Electrodes = 30 pairs
Inlet pressure = 4 bar
Magnetic flux density = 3.5 Wb/m^2
Material for electrodes = Graphite, water cooled copper.

Russia has been the pioneer of this new technology. The world's first U-02 MHD unit was designed by the Russian scientists and power engineers in 1964.

Under intergovernmental agreement, Indian scientists from BARC and power engineers from BHEL worked on a pilot plant of MHD of 5 MW capacity with close interaction with scientists of the High Temperature Science Institute of Moscow. The pilot plant was set up at BHEL, Trichy. BARC has developed special magnet, MHD duct and power tap-off system. BHEL was responsible for the development and installation of a fuel gas generator, oxygen plant, water treatment plant, high-temperature regeneration air heaters and valves, the main combustion chamber, and nozzles, as well as a seed-injection and seed-recovery system.

The main specifications of the pilot plant are:

Thermal input I stage = 5 MW
II stage = 15 MW
Gas temperature = 2600°C
Flux density = 3 Tesla.
Seeding agent = Potassium carbonate
Electrodes = Water cooled copper.

4.11 ADVANTAGES OF AN MHD POWER GENERATOR

The main advantages of a MHD power generator are as follows:

1. The conversion efficiency of an MHD power generator in combined cycle plants can be as high as 60–65%.
2. Large amounts of power can be generated.
3. It is very reliable and robust without moving parts.
4. Pollution-free power can be generated in a closed-cycle system.
5. The plant can be operated in full capacity in a very short time.
6. The plant is very compact.
7. Capital cost can be lower than conventional power plants.
8. The operating cost will be lower than conventional power generation.
9. It is a duct-conversion device eliminating very large plants which reduces loss of energy and enhances reliability of operation.
10. The higher energy utilization helps in saving of fuel and in pollution.

4.12 LIMITATIONS OF MHD TECHNOLOGY

The main limitations hindering the commercial application of MHD technology are as follows:

1. The efficiencies attained so far at pilot plant stage have been relatively low.
2. The power output of an MHD generator is proportional to the square of the magnetic flux density. The electro–magnets large amount of power to create strong magnetic fields. The MHD technology is waiting for the development of superconductor materials which will require very little power even at ambient temperatures.
3. The combustor, MHD duct, electrodes and air preheaters are exposed to very corrosive combustion gases at very high temperatures. The life of the equipment has been very short.
4. The ash (or slag) residue from the burning coal is carried over with the combustion gases and tends to cause erosion of exposed surfaces. However, deposition of the slag on such surfaces may provide some protection.

5. There is a serious problem of separation of seed material from the fly ash and reconversion of potassium sulphate to potassium carbonate.
6. Special fuel gas and preheating of air are needed to provide adequate working fluid temperature.
7. There are serious problems associated with the fabrication of MHD duct, high temperature, and high-pressure heat exchangers and reactors.

EXERCISES

1. Explain the principle and operation of MHD generator.
2. Derive equations for power output and efficiency of an MHD generator.
3. How are MHD systems classified? Describe them in brief.
4. What are the advantages of MHD technology?
5. What are the limitations of MHD conversion technology?
6. Write short notes on:
   (i) Gas velocity
   (ii) Gas electrical conductivity
   (iii) Magnetic flux density
   (iv) MHD duct
7. Give names of materials used for electrodes, duct, and seeding.
8. What is hybridization of MHD power generation? Explain with the help of a flow diagram.
9. Derive an equation for thermal efficiency of an MHD power cycle. What factors can affect the thermal efficiency?
10. Write a brief note on the Indian experience in the area of MHD technology.

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2. *Introduction to Modern Magnetohydrodynamics*, Sebastien Galtier, Cambridge University Press.

CHAPTER 5

THERMOELECTRIC POWER GENERATION

5.1 INTRODUCTION

A loop of two dissimilar metals develops an electric potential (EMF) when the two junctions of the loop are kept at different temperatures. This is called Seebeck effect, discovered by Thomas Johann Seebeck in 1822. This effect is used in a thermocouple to measure temperature. A thermoelectric generator is a device that directly converts heat energy into electrical energy using the Seebeck thermoelectric effect.

The device is very simple but thermal efficiency is very low of the order of 3%. Efficiency of a thermoelectric generator depends upon the temperature of hot and cold junctions and the material properties. The semiconductor materials have more favorable properties that can withstand high temperatures and can give reasonable efficiency. Where cheap fuels like waste heat are available, thermoelectric generators can be developed for base load and standby power generation. Another important application is the use of radioactive decay heat to generate power in space and other remote locations. The use of solar energy to supply heat for generating electricity can be an attractive application of thermoelectric devices if high-efficiency material can be developed.

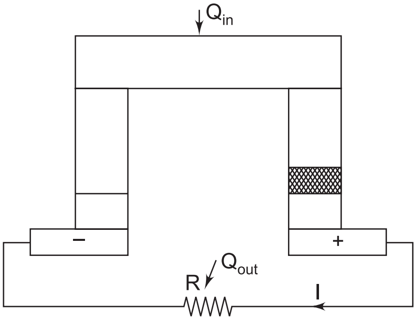

FIGURE 5.1 Thermoelectric generator.

The operation of a thermoelectric generator is shown in Figure 5.1.

The net useful power output is given by:

$$W = I^2 R \text{ [W]}$$

where I = current [A]

R = External load resistance (Ω)

The current in the circuit is given by

$$I = \frac{\alpha \Delta T}{(R_i + R)} \text{[A]}$$

where α = Seebeck coefficient [v/k]

ΔT = temperature difference between hot and cold junctions [K]

R_i = internal resistance of thermoelectric generator (Ω).

The magnitude of potential difference depends on the pair of conductor materials and on temperature difference between the junctions. For a loop made of copper and constantan wires, the value of Seebeck coefficient is 0.04 mV/K. For a temperature difference of 600 K between the junctions, a voltage of 24 mV will be developed. In order to achieve higher potential difference, many generators must be connected. For increasing the useful power output, parallel and series connections are used.

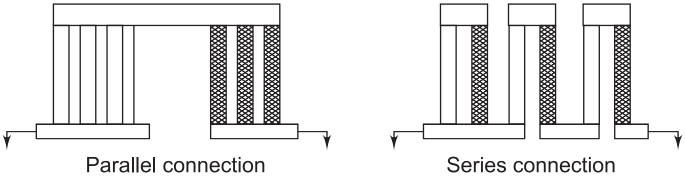

FIGURE 5.2 Cascading of thermoelectric generators.

5.2 THERMOELECTRIC EFFECTS

Thermoelectric effects involve interchange between thermal energy and electrical energy. There are four thermoelectric effects:

(*i*) Seebeck effect
(*ii*) Peltier effect
(*iii*) Thomson effect
(*iv*) Joule effect.

These phenomena form the basis for the design and analysis of thermoelectric generators.

5.2.1 Seebeck Effect

Presence of a temperature gradient in a conductor induces an electric potential gradient even when current flow is zero.

$$\left[\frac{dV/dL}{dT/dL}\right]_{I=o} = \alpha$$

where dV/dL = induced potential gradient [V/m]
dT/dL = applied temperature gradient [K/m]
I = electric current

α is called the Seebeck coefficient for a single material. It has the units of volt per degree temperature difference or Kelvin. The value of α depends upon the materials used.

The maximum induced potential gradient is called Seebeck EMF.

$$\int_{L_1}^{L_2} \frac{dV}{dL} dL = \int_{L_1}^{L_2} \alpha \frac{dT}{dL} dL = \int_{T_1}^{T_2} \alpha \, dT$$

For two materials p and n, the Seebeck EMF is

$$V_{pn} = \int_{T_1}^{T_2} \left(\alpha_p - \alpha_n\right) dT$$

where T_1 = temperature of hot junction at which heat is supplied.
T_2 = temperature of cold junction at which heat is rejected.

$$V_{pn} = \int_{T_1}^{T_2} \alpha_{pn} dT.$$

where $$\alpha_{pn} = \alpha_p - \alpha_n = \left[\frac{dV_{pn}}{dT}\right]_{I=0} = \lim_{\Delta T \to 0}\left[\frac{\Delta V_{pn}}{\Delta T}\right]_{I=0}$$

α_{pn} is called the differential Seebeck coefficient or thermoelectric power. The variation of Seebeck coefficient with temperature is shown in Figure 5.3. The Seebeck coefficient is positive for *p*-type semiconductor and negative for *n*-type semiconductor.

Therefore,

$$\alpha_{pn} = \alpha_p - (-\alpha_n) = \alpha_p + \alpha_n$$

The Seebeck EMF will be very high if the thermoelectric generator is made from *p*-type and *n*-type semiconductors. The heat loss due to Fourier effect will also be reduced as the thermal conductivity of semiconductor is less than that of metal.

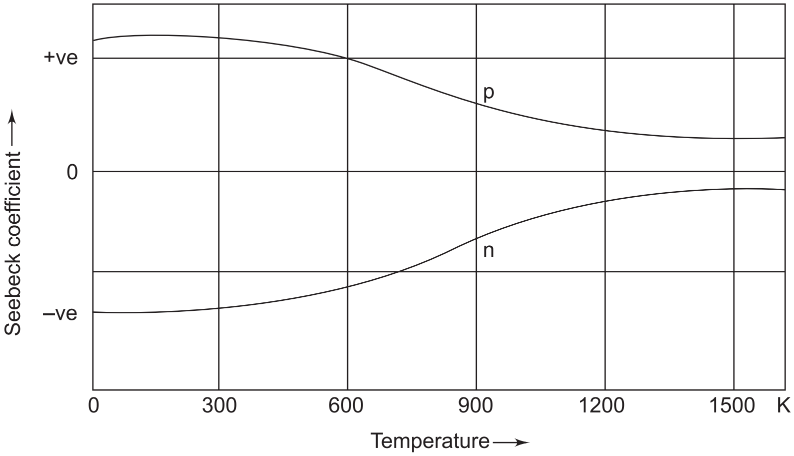

FIGURE 5.3 Variation of Seebeck coefficient with temperature.

5.2.2 Peltier Effect

When an electric current (I) flows through the junction of two materials, Peltier heat is produced. This is called Peltier effect. The Peltier effect is a reversible effect because if heat is produced when a current flows in one direction, the amount of heat is absorbed at the junction if the current is reversed.

Peltier heat per unit time,

$$Q_{p,n} = \pi_{p,n} \,.\, I$$

where $\pi_{p,n}$ is called Peltier coefficient.

Peltier coefficient is the heat produced at the junction per unit current flow, per unit time

$$\pi_{p,n} = \pi_p - \pi_n = \frac{Q_{p,n}}{I} = \alpha_{p,n}.I.$$

5.2.3 Thomson Effect

When electric current flows through a material having a temperature gradient, there is production (or absorption) of heat. This phenomenon is called Thomson effect. It is also a reversible process because reversing the direction of current flow reverses the direction of heat transfer without change in magnitude.

The Thomson coefficients

$$\sigma = \frac{dQ_T/dL}{(dT/dL).I.}$$

where dQ_T/dL = heat interchange per unit time per unit length of material

dT/dL = temperature gradient across the material.

Thomson coefficient (σ) is defined as the Thomson heat produced per unit time per unit electric current and per unit temperature gradient.

The Thomson heat per unit time is given by

$$dQ_T/dL = \alpha\ I.\ dT/dL$$

The Seebeck effect, the Peltier effect, and Thomson effect are more pronounced in semiconductors as compared to metals.

5.2.4 Joule Effect

When an electric current flows through a material with resistance R, an amount of heat is produced per unit time. This is called Joule effect.

The Joule heat produced,

$$Q_j = I^2R$$

This is an irreversible process, similar to mechanical friction.

5.2.5 Kelvin Relations

The relations between the Seebeck, Peltier, and Thomson coefficients were derived by Kelvin as follows:

$$\pi_{p,n} = \alpha_{p,n}.\ T$$

$$\sigma_{p,n} = T.\frac{d\alpha_{p,n}}{dT}$$

where α_p, α_n = Seebeck coefficients [V/k]

π_p, π_n = Peltier coefficients [V]

σ_p, σ_n = Thomson coefficient

Example 5.1: *The Seebeck coefficient of a material is*

$$\alpha = [5 \times 10^4 + 400\ T - T^2] \times 10^{-7}\ [V/K]$$

Calculate the Peltier and Thomson coefficients.

Solution: From Kelvin relations,

$$\begin{aligned}\pi &= \alpha T\\ &= [5 \times 10^4 + 400\ T - T^2] \times 10^{-7} \times T\ [V]\\ &= [5 \times 10^4\, T + 400\ T^2 - T^3] \times 10^{-7}\ [V]\end{aligned}$$

$$\begin{aligned}\sigma &= T.\frac{d\alpha}{dT}\\ &= T\,[400 - 2T] \times 10^{-7}\ [V/K]\\ &= [400\ T - 2T^2] \times 10^{-7}\ [V/K].\end{aligned}$$

Example 5.2: *Find the Thomson heat transferred to the surroundings from a wire whose end points are maintained at 373 K and 273 K respectively: A current of 10 mA is flowing in the wire and its absolute thermoelectric power increases linearly with the temperature at a rate.*

$$\frac{d\alpha_p}{dT} = 5.4 \times 10^{-9}\ [V/K^2].$$

Solution:

From Kelvin relations

$$\sigma_p = T\frac{d\alpha_p}{dT} = (5.4 \times 10^{-9})T\ [V/K]$$

The Thomson heat,

$$Q_T = I\int_{T_1}^{T_2} \alpha_p dT.$$

$$= (10\times10^{-3})\times(5.4\times10^{-9})\int_{273}^{373} dT$$

$$= 1.74\ \mu\text{W}.$$

5.3 PRINCIPLE OF OPERATION OF A THERMOELECTRIC POWER GENERATOR

The thermo-elements of a thermoelectric generator are made up of semiconductors p-type and n-type. Heat is supplied to the hot junction and heat is received from the cold junction. Both the junctions are made of copper as shown in Figure 5.4.

Let T_1 = Source temperature [K]

T_0 = Smith temperature [K]

L_p, L_n = Length of semiconductor elements [m]

A_p, A_n = Cross-sectional area of thermoelectric elements [m^2]

k_p, k_n = Thermal conductivity of elements [W/mK]

ρ_p, ρ_n = Electric resistivity of elements [Ω-M]

α_p, α_n = Seebeck coefficient [V/K]

π_p, π_n = Peltier coefficient [V].

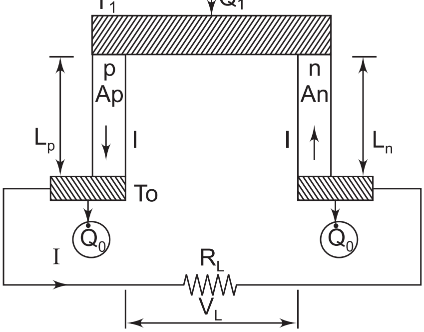

FIGURE 5.4 Circuit diagram of thermoelectric power generation.

Now, thermal conductivity of elements, k_p , k_n = $\frac{kA}{L}$ $[W/K]$

$$\text{Electrical resistance of elements } (\Omega) = \frac{\rho L}{A}.$$

$$\text{Seebeck coefficient, } \alpha_{p,\,n} = \underset{\Delta T \to 0}{Lt} \frac{\Delta V}{\Delta T}$$

$$\text{Peltier heat, } Q_{p,\,n} = \pi_{p,\,n} \,.\, I.$$

$$\text{Peltier coefficient } \pi_{p,\,n} = \alpha_{p,\,n} \,.\, T.$$

From 1st law of thermodynamics as applied to the upper plate (control volume), the temperature difference $(T_1 - T_0)$ will generate a Seebeck voltage $[\alpha_{p,n}\ (T_1 - T_0)]$. There will be an electrical current I which will flow through the external load, R_L. A COMSOL model of a thermoelectric module is available in *COMSOL 5 for Engineers* (Tabatabaian, 2016).

5.4 PERFORMANCE ANALYSIS OF THERMOELECTRIC GENERATOR

The heat supplied to hot junction, $\dot{Q}_1$ will be conducted into two legs $\dot{Q}_k$.

The Peltier heat $\dot{Q}_p$ will be produced at the junction due to current flowing through the circuit.

Joule heat $\dot{Q}_J$ will flow into the junction. It is assumed that half Joulean heat $(\dot{Q}_J/2)$ appears at each junction.

Heat balance at the junction will give

$$\dot{Q}_1 + \frac{1}{2}\dot{Q}_J = \dot{Q}_p + \dot{Q}_k \qquad \ldots(1)$$

where $\dot{Q}_p = \pi_{p,n}\, I = \alpha_{p,n}\, I \,.\, T_1$

$$\dot{Q}_J = I^2 R = I^2\,(R_p + R_n)$$

$$= I^2 \left[\frac{\rho_p L_{\dot{P}}}{A_p} + \frac{\rho_n L_n}{A_n}\right]$$

$$\dot{Q}_k = k\Delta T = (k_p + k_n)\,(T_1 - T_0)$$

$$= \left(\frac{k_p A_p}{L_p} + \frac{k_n A_n}{L_n}\right)(T_1 - T_0)$$

Substituting the above values into equation (1),

$$\dot{Q}_1 = \alpha_{p,n} I T_1 - \frac{1}{2}\left[\frac{\rho_p L_p}{A_p} + \frac{\rho_n L_n}{A_n}\right] + \left[\frac{k_p A_p}{L_p} + \frac{k_n A_n}{L_n}\right](T_1 - T_0)$$

The useful power generated,

$$W_L = I^2 R_L = \frac{V_L^2}{R_L}$$

The voltage across the load,

$$V_L = \alpha_{p,n}(T_1 - T_0) - I(R_p - \mathrm{R}_n)$$

5.4.1 Figure of Merit

By Kinchhoff's Law,

$$I = \frac{\alpha_{p,n}(T_1 - T_0)}{R_L + R_p + R_n}$$

Let $$m = \frac{R_L}{R_P + R_n} = \text{resistance ratio}$$

$\therefore$ $$m + 1 = \frac{R_p + R_n + R_L}{R_p + R_n}$$

Now $$I = \frac{\alpha_{p,n}(T_1 - T_0)}{(R_p + R_n)(1 + m)}.$$

$$W_L = \frac{\alpha_{p,n}^2 (T_1 - T_0)^2}{(R_p + R_n)^2 (1 + m)^2}(R_p + R_n)m.$$

$$= \frac{m}{(1 + m)^2}\frac{\alpha_{p,n}^2 (T_1 - T_0)^2}{(R_p + R_n)}$$

The required heat input,

$$\dot{Q}_1 = \alpha_{p,n}^2 \frac{T_1(T_1 - T_0)}{(R_p + R_n)(1+m)} - \frac{1}{2}\frac{\alpha_{p,n}^2 (T_1 - T_0)^2}{(1+m)^2(R_p + R_n)} + (k_p + k_n)(T_1 - T_0).$$

The efficiency of thermoelectric generator,

$$\eta = \frac{W_L}{\dot{Q}_1} = \frac{\dfrac{m}{(1+m)^2} - \dfrac{\alpha_{p,n}^2}{R_p + R_n}(T_1 - T_0)^2}{\alpha_{p,n}^2 \dfrac{T_1(T_1 - T_0)}{(R_p + R_n)(1+m)} - \dfrac{1}{2}\dfrac{(T_1 - T_0)^2 \alpha_{p,n}^2}{(1+m)^2(R_p + R_n)} + (k_p + k_n)(T_1 - T_0)}$$

$$= \frac{T_1 - T_0}{T_1} \cdot \frac{m}{(1+m)\dfrac{T_1 - T_0}{T_1} - \dfrac{1}{2}\dfrac{T_1 - T_0}{T_1} + \dfrac{(k_p + k_n)(R_p + R_n)(1+m)^2}{\alpha_{p,n}^2 . T_1}}$$

Let $$\frac{\alpha_{p,n}^2}{(k_p + k_n)(R_p + R_n)} = Z$$

where Z is called figure of merit and has the dimension of [1/T].

The figure of merit as defined above consists of the material properties of the two semiconductors. The η increases with the increase of Z. The dimensionless parameter ZT vs the efficiency is also considered for thermoelectric system performance.

5.4.2 Maximum Power

Let $R = R_p + R_n$

and $K = k_p + k_n$

when the product (R, K) is minimum, figure of merit Z is maximum and efficiency η is also maximum

$$(R, K) = \left(\frac{\rho_p L_p}{A_p} + \frac{\rho_n L_n}{A_n}\right)\left(\frac{k_p A_p}{L_p} + \frac{k_n A_n}{L_n}\right)$$

Let $$\gamma_p = \frac{A_p}{L_p}$$

and $$\gamma_n = \frac{A_n}{L_n}$$

$$\therefore \qquad (R,\ K) = \left(\frac{\rho_p}{\gamma_p} + \frac{\rho_n}{\gamma_n}\right)(k_p\gamma_p + k_n\gamma_n)$$

$$= k_p\rho_p + k_n\rho_n \cdot \frac{\gamma_p}{\gamma_n} + k_n\rho_n + k_n\rho_n$$

when materials are fixed, the values γ_n, γ_p, $\frac{A_p}{L_p}, \frac{A_n}{L_n}$ are fixed.

In order to minimize the product $(R,\ K)$

$$\frac{d(R,K)}{d\left(\frac{\gamma_n}{\gamma_p}\right)} = 0 = k_n\rho_p - k_p\rho_n\left(\frac{\gamma_n}{\gamma_p}\right)^{-2}$$

$$\therefore \qquad \frac{\gamma_n}{\gamma_p} = \sqrt{\frac{k_p\rho_n}{k_n\rho_p}}$$

$$\therefore \qquad (R,\ K)_{\min} = k_p\rho_p + k_p\rho_n\left[\frac{k_n\rho_p}{k_p\rho_n}\right]^{1/2} + k_n\rho_p\left[\frac{k_n\rho_n}{k_p\rho_p}\right]^{1/2} + k_n\rho_n$$

$$= \left[\sqrt{\rho_p kp} + \sqrt{\rho_n k_n}\right]^2$$

$$Z_{\max} = \left[\frac{\alpha_{p,n}}{\sqrt{\rho_p k_p} + \sqrt{\rho_n k_n}}\right]$$

$$\eta = \frac{T_1 - T_0}{T_1} \cdot \frac{m}{(1+m) - \frac{1}{2}\frac{T_1 - T_0}{T_1} + \frac{(1+m)^2}{ZT_1}}$$

For a given pair of materials with Z maximum and T_1, T_0 are fixed, η will depend upon optimum value of m.

$$\frac{d\eta}{dm} = 0$$

$$m_{\text{opt}} = \left[1 + Z.\frac{T_1 + T_0}{2}\right]^{1/2} = m_0$$

$$m_0 + 1 = \frac{Z}{m_0 - 1} \cdot \frac{T_1 + T_0}{2}.$$

$$\eta = \frac{T_1 + T_0}{T_1} . \frac{m_0 Z T_1}{(1+m_0)^2} \left[\frac{1}{1 - \frac{1}{2} \frac{Z T_1}{(1+m_0)^2} \frac{T_1 + T_0}{T_1} + \frac{Z T_1 (1+m_0)}{(1+m_0)^2}} \right]$$

$$= \frac{(T_1 - T_0) m_0 Z}{(m_0 + 1)^2 + (m_0 + 1) Z T_1 - \frac{1}{2} Z (T_1 - T_0)}$$

$$= \frac{(T_1 - T_0) m_0 Z}{\frac{m_0 + 1}{m_0 - 1} \times \frac{Z}{2} (T_1 + T_0) + (m_0 + 1) Z T_1 - \frac{1}{2} Z (T_1 - T_0)}$$

$$= \frac{(T_1 - T_0) m_0 (m_0 - 1)}{(m_0 + 1)(T_1 + T_0) + 2(m_0^{\,2} - 1) T_1 - (T_1 - T_0)(m_0 - 1)}$$

$$= \frac{(T_1 - T_0) 2 m_0 (m_0 - 1)}{2 m_0 T_1 \left[m_0 + \frac{T_0}{T_1} \right]}$$

$$\eta = \frac{T_1 - T_0}{T_1} . \frac{(m_0 - 1)}{m_0 + \frac{T_0}{T_1}}$$

The power output

$$W_L = \frac{m}{(1+m)^2} . \frac{\alpha_{p,n}^2 (T_1 - T_0)^2}{R_p + R_n}$$

For a given pair of elements,

$$\frac{dW_L}{dm} = 0 \text{ which gives } m = 1.$$

Therefore maximum power output

$$W_L = \frac{1}{4} \frac{\alpha_{p,n}^2 (T_1 - T_0)^2}{R_p + R_n}$$

Maximum efficiency corresponding to maximum power,

$$\eta_{\text{max power}} = \frac{T_1 - T_0}{T_1} \cdot \frac{1}{2 - \frac{1}{2}\frac{T_1 - T_0}{T_1} + \frac{4}{ZT_1}}$$

Example 5.3: *For a thermoelectric power generator, following parameters are given:*

Temperature of hot reservoir = 600 K.

Temperature of sin k = 300 K.

Figure of merit for the material Z = 2 × 10^{-3} K^{-1}

Determine the efficiency of the thermoelectric generator. What will be the Carnot efficiency?

Solution:

$$m_0 = \left[1 + \frac{Z}{2}(T_1 + T_0)\right]^{\frac{1}{2}}$$

$$= \left[1 + \frac{2 \times 10^{-3}}{2}(600 + 300)\right]^{\frac{1}{2}}$$

$$= \sqrt{1.9} = 1.38.$$

Efficiency of the thermoelectric generator,

$$\eta = \left(\frac{T_1 - T_0}{T_1}\right)\left[\frac{m_0 - 1}{m_0 + \frac{T_0}{T_1}}\right]$$

$$\eta = \frac{600 - 300}{600}\left[\frac{1.38 - 1}{1.38 + \frac{300}{600}}\right]$$

$$= 0.101 = 10.1\%$$

Carnot efficiency

$$\eta_c = \frac{T_1 - T_0}{T_1} = \frac{300}{600} = 0.5 = 50\%.$$

Example 5.4: *The source and sink temperatures of a thermoelectric generator are 923 K and 323 K respectively. The geometrical parameters are* $A_n = 2.3\ cm^2$, $L_n = 1.5\ cm$, $A_p = 1.303\ cm^2$, $L_p = 0.653\ cm$. *Using the optimum value of the product (R, K), calculate the maximum generator efficiency and efficiency for maximum power. Also calculate power output for both the cases. Use the following material properties.*

Seebeck coefficient

$$\alpha_n = -190 \times 10^{-6}\ V/K$$
$$\alpha_p = 190 \times 10^{-6}\ V/K$$

Specific resistivity,

$$\rho_n = 1.45 \times 10^{-3}\ \Omega\text{-cm}$$
$$\rho_p = 1.80 \times 10^{-3}\ \Omega\text{-cm}$$

Figure of merit,

$$Z_n = 2 \times 10^{-3}\ K^{-1}$$
$$Z_p = 1.7 \times 10^{-3}\ K^{-1}.$$

Solution: Conductivity,

$$k_n = \frac{\alpha_n^2}{\rho_n Z_n} = \frac{(190 \times 10^{-6})^2}{1.45 \times 10^{-3} \times 2 \times 10^{-3}}$$

$$= 0.0124\ \text{W/cm K}$$

$$\text{k}_p = \frac{\alpha p^2}{\rho_p z_p} = \frac{(190 \times 10^{-6})^2}{1.8 \times 10^{-3} \times 1.7 \times 10^{-3}}$$

$$= 0.0118\ \text{W/cm. K}$$

$$Z_{\max} = \frac{(\alpha_n - \alpha_p)^2}{\left(\sqrt{\rho_n k_n} + \sqrt{\rho_p k_p}\right)^2}$$

$$= 1.85 \times 10^{-3}\ K^{-1}$$

Thermal conductance

$$K = \frac{k_n A_n}{L_n} + \frac{k_p A_p}{L_p}$$

$$= \frac{1.24\times 10^{-2}\times 2.3}{1.5} + \frac{1.18\times 10^{-2}\times 1.303}{0.653}$$

$$= 0.0452 \text{ W/K}$$

Resistance of the generator,

$$R = R_n + R_p$$

$$= \frac{\rho_n L_n}{A_n} + \frac{\rho_p L_p}{A_p}$$

$$= \left[\frac{1.45\times 1.5}{2.3} + \frac{1.8\times 0.653}{1.383}\right]\times 10^{-3}$$

$$= 1.8 \times 10^{-3}\ \Omega$$

$$m_o = \sqrt{1 + \frac{Z}{2}(T_1 + T_0)}$$

$$= \sqrt{1 + \frac{1.85\times 10^{-3}}{2}(923 + 323)}$$

$$= 1.43$$

$$R_L = m_0 R = 1.43 \times 1.8 \times 10^{-3}$$

$$= 2.68\times 10^{-3}\ \Omega$$

Maximum efficiency,

$$\eta_{\max} = \left(\frac{T_1 - T_0}{T_1}\right)\left(\frac{m_0 - 1}{m_0 + \frac{T_0}{T}}\right)$$

$$= \frac{600}{923}\left[\frac{1.43 - 1}{1.43 + \left(\frac{323}{923}\right)}\right]$$

$$= 0.1570 = 15.70\ \%$$

$$\eta_{\text{max. power}} = \frac{\dfrac{T_1 - T_0 \cdot m}{T_1}}{\dfrac{(1+m)^2}{T_1}\dfrac{(KR)}{\alpha_{pn}^2} + (1+m) - \dfrac{1}{2}\left(\dfrac{T_1 - T_0}{T_1}\right)}$$

For maximum power output, $R_L = R$

$$\therefore \qquad m = 1$$

$$\eta_{\text{max. power}} = \frac{\dfrac{600}{923}\times 1}{\dfrac{(1+1)^2}{923}\times\dfrac{1}{Z_{\max}} + (1+1) - \dfrac{1}{2}\left(\dfrac{600}{923}\right)}$$

$$= \frac{0.65}{\dfrac{4}{923}\times\dfrac{1}{1.85\times 10^{-3}} + 2 - 0.325}$$

$$= 0.1618 = 16.18\%$$

Power output,

$$W_L = I^2 R_L$$

$$= \frac{\alpha_{p,n}^2 (T_1 - T_0) R_L}{(R + R_L)^2}$$

$$= \frac{\alpha_{p,n}^2 (T_1 - T_0)^2}{(1 + m_0)^2 R_L}$$

$$= \frac{(-190 - 190)^2 \times 10^{-12} \times 600^2}{(1 + 1.43)^2 \times 2.63 \times 10^{-3}}$$

$$= 3.318 \text{ W.}$$

Maximum power output (when $R_L = R$)

$$W_{\max} = \frac{\alpha_{p,n}^2 (T_1 - T_0)^2 R_L}{(R + R_L)^2}$$

$$= \frac{\alpha_{p,n}^2 (T_1 - T_0)^2 R_L}{4R_L^2}$$

$$= \frac{(-190-190)^2 \times 10^{-12} \times 600^2}{4 \times 1.84 \times 10^{-3}}$$

$$= 7.12 \text{ W}$$

Example 5.5: *A 100 MW, 115 V thermoelectric generator is designed to operate between 1500 K and 1000 K. The material properties of thermal elements are:*

$\alpha_{p,n} = 0.0012$ *V/K at 1250 K*
$k_n = 0.02$ *W/cm K.*
$k_p = 0.03$ *W/cm K*
$\rho_n = 0.01\ \Omega$ *cm*
$\rho_p = 0.12\ \Omega$ *cm.*

The geometrical parameters have been optimized as:

$A_n = 43.5$ *cm*^{2}
$A_p = 48.6$ *cm*^{2}
$L_n = Lp = 0.49$ *cm*

The current density is limited to 20 A/cm^2*. Calculate:*

(i) *Maximum efficiency*
(ii) *No. of thermocouples in series*
(iii) *Open circuit voltage*
(iv) *Heat input and heat rejected at full load.*

Solution:

$$\eta_{\max} = \left(\frac{T_1 - T_0}{T_1}\right)\left(\frac{m_0 - 1}{m_0 + \frac{T_0}{T_1}}\right)$$

$$m_0 = \sqrt{1 + \frac{Z}{2}(T_1 + T_0)}$$

$$Z = \left[\frac{(\alpha_n - \alpha_p)}{\sqrt{\rho_n k_n} + \sqrt{\rho_p k_p}}\right]^2$$

$$= \left[\frac{0.0012}{\sqrt{0.02 \times 0.01} + \sqrt{0.03 \times 0.12}}\right]^2$$

$$= 13 \times 10^{-4}\ \text{K}^{-1}$$

$$m_0 = \sqrt{1 + \frac{13 \times 10^{-4}}{2}(1500 + 1000)}$$

$$= 1.635$$

(*i*)
$$\eta_{\max} = \left(\frac{T_1 - T_0}{T_1}\right)\left(\frac{m_0 - 1}{m_0 + \frac{T_0}{T_1}}\right)$$

$$= \left(\frac{1500 - 1000}{1500}\right)\left(\frac{1.635 - 1}{1.635 + \frac{1000}{1500}}\right)$$

$$= 0.091 = 9.1\%$$

(*ii*)
$$V = \alpha_{p,n}\,(T_1 - T_0)$$

$$= 0.0012\,(1500 - 1000)$$

$$V = 0.6\ \text{V}$$

$$R = R_p + R_n = \frac{\rho_p L_p}{A_p} + \frac{\rho_n L_n}{A_n}$$

$$= \frac{0.01 \times 0.49}{43.5} + \frac{0.012 \times 0.49}{48.6}$$

$$= 2.34 \times 10^{-4}\ \Omega$$

$$V_L = V_0 - IR$$

$$= V_0 - (R_p + R_n)\,I$$

$$= 0.6 - (2.34 \times 10^{-4})\,48.6$$

$$= 0.3744\ \text{V}$$

$$\text{No. of couples in series} = \frac{115}{V_L} = \frac{115}{0.374} = 309$$

(*iii*)
$$V_0 = V \times 309$$

$$= 0.6 \times 309$$

$$= 185.4\ \text{V}$$

(*iv*) Heat input at full load,

$$Q_1 = \frac{W_L}{\eta} = \frac{100}{0.091} = 1100 \text{ kW}$$

Heat rejected at full load,

$$\begin{aligned} Q_0 &= Q_1 - W_L \\ &= 1100 - 100 = 1000 \text{ kW.} \end{aligned}$$

5.5 SELECTION OF MATERIALS FOR THERMOELECTRIC GENERATORS

The efficiency of a thermoelectric generator depends upon suitable properties of the elements. The material should have high value of figure of merit Z and be capable of operation at a very high temperature.

1. The thermal conductivity of the thermoelectric element should be as low as possible. The value of k can be reduced by introducing suitable impurities.
2. The mobility of current carriers (electrons or holes) should be as high as possible or electrical conductivity should be raised by introducing suitable impurities.
3. One element should be purely p-type and the other n-type. The semiconductor should have low ionization energy and narrow forbidden band.
4. The thermo elements should have variable impurity content so that electron concentration should depend upon the operating temperature.
5. The material should be corrosion resistant, should have high strength, and elasticity so that it does not crack due to thermal stresses.
6. The bridge material should have high thermal and electrical conductivity and be stable against thermal stresses.
7. The use of variable properties of thermoelectric elements becomes very important when thermocouple pile or cascaded operation is required. The working temperatures can be different.

The following group of material are available:

(*i*) Metals
(*ii*) Semiconductors
(*iii*) High temperature semiconductors.

5.5.1 Metals

(*i*) For most metals, the value of Seebeck coefficient is less than 10×10^{-6} V/K.

The ratio of electrical conductivity ($1/\rho$) to the real conductivity (k) for all metals can be predicted from quantum mechanics.

$$\rho k = \frac{\pi^2}{3}\left(\frac{k}{e}\right)^2 T = 2.44 \times 10^{-8} T.$$

(*ii*) The figure of merit ($Z = \alpha^2/\rho k$) at an average temperature of 500 K works out close to 8.2×10^{-6}.

(*iii*) At $T_1 = 700$ K and $T_0 = 300$ K, efficiency is 8.5×10^{-4} or 0.085% which is very very low for practical applications.

(*iv*) For best pair of metals (Bi-Sb),

$$\alpha = 100 \times 10^{-6} \text{ V/K}$$
$$k = 9 \times 10^{-6} \text{ W/K}$$
$$z = 1.1 \times 10^{-3}$$

for $T_1 = 450$ K

$$T_0 = 300 \text{ K}$$
$$\eta = 3.1\%.$$

5.5.2 Semiconductors

Semiconductors are more suitable materials for thermoelectric generators than metals due to the following properties:

(*i*) Semiconductors have higher values of Seebeck coefficient.
(*ii*) The figure of merit, Z exceeds 1×10^{-3}.
(*iii*) Efficiency approaches 10%. An efficiency of 15% or more is attainable, as technology progresses.
(*iv*) These have higher values of melting point, thus permitting operation at a higher temperature.

(*v*) Bismuth telluride, lead telluride, germanium, and other semiconductors have properties suitable for thermoelectric generators.

(*vi*) *p*-type and *n*-type materials can be produced by alloying and doping of semi-conductors.

(*vii*) The figure of merit of some thermoelectric semiconductor materials are given in Table 5.1.

Table 5.1 Figure of Merit for Thermoelectric Materials

Sl.No.	Material	Figure of Merit Z (K^{-1})
1.	Bismuth telluride (doped with *Sb* or Se)	4×10^{-3}
2.	Lead telluride (Pb Te)	1.5×10^{-3}
3.	Germanium telluride (doped with bismuth)	1.5×10^{-3}
4.	Zinc antimonide (doped with silver)	1.5×10^{-3}
5.	Cesium sulphide	1.0×10^{-3}

5.5.3 High Temperature Semiconductors

(*i*) The melting point of Bi_2Te_3 is 584ºC and that of Pb Te is 922°C.

(*ii*) Silicates are considered the most promising of all high-temperature materials used for thermo-electrodes. For example, for $MnSi_2$ with $T_1 = 1300$ K and $T_0 = 300$ K, the thermal efficiency is as high as 9.7%.

(*iii*) Boride and carbide base high temperature materials can give an efficiency of 15 to 20%.

5.6 APPLICATIONS OF THERMOELECTRIC GENERATORS

The thermoelectric generators are already recognized as very convenient direct-energy conversion systems.

1. They are very simple in construction.
2. They are very compact.
3. There is an absence of moving parts.
4. They are suitable for remote and space applications.
5. It is a promising system for waste heat recovery.

5.6.1 Thermopile and Cascading Operation

The materials may have best figure of merit at high temperature than at low temperatures. But certain materials have favorable figure of merit at lower temperatures. The problem can be solved by cascading where heat rejected from one part of the system becomes the heat input to another part. The size of the device decreases from one stage to another as the average temperature is lowered. The heat input to each stage is less than to the stage above. The overall efficiency of the system is given by

$$\eta = 1 - \frac{Q_0}{Q_1} = 1 - (1 - \eta_1)(1 - \eta_2)$$

$$= 1 - (1 - \eta_s)^n.$$

The greater the number of stages, the greater the efficiency. If each stage of thermoelectric cascade generator is optimized for geometry and resistance ratio, each stage efficiency can be improved.

The output voltage can be increased by putting a number of thermocouple in series (Figure 5.2). Such an arrangement is called a thermopile.

5.6.2 Combined Thermoelectric and Steam Power Plant

A thermoelectric generator can be used as a topping plant to a steam power plant. The overall efficiency of the combined plant will increase due to higher source temperature. The scheme is shown in Figure 5.5.

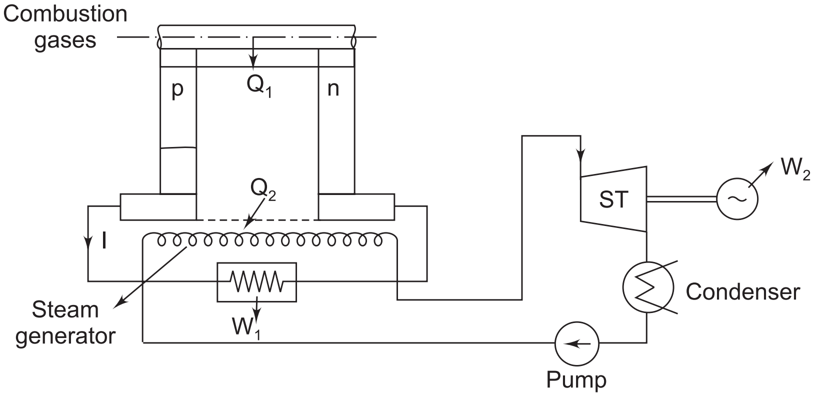

FIGURE 5.5 Combined thermoelectric and steam power plant.

The total output,

$$W = W_1 + W_2$$

5.6.3 Thermoelectric Waste Heat Stack

The waste heat from gas turbines, diesel engines, and stack gases from industries can be used to produce electricity by a thermoelectric generator.

The metal stack consists of a series of rings of two alternate metals connected at the inner and outer annular edges alternately. These rings are thermally and electrically insulated.

A schematic diagram is shown in Figure 5.6.

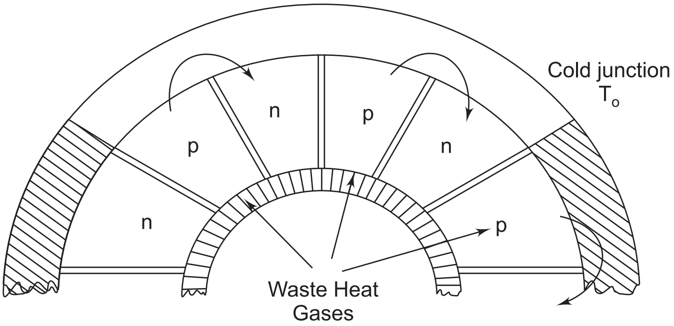

FIGURE 5.6 Thermoelectric waste heat stack.

5.6.4 Decay Heat of Radioactive Isotopes

The decay heat of radioactive isotopes has been used for the operation of small thermoelectric generators of the capacity of about 0.1 kW. Based on heat of decay of strontium 85, remote generators for signaling have been used.

5.6.5 Solar Energy

A combination of thermoelectric generator and solar collector can be employed to generate electricity from solar energy. This could be achieved by concentrating solar power to generate heat supplied to the thermoelectric system, with the option of having a combined heat and power system, as well.

5.7 LIMITATIONS

The main limitation of thermoelectric generators is low thermal efficiency.

Lots of work is needed to develop thermo-couple elements which can give reasonable efficiencies. However, the reliability of operation and low maintenance required could make it an ideal device for certain applications. For example, power supplied to measurement and control systems in pipelines, space applications where solar power is not readily available.

EXERCISES

1. What is Seebeck thermoelectric effect? Describe briefly a thermoelectric power generator.

2. Define figure of merit. Derive an expression for the efficiency of a thermoelectric generator.

3. (*a*) Describe the operation of a thermoelectric generator.

(*b*) Prove that the optimum value of resistance ratio, m that gives maximum thermal efficiency is

$$m_o = \sqrt{1 + Z_{\max}\left(\frac{T_1 - T_0}{2}\right)}$$

where $$m = \frac{R_L}{R_p + R_n}$$

Z = Figure of Merit.

4. Write short notes on:

(*i*) Thermoelectric effects.

(*ii*) Seebeck and Peltier coefficients.

(*iii*) Multistage thermoelectric generators.

(*iv*) Selection of thermoelectric materials.

(*v*) Figure of merit of a thermoelectric generator.

5. What is the optimum resistance ratio for the following?

(*a*) Maximum power

(*b*) Maximum efficiency.

6. Briefly discuss the merits of thermoelectric generators. What are the main limitations?

7. (*a*) Why are semiconductors preferred as thermocouple elements as compared to metals?
   (*b*) Explain the cascade multistage operation of thermoelectric generators.

8. With the help of suitable diagrams, explain how thermoelectric generators can be used for utility power generation, as well as waste heat utilization.

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CHAPTER 6

THERMIONIC POWER GENERATION

6.1 INTRODUCTION

A thermionic generator (or inverter) transforms heat directly into electrical energy by utilizing thermionic emissions. All metals and some oxides have free electrons that are released on heating. These electrons can travel through a vacuum space and can be collected on a cooled metal surface. These electrons can return to hot metal through an external load thereby producing electrical power.

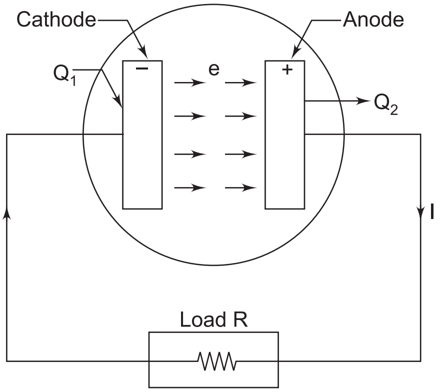

FIGURE 6.1 Thermionic generator.

As shown in Figure 6.1, a thermionic generator has two electrodes enclosed in a tube. The cathode is called an emitter and is heated enough to release electrons from its surface. The electrons cross a small gap and accumulate on a cooled metallic anode called collector. The space between the electrodes is maintained at high vacuum or filled with a highly conducting plasma like ionised cesium vapor to ensure minimum energy losses. The external load R is connected through anode to cathode. The electrons return to the cathode through the external load and electrical power is produced.

A thermionic generator is like a cycle heat engine using electron vapor as working fuel and its maximum efficiency is limited by Carnot law. It is a low-voltage high-current device where current densities of 20-50 A/cm^2 have been achieved at a voltage from 1 to 2V. Thermal efficiencies of 10-20% have been realized for thermionic systems with potentially higher values in the future.

A thermionic generator can be used for large power generation. The fuel elements of a nuclear reactor may be a very suitable high-temperature heat source for a thermionic generator. This can be surrounded by the cooled anode and the in-between space can be filled with ionized cesium vapor.

The energy of high-temperature combustion gases can be partly converted to electricity if the riser tubes of a boiler are provided with cathode and anode of a thermionic generator with the interspace filled with ionized cesium vapor.

In principle, any heat source, fossil or nuclear fuel, a radioactive material, or solar energy can be used in a thermionic generator. Many applications have been suggested for remote locations on the earth and in space as the device is robust and reliable in unattended operation.

6.2 PRINCIPLE OF OPERATION

The emissions of an electron from a metal surface is opposed by a potential barrier equal to the difference between the energies of an electron outside and inside the metal. Therefore, a certain amount of energy must be spent to release the electron from the surface. This energy is called surface work function, ϕ.

The maximum electron current per unit area emitted from the surface is given by the following Richardson-Dushman equation:

$$J = A_1 T^2 Exp\left(-\frac{\phi}{kT}\right)$$

where J = Current density $[A/\text{m}^2]$
T = Temperature $[K]$
ϕ = Work function $[eV]$
k = Boltzmann constant
$= 1.38 \times 10^{-23}$ $[\text{J}/K]$
A_1 = Emission constant
$= 120$ $[\text{A/cm}^2.K^2]$

The work function varies between 1 and 5 eV and data for different elements is given in Table 6.1 (1 eV = 1.602×10^{-19} J)

Table 6.1 Work Functions for Different Elements

Element Symbol	Work Functions (*eV*)	Element Symbol	Work Function (*eV*)
Ag	4.65	Mo	4.25
Al	3.60	Na	2.00
Ba	2.52	Ni	5.00
Ca	3.00	Pt	6.15
Cs	1.75	Rb	1.82
Cu	4.30	Th	3.50
K	1.90	T	4.55
Li	2.21	Zn	3.44

6.2.1 Fermi Energy Level

The kinetic energy of the free electrons at absolute zero temperature would occupy discrete energy levels from zero up to some maximum value defined by the Fermi energy level, E_F. Each energy level contains a limited number of free electrons. Above absolute zero temperature, some electrons may have energies higher than the Fermi level. The energy that must be supplied to overcome the weak attractive force on the outer most orbital electrons is the work function, ϕ, so that the electron leaving the emitter has an energy level $\phi + E_F$.

When the emitter is heated, some high-energy free electrons at the Fermi level receive energy equal to emitter work function ϕ_e and escape the emitter surface. They move through the vacuum gap and strike the collector. The kinetic energy KE (E_{Fa}) plus the energy equal to collector work function ϕ_a is given up and this energy is rejected as heat from the low-temperature collector.

The electron energy is reduced to the Fermi energy level of the anode E_{Fa}. This energy state is higher than that of the electron at the Fermi energy level of the cathode E_{Fc}. Therefore, the electron can pass through the external load from anode to cathode. The cathode materials are selected with low Fermi energy levels as compared to anode materials which must have higher Fermi energy level.

6.3 PERFORMANCE OF THERMIONIC GENERATOR

The positively charged cathode tends to pull the emitted electrons back. The electrons already in the vacuum gap exert a retarding force on the electrons trying to cross the gap. This produces a space charge barrier. Figure 6.2 shows the characteristic curve of a thermionic generator with an interspace retarding potential equivalent to δ volts above the anode work function ϕ_a.

Potential barrier,

$$V_c > \phi_c$$
$$V_a > \phi_a$$

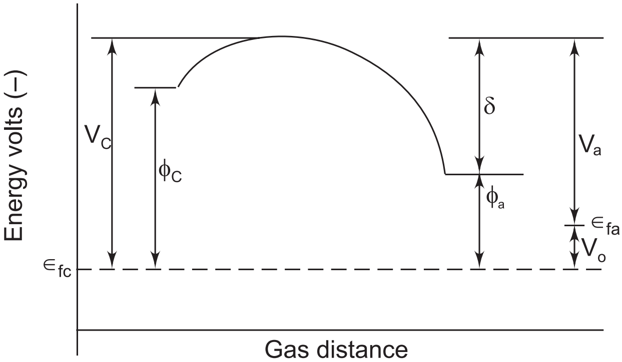

FIGURE 6.2 Characteristic curve.

The current densities are:

$$J_c = A_1 T_c^2 e^{-(V_c/kT_c)}[\text{A/cm}^2]$$

$$J_a = A_1\ T_a^2 e^{-(V_a/kT_a)}[\text{A/cm}^2]$$

The output voltage across the external resistance R,

$$V_o = V_c - V_a = \phi_c - \phi_a = \frac{1}{e}\left(\in_{fa} - \in_{fc}\right)$$

Each electron must overcome the interspace potential ($v_c - \phi_c$) and work function ϕ_c when it leaves the cathode.

The net energy carried,

$$Q_{1c} = J_c\ (v_c - \phi_e + \phi_c) = J_c\ V_c\ (\text{W/cm}^2)$$

Each electron also carries away its K.E., which is equal to $2kT_c$, *i.e.*,

$$Q_{2c} = J_c \frac{2kT_c}{e}(\text{W/cm}^2)$$

The back emission from the anode must similarly carry energy to the cathode. The net rate of energy supply to the cathode,

$$Q_1 = J_c\left(V_c + \frac{2kT_c}{e}\right) - J_a\left(V_a + \frac{2kT_a}{e}\right)$$

where $e = 1.602 \times 10^{-19}$ coulomb.

The power output of the generator,

$$W = V_o\ (J_c - J_a)$$

The thermal efficiency of the thermionic generator,

$$\eta = \frac{V_o(J_c - J_a)}{J_c\left[V_c + \frac{2kT_c}{e}\right] - Ja\left[V_a + \frac{2kTa}{e}\right]}$$

Now $V_o = V_c - V_a$

Substituting the following values:

$$\frac{V_c}{kT_c} = \beta_c; \frac{V_a}{kT_a} = \beta_a \text{ and } \frac{T_a}{T_c} = \theta$$

$$\eta = \frac{(\beta_c kT_c - \beta_a kT_a)(J_c - J_a)}{J_c\left(\beta_c kT_c + \frac{2kT_c}{e}\right) - J_a\left(\beta_a kT_a + \frac{2kT_a}{e}\right)}$$

$$= \frac{(\beta_c - \theta\beta_a)\left[1 - \theta^2 e^{(\beta_c - \beta_a)}\right]}{(\beta_c + 2) - \theta^2(\beta_2 + 2\theta)e^{(\beta_c - \beta_a)}}.$$

It is found that for all values of θ, the efficiency curve peaks are very near to the value of $\beta_a = \beta_c$.

∴ If $\beta_c = \beta_a$;

$$\eta = \eta_{\max} = (1-\theta)\frac{\beta}{\beta+2}\left|\frac{1-\theta^2}{1-\frac{\theta^2(\beta+2\theta)}{\beta+2}}\right|$$

But

$$\frac{1-\theta^2}{1-\frac{\theta^2(\beta+2\theta)}{\beta+2}} \approx 1$$

∴

$$\eta_{\max} = (1-\theta)\frac{\beta}{\beta+2}.$$

Carnot efficiency,

$$\eta_c = 1 - \frac{T_a}{T_c} = (1-\theta)$$

If $\beta = 18$,

$$\eta_{\max} = 0.9\,(1-\theta)$$

$\eta_{\max}$ occurs when $\beta_a = \beta_c$

or

$$\frac{V_c}{T_c} = \frac{V_a}{T_a}.$$

Example 6.1: *A thermionic generator has the following characteristics:*

Cathode work function, $\phi_c = 2.5\ V$
Anode work function, $\phi_a = 2.0\ V$
Temperature of cathode, $T_c = 2000\ K$
Temperature of anode, $T_a = 1000\ K$
Plasma potential drop, $\delta = 0.1\ V$

Assuming the value of emissivity as 0.2 for the electrode material used, calculate the efficiency of the generator and also compare with Carnot efficiency.

Solution: Net output voltage

$$\begin{aligned} V_o &= \phi_c - \phi_a - \delta \\ &= 2.5 - 2.0 - 0.1 \\ &= 0.4\ \text{V} \end{aligned}$$

Net current in the generator,

$$J = J_c - J_a$$

$$J_c = AT_c^{\,2}\,\frac{-\phi_c}{ekT_c}$$

$$= (1.20 \times 10^6)(2000)^2\, e^{\frac{-(1.6\times10^{-19}\times2.5)}{(1.38\times10^{-23})2000}}$$

$$= 2.4 \times 10^6\ \text{A/m}^2$$

Charge of electron,

$$e = 1.6 \times 10^{-19}\ \text{coulombs.}$$

Boltzmann constant,

$$\begin{aligned} k &= 1.38 \times 10^{-23}\ \text{J/K} \\ 1\ \text{eV} &= 1.6 \times 10^{-9}\ \text{J} \end{aligned}$$

$$J_a = A\ Ta^2\ e^{\frac{-\phi_a}{kT_a}}$$

$$= (1.20 \times 10^6)(1000)^2\, e^{\frac{-(1.6\times10^{-19}\times2.0)}{(1.38\times10^{-23})1000}}$$

$$= 1.2 \times 10^2\ \text{A/m}^2$$

$$\therefore \qquad J = J_c - J_a \approx J_c$$

$$= 2.4 \times 10^6\ \text{A/m}^2.$$

Heat supplied to the cathode,

$$\frac{Q_c}{A_c} = J\left[\phi_c + \frac{2kT_c}{e}\right) + \in \sigma\left(T_c^4 - T_a^4\right)\bigg]$$

$$= 2.4\times10^6\left[2.5+\frac{2\left(1.38\times10^{-23}\right)2000}{1.6\times10^{-19}}\right]$$

$$+0.2\times5.67\times10^{-12}\times10^{-7}\,(2000)$$

$$= 7.026 \times 10^6 \text{ W/m}^2$$

$$\eta = \frac{J\cdot V}{Q_c/A_c} = \frac{(2.4\times10^6)(0.4)}{7.026\times10^6}$$

$$= 0.137 = 13.7\%$$

Carnot efficiency,

$$\eta_c = \frac{T_c - T_a}{T_c} = \frac{2000-1000}{2000} = 0.5 = 50\%.$$

6.4 APPLICATIONS OF THERMIONIC GENERATOR

Some typical applications of thermionic generator are as follows:

1. Thermionic generator in the riser tube of a boiler
2. Thermionic generator in a nuclear reactor
3. MHD–thermionic-steam power plant
4. Space vehicle power supply applications

6.4.1 Thermionic Generator in the Riser Tube of a Boiler

The riser tubes of a boiler receive heat by radiations from combustion gases. The riser tube is provided by a cathode and anode of a thermionic generator.

The interspace is filled with ionized cesium vapor. The use of hot flue gases to produce extra power before the steam cycle improves the overall plant efficiency.

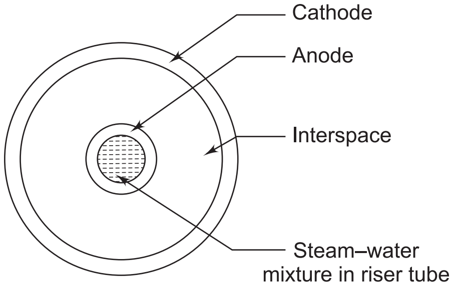

FIGURE 6.3 Thermionic generator in the riser tube of a boiler.

6.4.2 Thermionic Generator in a Nuclear Reactor

The fuel element containing the fissile material carries the cathode that is surrounded by the anode. The interspace is filled with ionized cesium gas. The anode is cooled by coolant from outside. Some of the energy released by reactor fission reactor is directly converted into electricity by thermionic conversion. The remaining heat is used in a conventional bottoming steam plant. The overall efficiency of the plant increases.

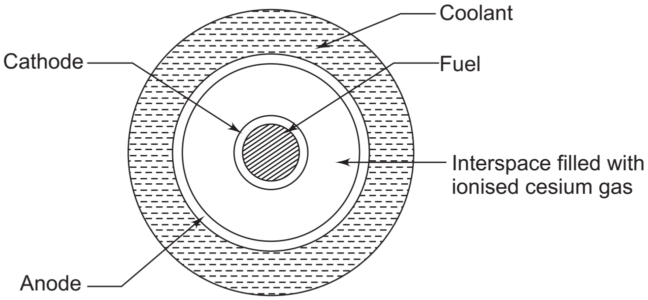

FIGURE 6.4 Thermionic generator in a nuclear reactor.

6.4.3 MHD–Thermionic Generator-Steam Power Plant

The waste heat from MHD generator at about 1900°C is used to heat the cathode of thermionic generator. The heat from anode is used in the boiler of a steam power plant. The overall efficiency of the combined plant will increase. Total power output = $W_1 + W_2 + W_3$

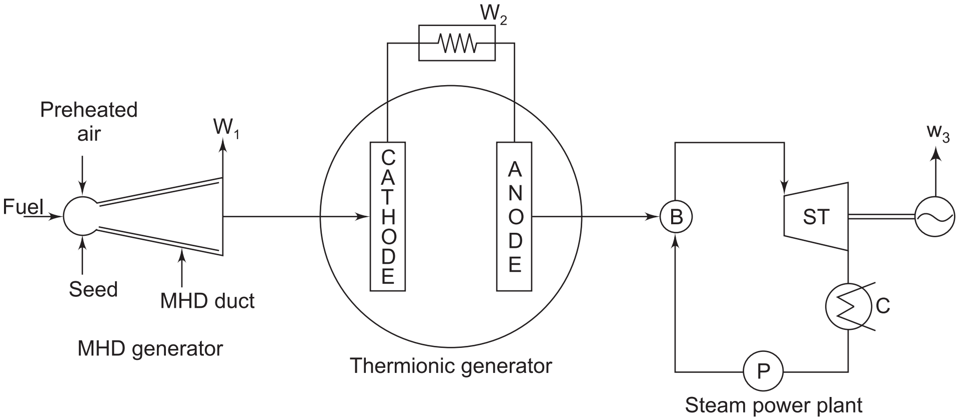

FIGURE 6.5 MHD-Thermionic generator–steam power plant.

6.5 LIMITATIONS OF A THERMIONIC GENERATOR

A thermionic generator is a direct energy conversion device with no moving parts. It is very robust, no supervision is needed for operation. It is very suitable for remote and space applications. It suffers from the following main limitations:

1. The operating temperature of the cathode is very high, necessitating the use of costly material such as tungsten or rhenium.
2. Special shields of ceramic are needed to protect the cathode from corrosive combustion gases.
3. The collector may also have to be made of molybdenum coated with cesium.
4. Ionized cesium vapor must be filled in the interspace to reduce the space charge barrier to promote electron emission from the cathode.

EXERCISES

1. What is meant by by "thermionic emission effect"? Describe the principle of operation and construction details of a basic thermionic generator.
2. Derive the expression for power output and efficiency of a thermionic generator.

3. (*a*) What are suitable materials for the emitter and collector of a thermionic generator?
   (*b*) What is the reason of filling the interspace with ionized cesium vapor?
4. Describe the following:
   (*a*) Surface work function
   (*b*) Fermi energy level
   (*c*) Interspace retarding potential.
5. What is the Richardson-Dushman equation? What is its relevance in the thermionic power generation?
6. Discuss the various applications of a thermionic generator for central power production. Describe MHD-thermionic generator–steam power plant with the help of a suitable flow diagram.
7. What are the main limitations of a thermionic generator?

CHAPTER 7

EXPLORING NEW ENERGY TECHNOLOGIES

7.1 INTRODUCTION

Modern societies require increasing amounts of energy for domestic, industrial, commercial, agricultural, and transport uses. These energy needs are being met by a combination of short-term, dependable fossil fuel supplies and long-run, renewable energy sources. Economic growth will require massive infusions of energy in the foreseeable future. Urbanization and agricultural productivity and productions depend on larger and larger amounts of power. There is an urgent need for development of new, more efficient, and clean energy sources and conversion technologies while having minimum or possibly zero emission to the environment.

7.2 REQUIREMENTS OF NEW ENERGY TECHNOLOGIES

Heavy demand for energy poses the problem of developing new, efficient methods of energy production based on latest achievements in science and technology. At the present time, the existing methods of converting different forms of energy into electricity are limited because these are mostly based on depleting chemical fuel reserves. The conversion technologies are not efficient enough based on large material consumption. Large amounts of heat and by-products are released, heating the nearby water sources and contaminating the environment with release of harmful waste matter into the atmosphere. This may be regarded as one of the most important socio-economic problems.

Research of new energy sources and development of efficient conversion technologies must meet the following requirements, among other:

1. The energy sources and conversion technology to usable form should be harmonious with the environment. These natural sources should be used as minimum as possible and the harmful waste should not be rejected to the environment by the energy system.
2. The source of energy should be a local resource. It should be available in considerable quantities.
3. The local source of energy should be used to conserve foreign exchange and generate local employment.
4. The conversion technologies should be based on available scientific and technological knowledge. It should be possible to design, manufacture, assemble, install, operate, and maintain the energy system by local people using local skills and materials.
5. The conversion technology should be flexible and modular and rapidly deployed.
6. There should be ease in adding new capacity, less risk in investment, lower interest on borrowed capital because of shorter lead times and reduced transmission and distribution costs.
7. It should be financially and economically competitive with current technologies.
8. There should be no technical and economic uncertainties in the new energy systems.
9. It should have high energy efficiency and low economic and financial costs.
10. The new energy source should have flexible applications for lighting, heating, cooling, and mechanical work.

7.3 DESIGN REQUIREMENTS

The design and analysis of a new energy system or technology must be approached from a system analysis viewpoint combining technical design with economic analysis and environmental concerns. There is no single solution to a given task in energy utilization, and each problem must be analyzed separately from fundamental principles. It is necessary to match the available energy source to the task at hand and there is no general solution. Proper design and optimization of a new energy system may require a high level of engineering analysis. The system engineer must decide based on the task at hand.

The design and analysis of a solar energy system is given below as an example of illustration.

7.3.1 Collection System

Energy delivery of a collector depends on its physical configuration, its operating temperature, and the climatic parameters of the solar radiation level, ambient temperatures, and wind speed. Collector performance is also determined by secondary variables, including fluid flow rates, collector orientation, geographic location, and system control strategy. Table 7.1 provides a collector-task classification showing the best combination of collectors and tasks.

The detailed design of a collector will depend upon the selection of the type of collector, type of focusing, concentration ratio, and type of selective coating for the absorber. All these are functions of fluid temperatures required as shown in Figure 7.1.

Table 7.1 Collector-Task Classification

Collector Type	Space Heating of Small Building	Space Heating of Large Building	Water Heating	Space Cooling	Process Heat	Crop Drying	Distillation
Flat Plate (liquid)	S	S	S	S/U	S	S	S
Flat Plate (air)	S	U	U	U	S	S	U
Evacuated Tube	S	S	–	S	S	–	–
Intermediate concentration	–	–	–	S	S	–	–
High concentration	–	–	–	–	S	–	–

S = Satisfactory, U = Unsatisfactory, – = Uneconomic or task mismatch.

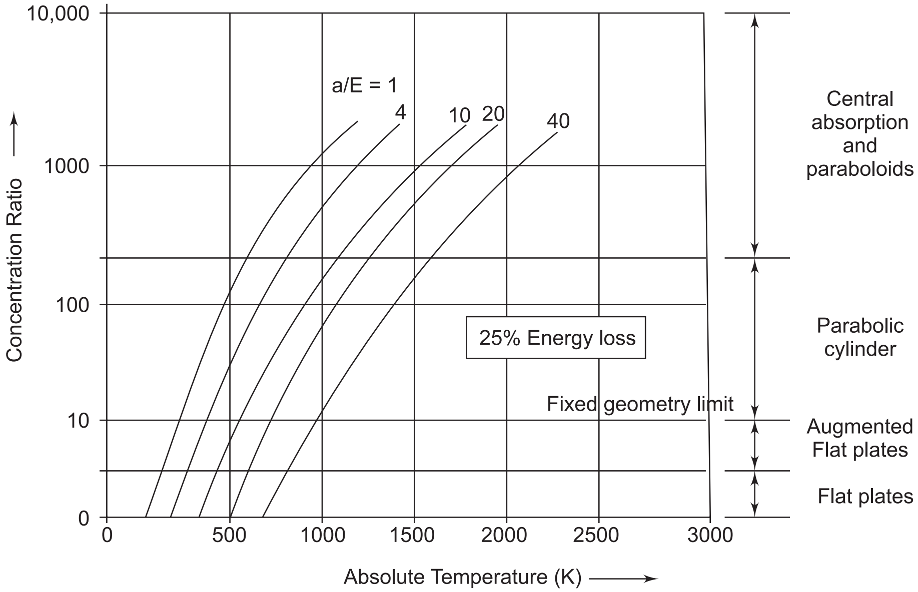

FIGURE 7.1 Effect of concentration ratio on absolute temperature.

7.3.2 Solar System Model

The rational design of a solar thermal system requires the knowledge of the dynamic interaction of all system components for solar collection, thermal storage, fluid circulation, energy distribution, control, and nonsolar auxiliary energy source.

Computers are generally required for calculation of numerical solar models because many component models are nonlinear and a closed-form simultaneous solution of the equation describing a system is not possible in all but the simplest cases. In addition, most solar systems operate in a continuously changing transient manner subject to short-time scale changes in all forcing functions. Since meaningful modeling results require delivery totals for large periods (months or years), and since solar systems respond on short-time scale (minutes or hours), a great many calculations are required. For these reasons, computerized models are the method of choice for analysis of most solar-thermal systems.

A simple block diagram of the computer model of a solar system using hourly data is shown is Figure 7.2.

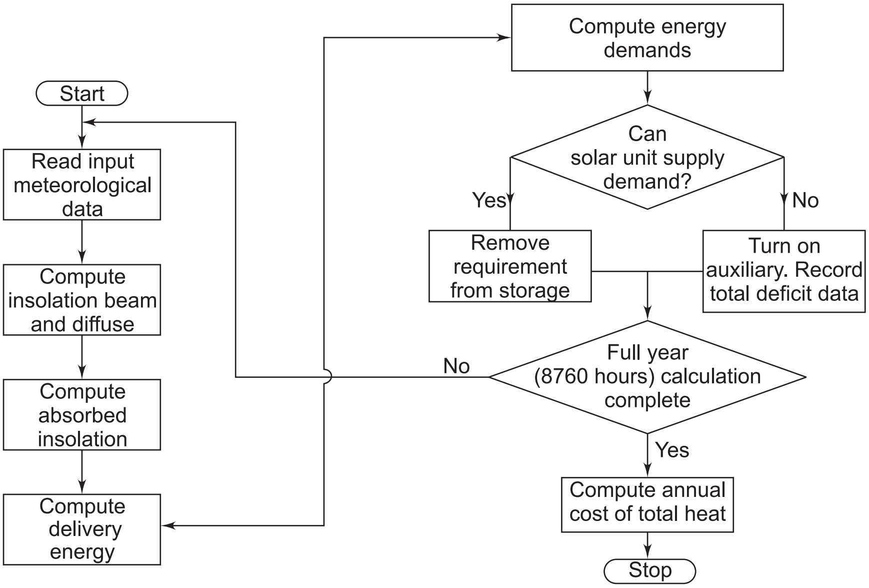

FIGURE 7.2 Simplified block diagram of computer simulation model of a solar thermal system.

7.3.3 Optimum Task to Energy Level Match

Solar energy is the only major source where entropy level of the form in which it is collected can be manipulated to provide an optimum task-to-entropy level match. This match can be accomplished by varying degree of concentration of solar energy or by improved receiver design, for example, with an evacuated cover. For high-entropy uses such as space heating, water heating and crop drying, low temperature, high-entropy solar energy collected by the flat-plate collectors provides the best match between the energy sources and task. The operation of a solar thermal power station requires low-entropy (high-temperature) thermal energy to match the task of producing low-entropy shaft work.

7.4 EXERGY ANALYSIS OF ENERGY SYSTEMS

The exergy analysis of an energy system enables us to identify the sources of irreversibility and inefficiency with the aim of reducing the losses and achieving the maximum resource and capital saving. This can be achieved by a careful selection of the technology and optimization of design of the system and components. Exergy analysis involves the determination of exergy efficiency or second-law efficiency.

7.4.1 Exergy Efficiency

The analysis of energy systems based on second law of thermodynamics calculates the changes in the quality of energy or entropy. The exergy of a system decreases as a process loses its quality, or entropy increases.

An exergy balance of an energy system gives:

$$E_{in} = E_u + E_d$$

where E_{in} = Rate of exergy input [kW]

E_u = Rate of useful product exergy [kW]

E_d = Rate of destruction or loss of exergy [kW]

Exergy efficiency, $\in$ of an energy conversion system is the ratio of actual performance of the system and ideal performance of the system.

$$\in = \frac{E_u}{E_{in}} = 1 - \frac{E_d}{E_{in}}$$

7.4.2 Exergy Efficiency of Solar Collectors

The exergy efficiency of solar collectors can be expressed as:

$$\in_{sc} = \frac{\dot{m}_{sc}\Delta_e}{E_{SR}}$$

$$= \frac{\eta_{sc}\, E\Delta_e}{E_{SR}\, \Delta h}$$

where $\dot{m}_{sc}$ = Mass flow rate of collector fluid [kg/s]

Δe = Specific Exergy increase of collector [kJ/kg]

Δh = Specific Enthalpy increase of collector [kJ/kg]

E = Incident solar radiation [kW]

E_{SR} = Exergy flow rate of solar radiation [kW]

η_{sc} = Efficiency of solar collector.

The efficiency of solar collector,

$$\eta_{sc} = \frac{\dot{m}_{sc}\,\Delta e}{E}$$

$$\frac{E_{SR}}{E} = 0.933$$

$$\in_{sc} = 0.933\,\eta_{sc}\left[1 - \frac{To}{\Delta T_{sc}}\right] ln\frac{T_2}{T_1}$$

where T_o = Ambient temperature [K]

T_1 = Inlet temperature of collector fluid [K]

T_2 = Outlet temperature of collector fluid [K]

ΔT_{sc} = Temperature increase in collector [K]

The exergy efficiency of a solar collector will increase with the increase of solar collector efficiency, η_{sc}.

The exergy efficiency of flat plate collector is low, because this type of solar collector transforms low-entropy (high-temperature) solar radiations into high-entropy (low-temperature) energy of air or water.

The exergy efficiency of a concentrating type solar collector is high as it produces low-entropy (high-temperature) fluids at 700 to 1400 K.

Example 7.1: *A flat plate collector heats water from 305 K to 335 K. Calculate the exergy efficiency of the collector if its efficiency is 48% and ambient temperature is 293 K.*

Solution:

$$T_0 = 293 \text{ K}$$

$$T_1 = 305 \text{ K}$$

$$T_2 = 335 \text{ K}$$

$$\Delta T_{sc} = T_2 - T_1 = 30 \text{ K}$$

$$\eta_{sc} = 48\%.$$

The exergy efficiency of solar collector,

$$\varepsilon_{sc} = 0.933\,\eta_{sc}\left[1 - \frac{T_0}{\Delta T_{sc}}\right] ln\frac{T_2}{T_1}$$

$$= 0.933 \times 0.48 \left[1 - \frac{293}{30}\right] ln \frac{335}{305}$$

$$= 0.037 = 3.7\%$$

The ratio, $$\frac{\varepsilon_{sc}}{\eta_{sc}} = \frac{0.037}{0.48} = 0.8 = 8\%$$

Example 7.2: *Air is heated in a central receiver solar power plant from 693 K to 1073 K. Calculate the exergy efficiency if ambient temperature is 303 K and collector efficiency is 70%.*

Solution: $T_0 = 303$ K

$T_1 = 693$ K

$T_2 = 1073$ K

$\Delta T_{sc} = 1073 - 693 = 380$ K

$\eta_{sc} = 70\% = 0.70$

The exergy efficiency of solar collector,

$$\varepsilon_{sc} = 0.933\eta_{sc}\left[1 - \frac{T_o}{\Delta T_{sc}}\right] ln \frac{T_2}{T_1}$$

$$= 0.933 \times 0.7\left[1 - \frac{303}{380}\right] ln \frac{1073}{693}$$

$$= 0.425 = 42.5\%$$

The ratio, $$\frac{\varepsilon_{sc}}{\eta_{sc}} = \frac{0.425}{0.70} = 60.7\%.$$

7.5 ECONOMIC EVALUATION OF ENERGY SYSTEMS

The following methods may be used for economic evaluation of energy systems:

1. Life-cycle costing method
2. Net benefit (cost saving) method
3. Net benefit/cost ratio method

7.5.1 Life-Cycle Costing Method

The total present value of total annual value of the alternative energy systems are calculated. The system with the lowest cost is the best economic alternative.

The present value of a system:

$$PV = I - \frac{RV}{(1+i)^n} + \frac{\Sigma OM_j}{(1+i)^j} + \Sigma p_{\text{con}} Q_{\text{con}} \left[\frac{1+e}{(1+i)^j} \right]$$

where I = Capital cost or investment cost
RV = Residual value at n$^{\text{th}}$ year
n = No. of years of economic evaluation
i = Interest rate
OM_j = Annual cost of operation, maintenance, repair and replacement in the year j.
p_{con} = Initial price of conventional energy
Q_{con} = Energy requirement (conventional)
e = Escalation rate of energy cost.

7.5.2 Net Cost-Saving Method

The present value of cost savings,

$$(PV)_{\text{net}} = \sum \left\{ -p_{\text{con}} \Delta Q_{\text{con}} \left[\left(\frac{1+e}{(1+j)^j} \right) \right] \right\} - \left[\Delta I - \frac{\Delta V}{(1+i)^h} \right] + \frac{\Sigma OM_j}{(1+j)^i}$$

where Δ = Change due to new energy system

7.5.3 Net Benefit/Cost Ratio Method

$$S/I = \frac{(PV_{\text{net}} + I)}{I}$$

$$(SI)_{\text{net}} = \frac{PV_{\text{net}}}{I}$$

where $(PV)_{\text{net}}$ = Present value of cost savings
I = Capital investment.

7.6 INTERNAL RATE OF RETURN FOR INVESTMENT IN NEW ENERGY TECHNOLOGY

A variety of technical, economic, and financial factors determine the financial feasibility and economic attractiveness of investments in new technologies. Investment decisions are made by comparing the cost of a project for new energy technology, which depends upon the price of capital with expected returns (yearly cash flow) with the existing technologies. The price of capital is either the interest rate of loans or the rate of return on equity or investment in the new technology. The degree of risk associated with a new technology affects the price of capital: high-risk ventures cost more.

Figures that are widely used to evaluate the financial and economic aspects of new projects are the internal rate of return (IRR), the gross payback period (GPB), and net present value (NPV) all of which are related.

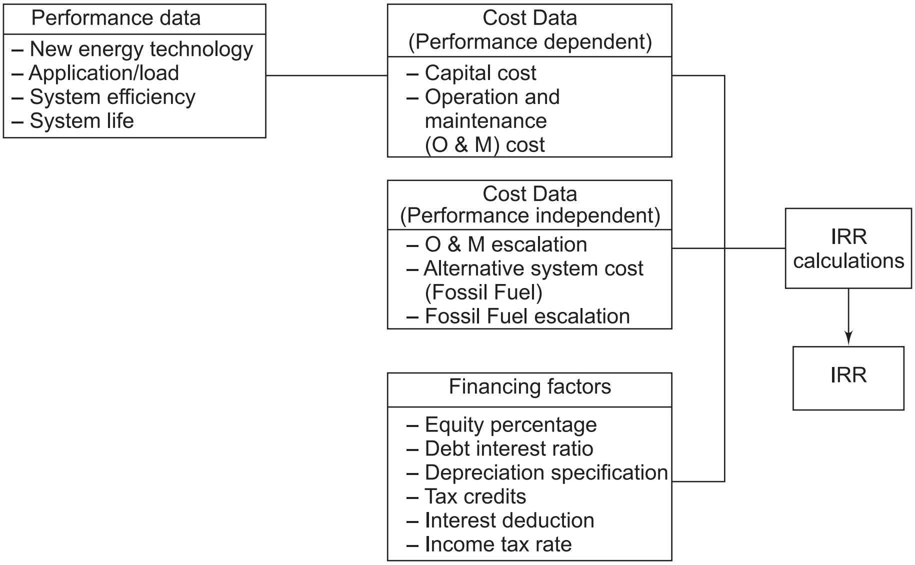

FIGURE 7.3 Calculation of IRR.

The internal rate of return (IRR), which measures how profitable a project is, is basically the discount rate (r) at which NPV is zero. For a technology with an expected equipment life of N years and expected net cash flow of Q_t in year t, the IRR (r) is defined by:

$$IRR\ (r) = \sum_{t=1}^{N} \frac{Qt}{(1+r)^t}$$

where the net cost flow (Q_t) is given by:

$$Q_t = (1 - T_t)\ (S_t - OM_t - ALP_t)$$

where for the year t,

S_t = Savings on fuel
OM_t = Operation and maintenance cost
ALP_t = Annual loan payment
T_t = Corporate income tax.

Given the capital cost, equipment lifetime, and cash-flow sequence, it is possible to calculate the IRR as shown in Figure 7.3. The IRR should be greater than the cost of capital.

EXERCISES

1. List the requirements of a new energy technology (system).
2. What are the design requirements of a new energy system? Illustrate with an example of solar collectors.
3. What is exergy efficiency? How will you determine the exergy efficiency of a solar collector?
4. What methods can be used for economic evaluation of a new energy system (technology)?
5. What is the significance of internal rate of return (IRR)? How is IRR used for investment decisions for a project on new energy system development?

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CHAPTER 8

SOLAR THERMAL ENERGY

8.1 INTRODUCTION

Solar energy is an essentially inexhaustible source potentially capable of meeting significant portion of world's future energy needs with a minimum of adverse environmental consequences. Solar energy is the most promising of the unconventional energy sources. In sheer size, it has the potential to supply all energy needs: electric, thermal processes, and chemical, and even transportation fuels.

The sun is a sphere of intensely hot gaseous matter, continuously generating heat by thermonuclear fusion reactions converting hydrogen atoms into helium atoms. This energy is radiated from the sun in all directions and a very small fraction of it reaches the earth. The earth and its atmosphere receive continuously 1.7×10^{14} kW of radiations from the sun, considering 1350 W/m^2 solar radiation and radius of earth, 6378 km. A world population of 10 billion with a total power need per person of 10 kW would require about 10^{11} kW of energy. It is thus apparent that if irradiation on only 1% of the earth's surface could be converted into useful energy with 10% efficiency, solar energy could fulfil the energy needs of the entire world population.

The immense magnitude of direct solar energy can be illustrated by the following estimates:

The average solar constant at sea level = 1 kW/m^2

The normal surface of the earth presented to the sun = πR^2

$$= \pi\,(6378\text{ km})^2$$

Total solar energy at sea level = 1.28×10^{14} kW

If 1% of earth's surface is used for converting solar energy into useful energy at an efficiency of 10% (a figure well below that of some available solar cells), the total energy generated per year = $1.28 \times 10^{14} \times 0.01 \times 0.1 \times 10 \times 365 = 4.67 \times 10^{14}$ kWh, assuming 10 hrs per day for solar radiation. This is close enough for the current annual rate of consumption of the whole world (about 1.6×10^{14} kWh).

Another interesting comparison is that the total fossil energy on earth is less than the solar energy incident upon the earth in one year. Solar energy is, however, very diffuse, cyclic and often undependable or intermittent. It, therefore, needs systems and components that can gather and concentrate it efficiently for conversion to any of the uses and that can do the conversion as efficiently as possible.

8.2 SOLAR RADIATION

8.2.1 Extraterrestrial Solar Radiation

The mean extraterrestrial radiation normal to the solar beam on the outer fringes of the earth's surface is called solar constant. Its value is approximately 1.353 kW/m^2. This varies by ± 3.4% during the year due to elliptical orbit of the earth. The radiant energy from the sun distributed over a range of wavelengths and can be approximated by spectrum of a black body at 5762 K.

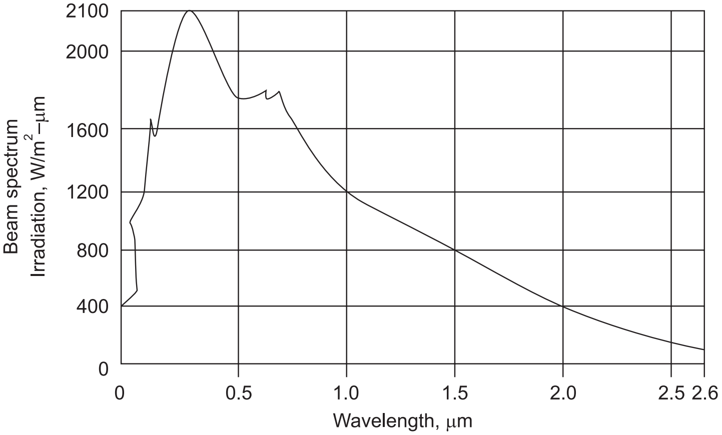


FIGURE 8.1 Solar-energy beam radiation.

The area under the curve,

$$\begin{aligned} S &= 1353 \text{ W/m}^2 \\ &= 1.353 \text{ kW/m}^2 \\ &= 4871 \text{ kJ/h.m}^2 \end{aligned}$$

Peak radiation wavelength λ_{max} (in µm) from a surface with temperature T (in Kelvin) can be calculated using Wien's relationship, $\lambda_{max} = 2898/T$.

8.2.2 Terrestrial Solar Radiation

Extraterrestrial solar radiation is all of beam radiation type, also called direct radiation. This is received from the sun in essentially straight rays or beams that are unscattered by the atmosphere. The solar energy falling on the earth's surface is called terrestrial radiation. The rate of terrestrial radiation falling on a unit surface area in W/m^2 is variably referred to as radiation, irradiation, irradiance, insolation, or energy flux. Terrestrial radiation is not constant and varies significantly.

1. It varies daily because of earth's rotation around the sun.
2. It changes seasonably because of sun's declination angle, that is, the angle between the sun's rays and earth's equatorial plane normal to the polar axis.
3. It changes due to spatial changes between the sun and the earth due to elliptical motion of earth. During summer, the earth's axis is tilted toward the sun and northern hemisphere receives more radiation than the southern hemisphere and vice-versa during winter.
4. It changes from location to location on earth due to the movement of clouds.

The extra-terrestrial radiations are attenuated by the following processes:

1. *Scattering*: A part of a radiation beam is scattered laterally and attenuated by air molecules, water vapor and dust in the atmosphere. The scattered and diffuse radiation is mostly of shorter wavelength.
2. *Absorption*: The solar radiation is absorbed by ozone (O_3), water vapor (H_2O), and carbon dioxide (CO_2).

About 25–50% of solar energy is lost by scattering and absorption. The global solar radiation incident on earth's surface comprises both beam (direct) and diffuse solar radiation. The intensity of global radiation on one square metre of earth's surface in a unit time depends on the geographical latitude, season of the year, time of the day, and on weather conditions, especially cloud cover of the sky.

The annual global solar radiation varies widely from 800 kWh/m^2 to 2400 kWh/m^2 depending on the location. Another parameter of solar radiation at a location is the daily and annual sunshine hours. The value can be anything from 1,400 to 3,500 hours per year. Solar radiation data for various cities of the world have been measured and recorded, available in solar maps usually sponsored by government agencies. Solar maps provide useful information for solar radiation and are used for designing solar power systems. For example, solar yield or potential, which is the solar energy available per solar capacity/power of the system. In the southern part of British Columbia in Canada it is about 1009, or for every kW of system installed we get 1009 kWh of energy per year.

8.3 SOLAR RADIATION GEOMETRY

8.3.1 Radiation Angles

Average cumulative daily solar radiation on a horizontal surface per day are available for different locations. The available terrestrial solar energy at a given time and place is influenced not only by time of the day (hour angle, ω) or year (sun's declination angle, δ), location (latitude angle, θ) and scattering, but also by cloudiness. The incident radiation on earth's surface is influenced by the solar angles and is usually presented in terms of dimensionless Air Mass/AM, m_a defined as follows.

Air mass is the ratio of optical thickness of the atmosphere through which beam radiations pass to the surface to its optical thickness if the sun were at the zenith, that is, directly above. AM can be calculated as the reciprocal of cosine of the angle between a vertical stick, with height h placed on the ground and the line connecting top of the stick to end point of its shadow. Having the stick's shadow length as s, we have

$$m_a = 1/\cos(\theta_z) = \sqrt{1+(s/h)^2}$$

In addition to three basic angles, that is, latitude (θ), hour angle (ω), and sun's declination (δ), certain additional angles are also useful in solar radiation data.

1. *Altitude angle* α *(solar altitude)*: It is a vertical angle between the projection of the sun's rays on the horizontal plane and the direction of the sun's rays passing through a point.
2. *Zenith angle* (θ_z): It is a vertical angle between the sun's rays, and a line perpendicular to the horizontal plane through a point. Therefore, θ_z and α are complementary angles.

$$\theta_z = \frac{\pi}{2} - \alpha$$

3. *Solar azimuth angle*, γ_s: It is a horizontal angle between the north and the horizontal projection of the sun's rays.

8.3.2 Relationship among Solar Angles

The solar angles (α, θ_z, γ_s) can be represented in terms of basic angles (θ, ω, δ) by the following relations:

$$\text{Cos } \theta_z = \cos\phi \cos\omega \cos\delta + \sin\phi \sin\delta$$

$$\theta_z = \frac{\pi}{2} - \alpha$$

$$\therefore \quad \cos\theta_z = \sin\alpha$$

$$\cos\gamma_s = \sec\alpha\,(\cos\phi \sin\delta - \cos\delta \sin\phi \cos\omega)$$

and $$\sin\gamma_s = \sec\alpha \cos\delta \sin\omega.$$

The air mass,

$$m_a = 1/\cos\theta_z \quad \text{for } \theta_z = 0° \text{ to } 70°$$

For extra-terrestrial radiation, $m_a = 0$
For sun at the zenith, $m_a = 1$ at sea level
For $\theta_z = 60°$, $m_a = 2$.

Typical value of m_a is 1.5 and its range is 1 to 4.

8.3.3 Clearance Index

All the effects of solar angles, scattering, absorption, and cloudiness may be combined in one parameter called the Clearness Index, C_i.

The clearance index is the ratio of the average radiation on a horizontal surface for a given period to the average extra-terrestrial radiation for the same period. The averaging could be monthly, daily, or hourly. Therefore,

C_i would be a monthly, daily, or hourly clearness index. It varies widely from 30% to 70% in some locations on earth. Even in the daytime due to bad weather, C_i could be zero.

Example 8.1: *Calculate the sun's altitude angle and azimuth angle at 7.30 am solar time on August 1 for location at 40° north latitude.*

Solution:

$$\phi = 40^\circ$$

$$\omega = 15 \times 4.5 = 67^\circ\ 30$$

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

$$n = 213 \text{ for 1st August}$$

$$\therefore \quad \delta = 17.91^\circ$$

$$\cos\theta_z = \sin\alpha = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta$$

$$= \cos 40^\circ \cos 17.91^\circ \cos 67.5^\circ + \sin 40^\circ \sin 17.91^\circ$$

$$\alpha = 28.46^\circ$$

$$\sin\gamma_s = \sec\alpha\cos\delta\sin\omega$$

$$\sin\gamma_s = \sec 28.46^\circ \cos 17.91^\circ \sin 67.5^\circ$$

$$\therefore \quad \gamma_s = 89^\circ\ 1'\ 36''.$$

8.4 MEASUREMENT OF SOLAR RADIATIONS

The total radiation is the sum of both the beam and diffuse radiation components.

The following measurement of solar radiations are made:

1. *Beam radiations on a horizontal surface*: Pyrheliometer is used to measure the beam radiation on a horizontal surface. It is a small telescope mounted on a drive mechanism and follows the sun throughout the day.
2. *Diffuse radiation on a horizontal surface*: Pyranometer with a shade ring is used to measure the diffuse radiation on a horizontal surface.
3. *Total radiation on a horizontal surface*: Pyranometer without a shade ring is used to measure the total or global radiations.

4. *Sunshine duration*: A sunshine recorder is used to measure the hours of bright sunshine during the day. A lens burns a trace on a card when exposed to the sun. The length of the trace directly measures the duration of bright sunshine.
5. *Beam radiation on a normal surface*: The total radiation received by a surface normal to the beam radiation is more than that on a horizontal surface. Therefore, a radiation collecting surface would be more effective when held perpendicular to the direction of the sun rays. The collector surface should track the sun by changing angle of installation.

8.5 SOLAR COLLECTORS

A solar collector is a receiving device which absorbs the incident solar radiation and heat a fluid like water or air. The solar radiation is converted into useful heat which can be used as such or can be converted into electrical power. The collectors can be classified into low temperature, medium temperature, and high temperature collectors. Mainly, there are two types of collectors:

1. Flat plate collectors
2. Concentrating collectors

8.5.1 Flat Plate Collectors

These are used for temperatures below 100°C. These can use both beam and diffuse solar radiation. They are installed in a fixed tilted position optimally oriented toward the equator.

The main components of a flat plate collector are shown in Figure 8.2.

1. Transparent cover
2. Absorber plate
3. Heat transfer fluid tubes
4. Thermal insulator
5. Casing

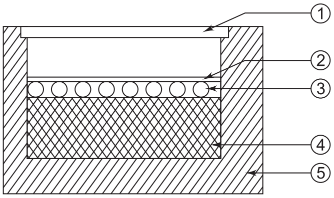


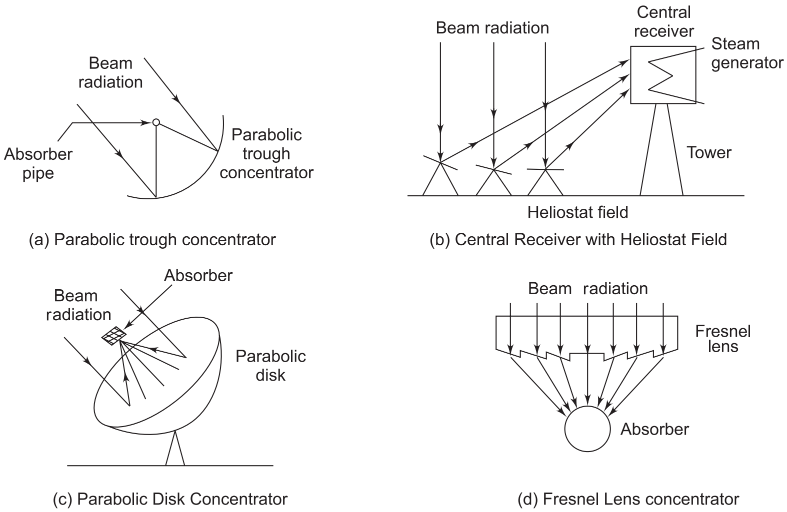
FIGURE 8.2 Flat plate collector.

Flat plate collectors used for water heating and space heating can produce 250 to 400 kWh per year and per square meter of useful heat. Evacuated tube collectors can produce useful heat at a temperature up to 250°C. The efficiency of the collector reduces with the increase of fluid temperature.

Evacuated Tube Collector: The efficiency of a collector is calculated from intensity of solar radiation, optical and heat losses. Evacuated tube collectors are used for reduction of losses. The main applications are water heating, space heating, refrigeration, air-conditioning, and process heat production. Energy in the range of 300 to 600 kWh/m^2 per year can be attained.

8.5.2 Concentrating Collectors

These are used for medium- and high-temperature applications. Various types of concentrating solar collectors are shown in Figure 8.3. It consists of a concentrating device which may be a reflecting mirror or Fresnel lenses. The beam radiations are concentrated and focused on to the absorber. Different types of collectors have different values of concentration ratio.



(a) Parabolic trough concentrator
(b) Central Receiver with Heliostat Field
(c) Parabolic Disk Concentrator
(d) Fresnel Lens concentrator

FIGURE 8.3 Concentrating solar collectors.

The concentration ratio is defined as:

$$C = \frac{A_a}{A_r}$$

where A_a = Aperture area of the concentrator [m^2]

A_r = Area of absorber [m^2].

Parabolic trough concentrator is a linear concentrator. The value of C may be 20 to 100. Parabolic disk concentrator is a point focus concentrator. The value of C may be 100 to 4000 for parabolic disk and heliostat field concentrator.

The mirror and Fresnel lenses can focus only beam radiation. These concentrators are rotated through tracking mechanism to follow the motion of the sun in the sky. Temperatures as high as 100°C can be achieved. These are mainly used in solar plants for power generation and process heat supply.

8.6 FLAT PLATE COLLECTORS

8.6.1 Total Solar Radiation Incident on an Inclined Solar Collector

Solar collectors are installed either in a fixed position or track the sun's motion in the sky. Total solar radiation incident on an inclined flat plate collector consists of:

1. Beam radiation
2. Diffuse sky radiation
3. Diffuse radiation reflected from the earth's surface

The flat plate collectors are installed in fixed position inclined toward the equator, that is, to the north in the southern hemisphere and to the south in the northern hemisphere. Typically, the collector tilt angle β is selected as follows:

$$\beta = \phi \pm 15^\circ$$

where ϕ = latitude of the location in degrees

The hourly beam solar radiation is given by (northern hemisphere)

$$I_{bc} = I_b \cos\theta_c / \cos\theta$$

$$= \frac{I_b\left[\cos(\phi-\beta)\cos\delta\cos\omega + \sin(\phi-\beta)\sin\delta\right]}{\cos\phi\cos\delta\cos\omega + \sin\phi\cos\delta}$$

where I_{bc} = Hourly beam solar radiation on inclined collector surface [kWh/m^2-hr]
I_b = Hourly beam solar radiation incident on a horizontal surface [kWh/m^2-hr]
θ = Angle of incidence of beam solar radiation on a horizontal plane [°]
θ_c = Angle of incidence of beam solar radiation on tilted solar collector toward equator [°]
β = Angle of tilt of solar collector [°]
ϕ = Geographical latitudes [°]
δ = Sun's declination [°]
ω = Hour angle [°].

The geographical latitude ϕ varies from 0° (equator) to +90° (north pole) in northern hemisphere and 0° to 90° (south pole) in the southern hemisphere. ϕ for Delhi is 28.6° N.

The sun's declination δ varies between –23.45° to +23.45° over the year as shown by graph in Figure 8.4. The seasonal variation of the terrestrial radiation on a horizontal surface at any one location on the earth's surface is accounted by the variation of σ.

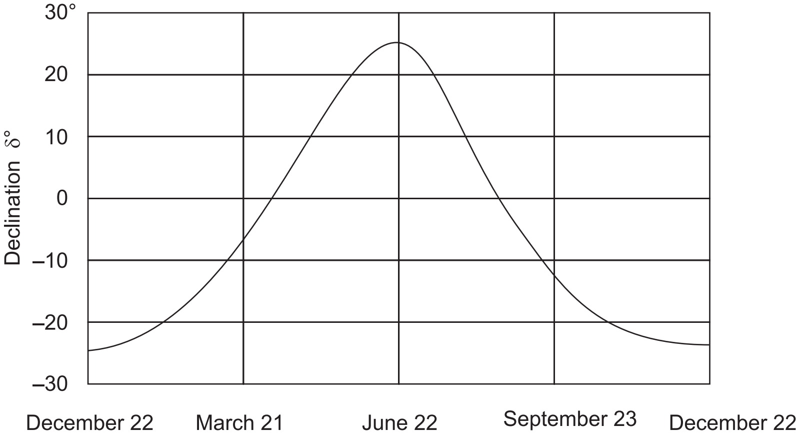


FIGURE 8.4 Seasonal variation in the sun's declination angle, δ.

The hour angle ω is equal to zero at noon (the sun is at zenith). One hour is equivalent to 15°. The hour angle is positive in the morning, 0° at noon and negative in the afternoon.

Example: At 10 am, $\omega = +30°$ and at 2 pm, $\omega = -30°$.

The daily beam radiation incident on an inclined collector surface tilted toward the equator is given by the following relation. The collector surface faces true south in the northern hemisphere and true north in the southern hemisphere.

$$E_{bc} = \frac{E_s\left[\cos(\phi-\beta)\cos\delta\cos\omega_{sc} + \left(\frac{\pi}{180}\omega_{sc}\right)\sin(\phi-\beta)\sin\delta\right]}{\left[\cos\phi\cos\delta\cos\omega_s + \left(\frac{\pi}{180}\omega_s\right)\sin\phi\sin\delta\right]}$$

where E_{bc} = Daily beam radiation [kWh/m^2 per day]

E_b = Daily beam radiation incident on a horizontal surface [kWh/m^2 per day]

ω_{sc} = Sunset hour angle for the inclined collector surface [°]

ω_s = Sunset hour angle for the horizontal surface [°]

The sunset hour angle can be calculated as follows:

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta)$$

$$\omega_{sc} = \cos^{-1}(-\tan(\phi-\beta)\tan\delta)$$

The hourly total solar radiation incident on inclined collector surface can be calculated as follows:

$$I_c = I_bR_b + I_d\frac{(1+\cos\beta)}{2} + I\rho_G\frac{(1-\cos\beta)}{2}$$

where I_c = Total hourly solar radiation incident on unit surface area of inclined collector surface [kWh/m^2 per hour]

I = Hourly global solar radiation on a horizontal surface (kWh/m^2-hr)

I_b = Hourly beam radiation on a horizontal surface [kWh/m^2-hr]

I_d = Hourly diffuse radiation on a horizontal surface [kWh/m^2-hr]

ρ_G = Reflectivity of earth's ground surface.

The ratio of total solar radiations per hour on the collector surface to the global solar radiation per hour on a horizontal surface.

$$R = \frac{I_c}{I} = \frac{I_{bc}}{I_b + I_d} = \frac{I_{bc}}{I\dfrac{(1+\cos\beta)}{2}} + I\rho_G \frac{(1-\cos\beta)}{2}$$

The total solar radiation per day on a unit area of inclined collector surface is

$$E_c = E_R = E_{bc} + E_d \frac{(1+\cos\beta)}{2} + E\rho_G \frac{(1-\cos\beta)}{2}$$

where E_c = Total solar radiation per day per unit area of inclined collector surface [kWh/m^2 per day]

E = Total global solar radiations per day per unit area on horizontal surface [kWh/m^2 per day]

E_b = Total beam solar radiation per unit area per day on horizontal surface [kWh/m^2 per day].

E_d = Total diffuse solar radiations per unit area per day on horizontal surface [kWh/m^2 per day].

Now, $$R = \frac{\text{Total solar radiation on tilted collector surface per day}}{\text{Global solar radiation on a horizontal surface per day}}$$

$$= \frac{E_{bc}}{E} = \frac{E_{bc}}{E_b + E_d} = E\frac{(1+\cos\beta)}{2} + E\rho_G \frac{(1-\cos\beta)}{2}$$

The above relations have been derived using spherical trigonometry.

Example 8.2: *Calculate total insolation per hour on a flat plate collector installed in New Delhi. The site latitude is 28.6^o, the date is June 15 and time is 1 pm (solar time). The collector surface is tilted at an angle 20^o with the horizontal facing south.*

The total radiation per hour on a horizontal plane is 2.5 MJ/m^2 hr and ratio of diffuse radiation is 0.37. The ground reflectivity is 0.2.

Solution: June 15 is 166th day of the year

The angle of declination

$$\delta = 23.45^\circ \sin.\frac{[360(284+n)]}{365}$$

$$= 23.45^\circ \sin.\frac{[360(284+166)]}{365} = 23.3^\circ$$

$$R_b = \frac{I_{bc}}{I_b} = \frac{[\cos(\phi-\beta)\cos\delta + \sin(\phi-\beta)\sin\delta]}{[\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta]}$$

$$\phi = 28.6^o$$

$$\beta = 20^o$$

$$\omega = -15^o \text{ for 1 pm}$$

$$\therefore \quad R_B = \frac{\cos(28.6^\circ - 20^\circ)\cos 23.3^\circ \cos(-15^\circ) + \sin(28.6^\circ - 20^\circ)\sin 23.3^\circ}{\cos 28.6^\circ \cos 23.3^\circ \cos(-15^\circ) + \sin 28.6^\circ \sin 23.3^\circ}$$

$$= 0.96703$$

Total radiation per hour per unit area on collector surface,

$$I_c = I\left[R_b\left(1-\frac{I_d}{I}\right) + \frac{I_d}{I}\left(\frac{1+\cos\beta}{2}\right) + I\rho_G\frac{(1-\cos\beta)}{2}\right]$$

$$= 2.5\left[0.96703(1-0.37) + 0.37 = \left(\frac{1+\cos 20^\circ}{2}\right) + 0.2\frac{(1-\cos 20^\circ)}{2}\right]$$

$$= 2.43526 \text{ MJ/m}^2\text{-hr}$$

$$R = \frac{I_c}{I} = \frac{2.43526}{2.5}$$

$$= 0.9741.$$

8.6.2 Performance Evaluation

The useful heat output of flat-plate collector is given by

$$Q_c = A[I_c F_R (\tau\alpha)_e - F_R U_c (T_{in} - T_a)] \text{ [W]}$$

where A = Surface area of collector or absorber [m^2]

I_c = Intensity of solar radiation incident on the collector [W/m^2]

F_R = Heat removal factor of the collector

$(\tau\alpha)_e$ = Effective product of transmissibility τ of the transparent cover and absorptivity α of the absorber

U_c = Overall heat loss coefficient of collector [W/m^2]

T_{in} = Fluid inlet temperature [K]

T_a = Ambient temperature [K]

The efficiency of solar collector is defined as the ratio of the useful heat output of the collector and the solar energy flux incident on the collector.

$$\eta_c = \frac{Q_c}{AI_c} = \frac{F_R(\tau\alpha)_e - F_R U_c (T_{in} - T_a)}{I_c}$$

Let $\frac{T_{in} - T_a}{I_c} = X$

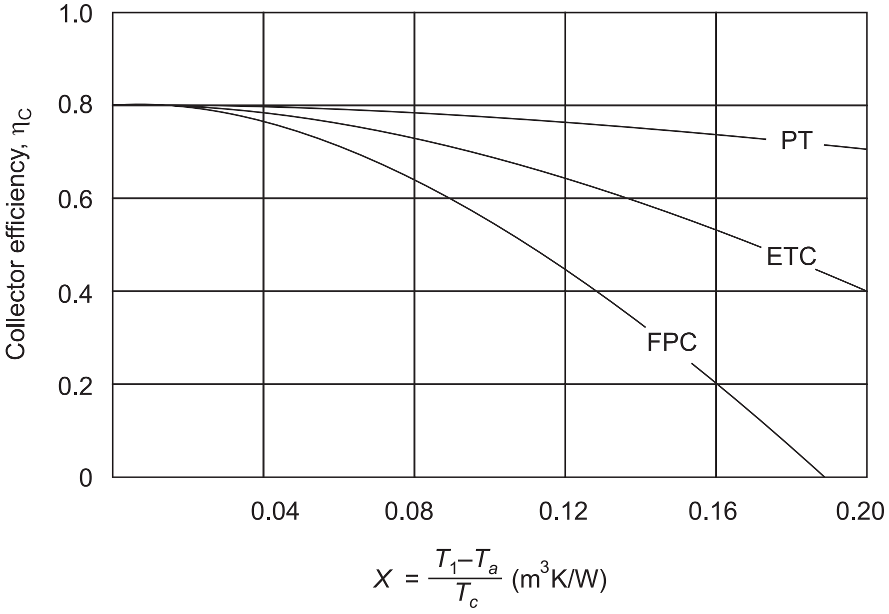
The performance curve of a collector can be plotted between η_c and X, see Figure 8.5.

The following parameters can be found out from the performance curves:

1. At $X = 0$, $\eta_c = F_R\,(\tau\alpha)_e$

   = Effective optical efficiency

2. The value of effective overall heat loss coefficient, F_R, U_C



PT = Parabolic Trough Collector
ETC = Evacuated Tube Collector
FPC = Flat Plate Collector

FIGURE 8.5 Performance curves of collectors.

The outlet temperature of the fluid from the collector can be found out as follows:

$$T_{out} = T_{in} + \frac{Q_c}{\dot{m}c_p}[K]$$

where T_{in} = Inlet temperature of fluid [K]

Q_c = Useful heat output of collector [W]

$\dot{m}$ = Mass flow rate of fluid [kg/s]

c_p = Specific heat of fluid [J/kg-K]

The stagnation temperature is the temperature of the absorber when there is no fluid flow.

At the no fluid flow condition:

$$Q_c = 0 \text{ and } \eta_c = 0 \text{ and if } T_{\text{in}} = T_{\text{stag}}$$

$$\therefore \quad T_{\text{stag}} = T_a + \frac{I_c F_R(\tau\alpha)_e}{(F_R U_G)R}$$

T_{stag} is high if I_c is high, $(\tau\alpha)_e$ is high and $(F_R U_c)$ is low.

Example 8.3: *A flat plate collector is working under the following conditions:*

1. The intensity of solar radiation on the collector surface = 760 W/m^2

2. Inlet temperature of fluid = 43°C

3. Ambient temperature = 26°C

4. Effective optical efficiency = 0.82

5. Effective heat loss coefficient = 4.1 W/m^2*K*

6. Mass flow rate of water = 0.017 kg/s.m^2

7. Cp for water = 4187 J/kg.K

Calculate outlet temperature of water, stagnation temperature and useful heat output.

Solution:

1. Useful heat output per m^2 of collector area,

$$\begin{aligned} q_c &= I_c F_R (\tau\alpha)_e - F_R U_c (T_{in} - T_a) \\ &= 760 \times 0.82 - 4.1 (43 - 26) \\ &= 553.5 \text{ W/m}^2 \end{aligned}$$

2. The outlet temperature of water,

$$T_{\text{out}} = T_{in} + \frac{q_c}{\dot{m}C_p}$$

$$= 43 + \frac{553.5}{0.017 \times 4187} = 50.78°\text{C}$$

3. Stagnation temperature of collector,

$$T_{\text{stag}} = T_a + \frac{I_C F_R (\tau\alpha)_e}{F_R U_c}$$

$$= 26 + \frac{760 \times 0.82}{4.1} = 178°C.$$

8.6.3 Material Selection

The performance and durability of flat-plate collector depends upon the proper selection of materials for critical components.

1. *Cover Plate*: The functions of a cover plate are:

- (*i*) to transmit maximum solar energy to the absorber plate
- (*ii*) to minimize heat loss from absorber plate to the environment
- (*iii*) to protect the absorber plate against direct exposure to weathering
- (*iv*) to receive maximum solar energy for the maximum duration in a day.

Therefore, the most important properties of cover plate should be
- (*i*) transmissibility
- (*ii*) strength
- (*iii*) durability
- (*iv*) nondegradability.

The most common materials used are:
- (*i*) tempered glass with low iron content
- (*ii*) plastics such as Lexan.

2. *Absorber Plate*: The most important properties of absorber plate should be:
- (*i*) high thermal conductivity
- (*ii*) high strength
- (*iii*) good corrosion resistance.

The common materials used are:

(*i*) copper due to high conductivity and resistance to corrosion
(*ii*) aluminum
(*iii*) steel
(*iv*) thermoplastics.

3. *Fluid Flow Channels*: The following materials are commonly used:

(*i*) Tubes made of same material as absorber plate soldered or welded to the bottom of absorber metal plate
(*ii*) Roll-bond panel made of formed copper or aluminum sheets to provide fluid channels.

4. *Thermal Insulation*: Thermal insulation of 5 to 10 cm thickness is placed behind the absorber plate to prevent heat losses from the bottom surface.

The insulation material can be:

(*i*) mineral wool
(*ii*) glass wool
(*iii*) heat resistance fiber glass.

5. *Selective Coating*: An effective way to reduce thermal losses from the absorber plate is by using selective absorber coating. This coating will make the absorber plate a good absorber of solar radiation of short wavelengths and a good reflector or poor emitter of thermal radiation of long wavelengths.

Other properties of selective coating should be:

(*i*) nondegradability against exposure to moisture
(*ii*) ability to withstand temperatures and thermal shocks
(*iii*) resistance to atmospheric corrosion and oxidation
(*iv*) reasonable cost.

Some common selective coatings along with their properties are given in Table 8.1.

Table 8.1 Material Properties of Some Common Coatings for Solar Collectors

Sl.No.	Coating	Type of Process	Absorptance (α)	Emittance ($\in$)
1.	Black Chrome	Electroplated	0.96	0.10
2.	Black Nickel	Electroplated	0.90	0.10
3.	Black Copper	Copper oxide	0.87–0.92	0.07–0.35
4.	Black Anodize	Aluminium oxide	0.94	0.07
5.	Solar foil	Black chrome over copper	0.96	0.10
6.	Nextel	Paint	0.98	0.89

8.7 DESIGN OF FLAT PLATE COLLECTOR

Low-temperature solar plants including various types of water and air heaters use flat plate collectors for collection and absorption of solar radiation and heating of working fluid. The design of a flat plate collector consists of the following:

1. Optical design of collector
2. Thermal design of collector
3. Selection of materials for critical components such as transparent cover, absorber plate with selective coating, fluid flow channels and thermal insulation.

8.7.1 Optical Design of Collector

The flat plate collector works on the principle of greenhouse effect. A transparent cover plate admits the short wavelength (peak about 0.5 µm) radiations from the sun and surroundings. These radiations heat the absorber plate and reradiates long wavelength (peak about 10 µm) radiations as the plate is at low temperature. The cover plate is opaque to these radiations. The greenhouse effect also happens due to earth's atmosphere and it is because of this effect that we can have a suitable average temperature of about 15 ºC instead of negative 19 ºC, if earth had no atmosphere around it.

The cover plate should have the following properties and functions:

1. Radiation received on the surface may be partly transmitted, partly absorbed, and partly reflected depending upon the properties of the cover.

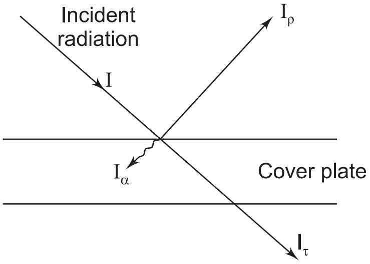


FIGURE 8.6 Solar radiation.

2. As shown in Figure 8.6

$$I = I_\alpha + I_\rho + I_\tau$$

where I = Amount of incident radiation

I_α = Amount of radiation absorbed

I_ρ = Amount of radiation reflected

I_τ = Amount of radiation transmitted

Now, $I_\alpha = \alpha I$

$I_p = \rho I$

$I_\tau = \tau I$

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

where $\alpha = \dfrac{I_\alpha}{I}$ = Absorptivity of cover plate

$\rho = \dfrac{I_\rho}{I}$ = Reflectivity of cover plate

$\tau = \dfrac{I_\tau}{I}$ = Transmissibility of cover plate

3. A perfectly transparent plate will have

$$\tau = 1$$

$$\rho = \alpha = 0$$

4. Most real materials are only partly transparent. The transmittance is dependent both upon the reflection and absorption radiation.

Transmissibility can be calculated as follows:

$$\tau = 1 - \rho - \alpha$$

(*i*) Calculate τ_p considering reflection alone and taking $\alpha = 0$
(*ii*) Calculate transmissibility τ_a considering absorption only and $\rho = 0$
(*iii*) Calculate transmissibility τ taking care of both reflection and absorption as follows:

$$\tau = \tau_\rho \times \tau_\alpha$$

5. Calculation of τ_p

Transmittance of a single cover plate when $\alpha = 0$

$$\tau_{p1} = \frac{1-\rho}{1+\rho}$$

Transmittance for a system of n covers,

$$\tau_{p,n} = \frac{1-\rho}{1+(2n-1)\rho}$$

6. Calculation of τ_α

Transmittance of a single cover when $\rho = o$

$$\tau_\alpha = e^{-kL}$$

Transmittance of n covers when angle of reflection = θ_2

$$\tau_a = e^{\frac{-nkL}{\cos\theta_2}}$$

where k = Extinction coefficient
= 0.01/cm for clear and white glass
= 0.32/cm for poor quality glass
L = Actual path of radiation through the cover plate

7. Transmittance Absorptance Product: The radiation passing through the cover system strikes the absorber plate. Most of the radiation is absorbed but some part is reflected back.

The radiation absorbed = $\tau\alpha$

The radiation reflected back = $(1 - \alpha)\tau$

This reflected radiation is mostly diffuse radiation which is again reflected back to absorber plate by the cover plate. This process continues.

The sum of total radiations absorbed will be more than $\tau\alpha$.

Total radiation absorbed

$$<\tau\alpha> = \tau\alpha \sum_{n=0}^{n=\infty} \left[(1-\alpha)\rho_d\right]^n = \frac{\tau\alpha}{1-(1-\alpha)\rho_d}.$$

where ρ_d = Diffuse radiation reflected by cover plate

= 0.16 for incident angle of 60º.

Example 8.4: *A flat plate collector has two glass covers each 3 mm thick, having refractive index of 1.526 and an extinction coefficient (k) of 0.0161/ mm. Calculate the transmittance taking into account the absorption and reflection for normal incidence.*

Solution:

$$\tau_\alpha(0) = e^{-nkL} \text{ for normal incidence}$$

$$= \mathrm{e}^{-2\times 0.0161\times 3} = 0.908$$

$$\rho(0) = \left[\frac{n-1}{n+1}\right]^2 = \left[\frac{1.526-1}{1.526+1}\right]^2 = 0.0434$$

$$\tau_\rho(0) = \frac{1-\rho}{1+(2n-1)\rho}$$

$$= \frac{1-0.0434}{1+(2\times 2-1)\times 0.0434} = 0.846.$$

$$\therefore \quad \tau(0) = \tau_\alpha(0) \times \tau_\rho(0) = 0.908 \times 0.846 = 0.768.$$

8.7.2 Thermal Design of Collector

The solar radiations striking the absorber plate raise its temperature. Under the plates, fluid carrier tubes are bonded through which working fluid flows and gets heated. The energy balance for the whole collector can be written to find out the useful heat output of the flat plate collector.

The useful heat output of the collector,

$$Q_c = A\,[I_c\,F_R\,(\tau_e)_e] - F_R\,U_c\,(T_{in} - T_a)],\ \text{[in W]}$$

where A = Surface area of collector or absorber [m^2]

I_c = Intensity of solar radiations incident on the collector [W/m^2]

F_R = Heat removed factor of the collector

$<\tau\alpha>_e$ = Effective product of transmissibility τ of the transparent cover and absorptibility α of the absorber

U_c = Overall heat loss coefficient of collector [W/m^2]

T_{in} = Fluid inlet temperature [ºC]

T_a = Ambient temperature [ºC]

Effective heat loss = $AU_c(T_p - T_a)$

where, T_p = Temperature of absorber plate [°C].

1. *Evaluation of overall Heat Loss Coefficient* ($\boldsymbol{U_C}$): The energy loss from the collector absorber plate consists of radiation and convection to the cover and edges and conduction through the back insulation. Thermal network of a flat plate collector is shown in Figure 8.7.

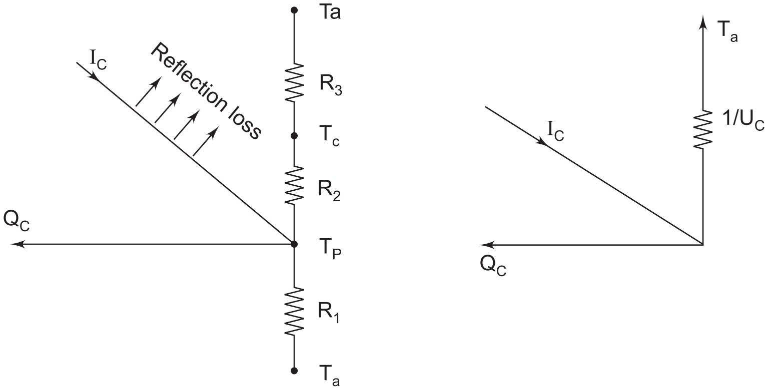


FIGURE 8.7 Thermal network of a flat plate collector.

(i) Insulation resistance (R_1)

$$U_1 = \frac{1}{R_1} = \frac{k}{x}$$

where k = Insulation thermal conductivity

x = Insulation thermal thickness.

(ii) *Heat loss resistance from absorber plate* (R_2)

This constitutes convective resistance and radiation resistance.

$$R_2 = \frac{1}{h_p + h_r}$$

where h_p = Heat transfer coefficient between two inclined parallel plates, i.e., absorber plate and cover plate

h_r = Radiation heat transfer coefficient

$$= \frac{\sigma(T_p + T_c)(T_p^2 + T_c^2)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1}$$

where σ = Stefan Boltzmann's constant

T_p = Temperature of absorber plate (metal)

T_c = Temperature of cover plate (glass)

ε_c = Infrared emissivity of the cover plate

ε_p = Infrared emissivity of absorber plate

(iii) *Heat loss resistance from top cover to surrounding* (R_3)

$$R_3 = \frac{1}{h_T + h_\omega}$$

where h_T = Radiation conductance from top cover to sky

$$h_T = \varepsilon_c\, \sigma\, (T_c + T_{\text{sky}})\, ({T_c}^2 + {T^2}_{\text{sky}}) \times \frac{(T_c - T_{\text{sky}})}{(T_c - T_a)}$$

where $T_{\text{sky}} = T_a - 6$ (°C)

(iv) *Overall loss coefficient* (U_c)

$$U_c = \frac{1}{R_1 + R_2 + R_3}.$$

2. *Evaluation of Heat Removal Factor* (F_R): Heat removal factor (F_R) is defined as the ratio of actual useful energy collected by the fluid to the useful energy collected if the entire collector absorber surface were at the temperature of fluid entering the collector

$$F_R = \frac{\dot{m}C_p}{U_c A}\left[1 - e\frac{-U_c AF'}{\dot{m}C_p}\right]$$

where $\dot{m}$ = Mass flow rate of fluid [kg/s]

C_p = Heat capacity of fluid [kW/kg-K]

F' = Collector efficiency factor

F_R can also be solved with the help of Figure 8.5.

8.8 APPLICATIONS OF FLAT PLATE COLLECTOR

Those countries that are in regions of the world (between 35°N and 35ºS) receive the most average sunshine. The relative high population densities in the rural areas in these regions, and the high exposure to the sun therefore make it natural that applications of solar energy, which leads itself to decentralized power of small size, should be given high priority when trying to solve the energy problems in the developing countries.

Solar energy may be used in many markets such as active and passive space heating and cooling, industrial process heating, desalination and water heating, and in electric generation where power requirements are small and in remote areas. The development, welfare, and prosperity of rural villages depend upon the availability of cheap and abundant energy for domestic cooking, heating, lighting, community development, irrigation water, mechanized agriculture, and small industrial parks based on solar energy.

If the energy and power needs of the villages can be met from solar energy, the central/zonal power grids connecting thermal, nuclear, and hydro power plants can work in a more efficient and reliable manner at high-load factors feeding power only to industrial belts and big commercial centers. Tremendous investments and huge power losses in the long and unwieldy power lines to remote and scattered villages can be saved.

Therefore, there is an urgent need to use/develop the following solar appliances for villages.

1. Solar cookers that must fit well with the age-old habits of conventional cooking and should be accepted by the rural population without any reservation
2. Small solar-driven refrigeration units for preservation of food, storage of milk, medicine, and other products in the rural areas where little electric power is available
3. Solar water irrigation pumps to boost the agricultural production, which is vitally important in view of growing population
4. Solar water heaters for domestic use and dryers for agricultural products
5. Small power plants to produce electricity for domestic use, street lighting, and cottage industries

8.8.1 Solar Water Heaters

Solar plants for water heating can be used for the following:

1. *Swimming pools*: Solar water heaters can be used for heating water from 23° to 28°C for swimming pools.
2. *Domestic hot water* at 45°–60°C.
3. *Space heating*: Water is heated to 30°–90°C.
4. *Refrigeration and space cooling*: Heat is supplied to refrigerant vapor generator at 95° to 150°C.

(*a*) *Domestic water heating* is most widely used.

There are two types of water heating plants:

1. *Single loop thermosyphon circulation solar water heaters*: These can be used with ambient temperature above 0°C. It consists of a solar collector, hot water storage tank, and return tubes. The water is returned due to gravity and rises due to thermosyphon effect.

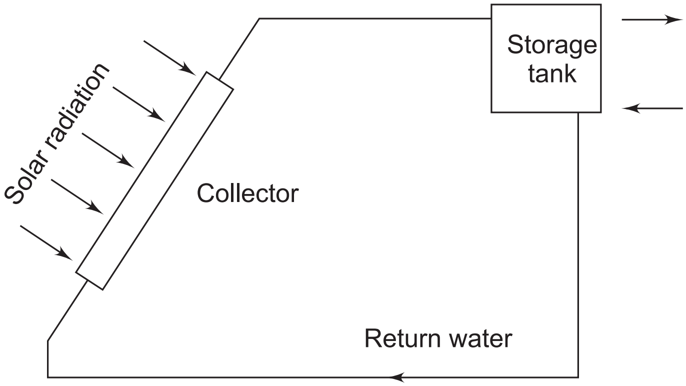


FIGURE 8.8 Simple solar water heater.

2. *Forced Circulation Water Heater*: It is used for supply of hot water in summer and winter even with ambient temperature below 0°C. It also includes a circulation pump with automatic control and a heat exchanger. An antifreeze solution of polypropylene or polyethylene is used as collector fluid. Water is used for storage in the hot water tank. A back-up heating facility is also used in addition to solar heating.

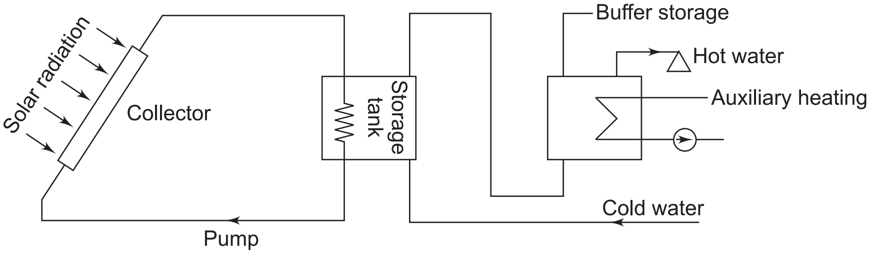


FIGURE 8.9 Forced circulation water heater.

(*b*) **Design of Solar Water Heater:**

(*i*) The heat quantity for hot water per month

$$Q_{HW} = d_W N_{\text{per}} C_{p_w} (T_{Hw} - T_{cw}) N_D, [J]$$

where dw = Daily hot water demand, (kg/day/person)

N_{per} = No. of hot water consumers

C_{p_w} = Specific heat of water [4187 J/kg. K]

T_{Hw} = Hot water temperature, [ºC]

T_{cw} = Cold water temperature, [ºC]

N_D = Number of days in the month

(*ii*) Heat required for space heating per month

$$Q_{\text{heat}} = U_B A_B DD \text{ (J/month)}$$

where A_B = Total external surface area of heated building (m^2)

U_B = Average heat loss coefficient of building (W/m^2–K)

DD = Number of degree-days per month (K-days)

(*iii*) Total surface area of collector required

$$A = \frac{Q_{HW}}{q_{\text{sol}}}$$

$$= \frac{\dot{m}_{Hw} c_{p_w} (T_{Hw} - T_{cw})}{E_c \eta_{\text{sol}}} (\text{m}^2)$$

where Q_{HW} = Amount of heat required for hot water supply (J)

q_{sol} = Heat output of collector (J/m^2)

m_{HW} = Amount of hot water required (kg)

E_c = Solar radiation on collector (J/m^2)

η_{sol} = Efficiency of solar plant

Example 8.5: *The following data may be used for the design of a solar water heater:*

1. solar radiation = 5 kW/m^2/day

2. hot water required = 1000 kg/day

3. hot water temperature = 45°C

4. cold water temperature = 14°C

5. C_{p_w} *= 1.163 Wh/kg K*

6. Mean efficiency of water heater = 48%.

Piping and storage heat losses may be neglected. If a single plant has an area of 2.2 m^2, find out the total area required and number of collector modules.

Solution:

1. Total heat required for hot water supply

$$\begin{aligned} Q_{HW} &= \dot{m}_{Hw}\, C_{p_w}\,(T_{Hw} - T_{Cw}) \\ &= 1000 \times 1.163\,(45 - 14) \\ &= 36053 \text{ Wh/day} \end{aligned}$$

2. Heat output of collector

$$\begin{aligned} q_{\text{sol}} &= E_c\, \eta_{\text{sol}} \\ &= 5 \times 0.48 = 2.4 \text{ kWh/m}^2\text{/day} \end{aligned}$$

3. Total collector area required

$$A = \frac{Q_{Hw}}{q_{\text{sol}}} = \frac{36053}{2400} = 15.02 \text{ m}^2$$

4. No. of solar collector modules required

$$n = \frac{A}{A_c} = \frac{15.02}{2.0} = 6.9, \text{ say } 7.$$

8.8.2 Solar Cookers

Direct cooking in rural areas is essential in the people's lives. For example, 80% of the basic energy needs of rural India is the provision of cooking energy, which amounts to 0.5 to 1 kWh/person/day with a peak power of 0.2 to 1.2 kW per capita. It is mostly met from traditional fuels like firewood and cow manure. The government of India is trying to introduce box-type solar cookers with financial subsidies but with poor success due to many technical drawbacks of the design. The temperature obtained is less than 100ºC and is insufficient for making local foods and for frying, which is very important to the cooking process. There is no provision for storage of heat, and cooking must be carried out while the sun is shining, which is an odd time for preparing breakfast and dinner. Cooking must be carried out in the open without privacy and in the sun, which is inconvenient and not suitable to local traditions.

Hot-Plate Solar Cooker

A small family-size solar cooker has been developed to overcome the drawbacks of solar cooking. It consists of a flat plate collector with mirror boosters. It is coupled to an oil storage insulated tank placed under the cooking platform inside the kitchen through a thermosyphon to the outside collector. The schematic diagram is shown in Figure 8.10. It can provide enough flux of heat energy at high enough temperature to a hot plate through a heat pipe.

The main components with specifications are as follows:

1. Solar collector (1 m^2)
2. Thermosyphon (32 mm NB pipe)
3. Hot oil storage tank (100 *L* Dowtherm™)
4. Thermometer (0–300°C)
5. Hot plate (2 kW)
6. Heat pipe (2 kW)
7. Control valve
8. Nonreturn valve

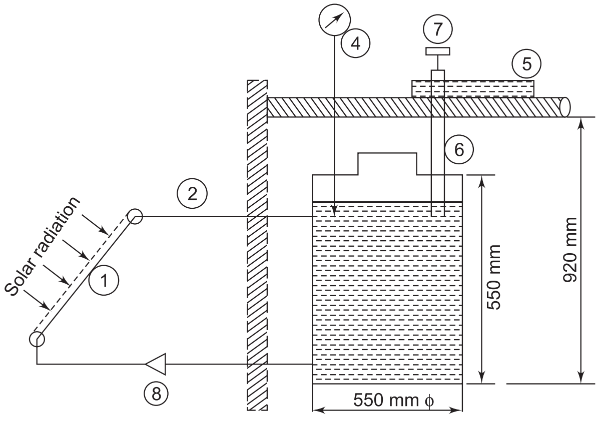


FIGURE 8.10 Hot-plate solar cooker.

The system would be suitable for cooking of conventional food at a convenient time for breakfast, lunch, and dinner inside the kitchen. It would replace a bottled gas cooking range and would be fitted permanently. It would fit in with age-old habits and practices of rural households. It is coupled to a thermal storage and can last for a day without sunshine. The heat flux can be conveniently controlled by turning a small control valve suitably placed at the hot plate. There are no operating and maintenance expenses and lifelong oil fill is provided. The prototype cost of approximately $50 can be substantially reduced during commercial design and mass manufacture.

8.8.3 Solar Refrigeration

A solar driven refrigerator is needed for preservation of food in rural areas where little electric power is available. Figure 8.11 depicts the flow diagram of a solar domestic refrigerator. Solid absorption zeolite refrigeration cycle can ensure long and trouble-free operation life because of absence of moving parts, as well as toxic and corrosive chemicals.

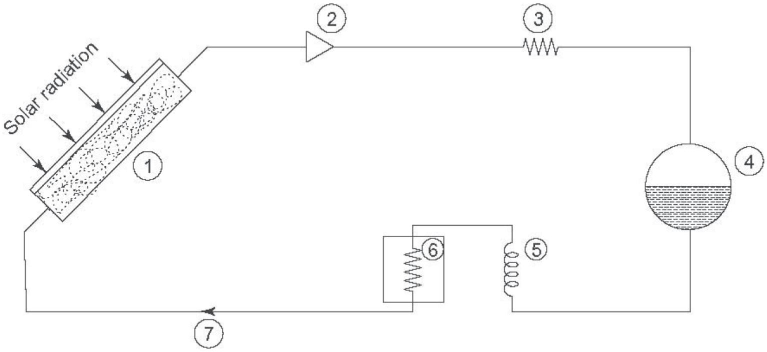


FIGURE 8.11 Solid zeolite absorption refrigerator.

The main components are as follows:

1. 1.5 m^2 zeolite filled solar collector
2. 10 NB nonreturn valve (ball type)
3. 4.2 m^2 panel coil condenser
4. 20 *l* water storage tank
5. 0.5 mm × 1.4 m capillary tube
6. 0.3 m^2 panel coil evaporator and ice tank
7. 32 NB Nonreturn value (Ball type)

It consists of 1.5 m^2 flat plate collector with 50 mm thick zeolite and can be fitted to 165 litre domestic refrigerator. Water vapor is driven out of collector by solar heating during the day. The vapors are condensed and stored in a tank until evening. As the collector cools at night due to sky radiation, a vacuum in the system causes the water in the evaporator to boil constantly at a temperature of –2°C at a presence of 4 mm of Hg. The frozen surface can make 9 kg of ice in 8 hours. The water vapor returns to the collector for re-absorption into zeolite and the system is ready for the next day. The ice can be removed for use or left to cool the refrigerator at times of no sunshine. The system can be scaled up into a small cold storage for preservation of food in rural areas.

8.8.4 Solar Milk Cooler

The total milk production per day per typical village on an average may be taken as 2,000 liters out of which the milk producers can consume 25% for self-use and convert about 45% into milk products like butter, ghee, and cheese. Therefore, 500–600 liters of milk per village is available for sale as liquid milk per day.

Rural processing of milk can add value to the product and increase rural income. The zeolite solar refrigeration system can be attached to a milk cooling-cum-storage tank made of single-embossed panel coils of stainless steel, the inside being plain sheet and outside made of embossed sheet. The water refrigerant circulates by thermosyphon effect in the walls and acts as a very efficient heat exchanger. The temperature difference between milk and water vapor is reduced to less than 0.5ºC. As water storage is in the bottom of tank, it makes it possible to cool even small quantities of milk.

8.8.5 Solar Water Pumps

Organic vapor Rankine cycle system with rotary machines, screw expander, reciprocating engine, or spiral expander has been used to drive water pumps. The schematic diagram of such a pump is shown in Figure 8.12.

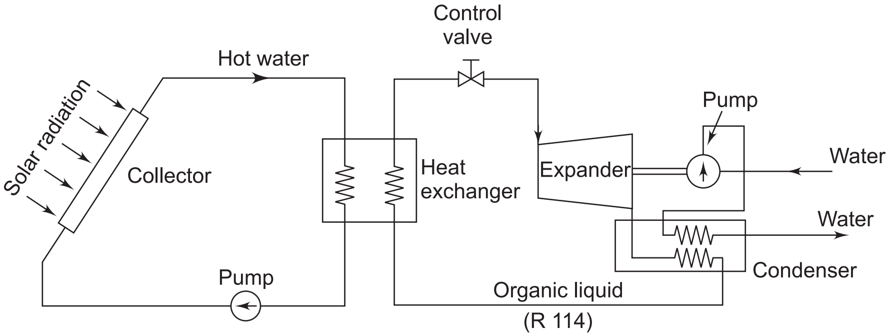


FIGURE 8.12 Solar pump.

The main specifications are:

1. Pump rating : 1 kW
2. Refrigerant : *R* 114
3. Collector area : 10 m^2
4. Total cost : $250 (estimate)

The solar heat can operate the pump for four hours a day. When not pumping, it can be used to drive a generator, thresher, or a lathe.

8.9 FOCUSING (CONCENTRATING) COLLECTORS

Different types of concentrating solar collectors have been discussed in Section 8.5.2. The performance characteristics have been discussed as follows:

8.9.1 Performance Evaluation

The useful heat output,

$$Q_c = F_R A_a \left[I_{bc} \eta_{\text{opt}} - \left(\frac{U_c}{C} \right) \right] [T_{\text{in}} - T_a] [\text{W}]$$

where, F_R = Heat removal factor of the collector
A_a = Unshaded aperture area, (m^2)
I_{bc} = Intensity of beam radiation on aperture of the collector, (W/m^2)
η_{opt} = Optical efficiency of the collector

U_c = Total heat loss coefficient of the collector, [W/m^2-K]
C = Concentration ratio of the collector
T_{in} = Inlet fluid temperature, (°C)
T_a = Ambient temperature, (0°C)

8.9.2 Optical Efficiency

Optical efficiency is the ratio of solar radiation absorbed and the beam radiation incident on the collector.

$$\eta_{\text{opt}} = \eta_{\text{opt}}(0°)\, C_{\text{opt}} = \rho\gamma\, \tau\alpha_{\text{a}}\, C_{\text{opt}}$$

where $\eta_{\text{opt}}(0°)$ = Optical efficiency at 0º incident angle of beam
C_{opt} = Correction factor for deviation from 0º
ρ = Reflectivity of mirror
γ = Intercept factor
τ = Transmissivity of the cover (if used)
α_a = Absorptivity of absorber.

The efficiency of collector,

$$\eta_c = \frac{Q_c}{A_a I_{bc}} = F_R \eta_{\text{opt}} - \left(\frac{F_R U_c}{C\, I_{bc}}\right)(T_{\text{in}} - T_a)$$

The efficiency of a collector as a function of absorber temperature for different concentration ratios is shown in Figure 8.13.

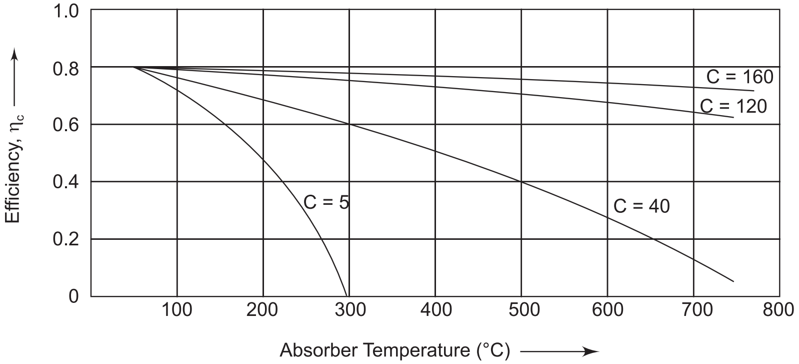


FIGURE 8.13 Performance curve of concentrating collector.

There can be phase change of fluid in a concentrating collector.

The output enthalpy,

$$h_{\text{opt}} = h_{\text{in}} + \frac{Q_c}{\dot{m}} \left[\text{J/kg} \right]$$

where h_{in} = Enthalpy of inlet fluid, (J/kg)
Q_c = Useful heat output, [W]
$\dot{m}$ = Mass flow rate of fluid, (kg/s)

8.9.3 Optical Design of Concentrating Collector

High-temperature solar plants are solar-electric conversion systems where the collectors gather the sun's energy and redirect it onto receivers that contain the working fluid of thermodynamic cycle.

The main designs of such plants are as follows:

1. *Solar-thermal Central-Receiver System (Solar Tower)*: A large field of reflecting mirrors called heliostats receive and redirect the sun's energy and concentrate it on a central receiver mounted on top of a tower. The heliostats are individually guided, since they cover a large field so that each plain mirror focuses the solar radiations on the central receiver at all hours of sunlight. In the receiver, the concentrated solar energy is absorbed by a circulating fluid. The fluid could be water which vaporises into steam that is used to drive a turbo-generator in a Rankine cycle, or an intermediate fluid that transports the heat to the steam cycle through a heat exchanger (Figure 8.3*b*).

2. *Parabolic Trough System*: Long troughs of cylindrical parabolic shape are lined with mirror to collect and concentrate the solar radiation onto a focal linear conduit through which the primary fluid flows, (Figure 8.3*a*). The fluid from different receivers is combined for a thermal-electric conversion.

3. *Disk-Sterling Engine System*: A mirrored parabolic disk tracks the sun and focuses the captured energy on a receiver which is mounted at the focal point of the parabola (Figure 8.3*c*). At the focal point a Sterling engines converts the thermal energy to mechanical or electrical energy.

4. *Fresnel Lense System*: The Fresnel Lense focuses the beam radiation on a receiver in which working fluid is heated and which can be used for power generation and process heat supply (Figure 8.3*d*).

Terminology

The focusing collectors involve additional optical losses.

1. *Optical Efficiency*: The optical efficiency of a focusing collector can be expressed as follows:

$$\eta_{\text{opt}} = \rho\gamma\ \tau\alpha_a C_{\text{opt}}$$

2. *Reflectance Loss* (ρ): It depends upon the reflectivity of mirror ρ and depends upon the nature and smoothness of the reflector surface.
3. *Intercept Factor* (γ): The energy received by absorber depends upon the part of the reflected radiation that is intercepted by the receiver. The intercept factor depends upon:
   - (*i*) The shape, size and orientation of reflector.
   - (*ii*) The shape, size and positioning of receiver relative to the reflector/concentrator.
4. *Concentration Ratio* (c): The ratio of effective area of the aperture to the area of solar energy absorber is called concentration ratio.

$$c = \frac{A_a}{A_c}$$

The collector efficiency increases with the increase of concentration ratio.

8.9.4 Comparison of Performance of Different Collectors

The technical and economic parameters of different collectors are tabulated in Table 8.2 for comparison.

Table 8.2 Performance Comparison of Different Collectors

Sl. No.	Type of Collector	Effective Optical Efficiency $F_R(\tau\alpha)$	Effective Heat Loss Coefficient $F_R U_c$ (W/m^2-K)	Operating Temperature (°C)	Cost *f*/m^2
1.	Flat plate collector with no cover	0.9	15–20	30	120–170
2.	Flat plate collector with single cover	0.8	35–40	<100	300–500

Sl. No.	Type of Collector	Effective Optical Efficiency F_R ($\tau\alpha$)	Effective Heat Loss Coefficient $F_R U_c$ (W/m^2-*K*)	Operating Temperature (°C)	Cost *f*/m^2
3.	Evacuated tube collector	0.7	1.5–1.8	<250	700–1000
4.	Parabolic trough collector	0.8	0.2–0.7 (C = 20 to 100)	400	~ 700

8.10 SOLAR THERMAL POWER PLANTS

Concentrating solar collectors are employed to heat a working fluid for power cycles. The following types of solar thermal power plants have been developed in different countries.

1. Parabolic trough solar power plant
2. Central receiver solar power plant
3. Dish/Sterling engine power plant
4. Solar chimney power plant

Desert and semidesert regions of the earth are most suitable sites which have annual insolation of 2000 to 2400 kWh/m^2 and sunshine durations 2400 to 3500 hours/year.

8.10.1 Parabolic Trough Solar Power Plant

It is also called solar-farm power plant as several solar modules consisting of parabolic trough solar collectors are interconnected. Every module consists of a collector as shown in Figure 8.14. It is rotated about one axis by a sun tracking mechanism.

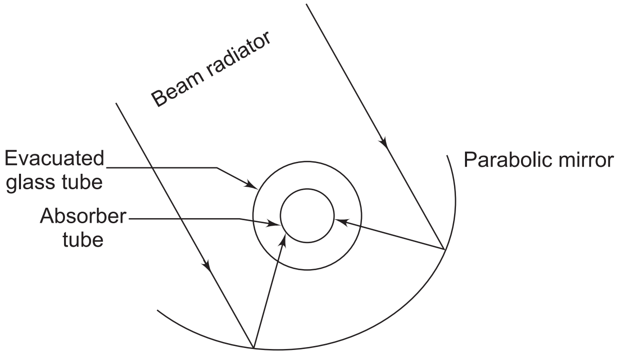


FIGURE 8.14 Parabolic solar collector.

Thermo-oil is mostly used as heating fluid as it has very high boiling point. Water/steam working fluid can also be used. The tubes have evacuated glass enclosure to reduce losses. The concentration ratio is between 40 and 100.

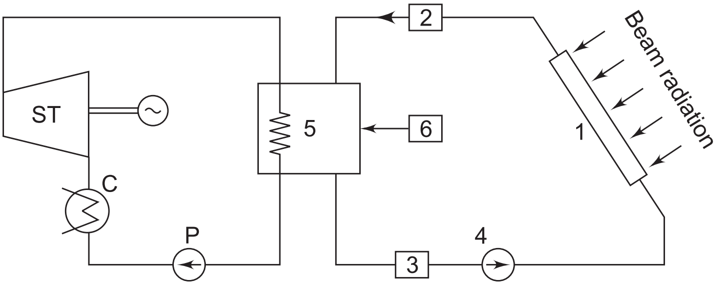


FIGURE 8.15 Parabolic trough solar power plant.

The maximum oil temperature is limited to 400°C as oil degrades above this temperature. Alternately steam at 550°C can be directly generated in the absorber tube.

These are commercially under operation in United States, Spain, UAE, Italy, Thailand. and other countries. The flow diagram of a parabolic trough solar power plant is shown in Figure 8.15. The working fluid is heated in collectors and collected in hot storage tank (2).

The hot thermo-oil is used in boiler (5) to raise steam for the steam power plant. The boiler is also provided with a back-up unit (6) fired with natural gas. The cooled oil is stored in a tank (3) and pumped (4) back to collector (1).

The specifications of two such plants are given below:

1.	Power capacity	30 MW	80 MW
2.	Thermal efficiency	37.5%	37.6%
3.	Aperture area	194×10^3 m^2	464×10^3 m^2
4.	Collector field efficiency	43%	53%
5.	Annual energy production	939 Wh	253 GWh
6.	Production cost	0.15 cent/kWh	0.10 cents/kWh

Performance Analysis

The heat output,

$$Q_c = n\, I_b\, A_a\, \eta_c, \text{ [W]}$$

where A_a = Aperture area of a parabolic trough module [m^2]
I_b = Radiation intensity [W/m^2]
n = Number of collectors
η = Collector efficiency

The efficiency of a module,

$$\eta_{\text{mod}} = \rho\alpha_{\text{abs}} - \frac{U_c(T_{\text{abs}} - T_a)}{CI_b}$$

where ρ = Reflectivity of mirror
α_{abs} = Absorptivity of tubes
U_c = Overall heat loss coefficient [W/m^2-K]
Tabs = Temperature of absorber [K]
C = Concentration ratio
I_b = Intensity of beam radiation [W/m^2]

Example 8.6: *Determine the heat output and exit temperature of thermo-oil for the following power plant:*

1. *Solar heat intensity = 750 W/m*^{2}

2. *Unshaded aperture area = 240 m*^{2}

3. *Concentration ratio = 40*

4. *Inlet oil temperature = 280°C*

5. *Mass flow rate = 0.6 kg/s.*

6. *Specific heat of oil = 3200 J/kg-K*
7. *Ambient temperature = 30°C*
8. *Optical efficiency = 0.74*
9. *Heat loss coefficient = 7 W/m^2-K*
10. *Heat removal factor = 0.96*

Solution:

1. Heat output,

$$Q_c = F_R A_a \left[I_{bc}\eta_{\text{opt}} - \frac{U_C}{C}(T_{\text{in}} - T_a) \right]$$

$$= 0.96 \times 240 \left[750 \times 0.74 - \frac{7}{40}(280 - 30) \right]$$

$$= 117792 \text{ W.}$$

2. Fluid outlet temperature,

$$T_{\text{out}} = T_{\text{in}} + \frac{Q_c}{\dot{m}C_p}$$

$$= 280 + \frac{117794}{0.6 \times 3200}$$

$$= 341.35°\text{C}$$

8.10.2 Central Receiver Solar Power Plants

These are also called solar-tower power plants. The plant can be divided into solar plant and conventional steam power plant. The flow diagram is given in Figure 8.16.

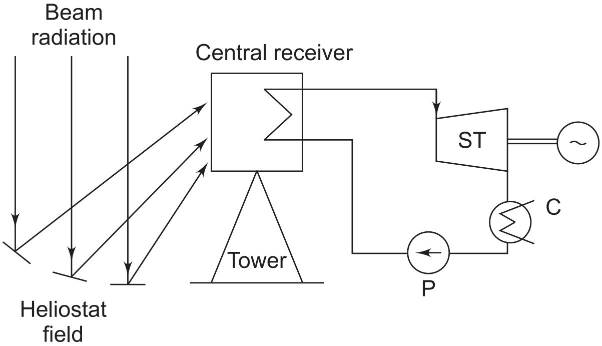


FIGURE 8.16 Central receiver solar power plant.

A heliostat field consisting of many flat mirrors of 25 to 150 m^2 area reflects the beam radiation onto a central receiver mounted on a tower. Each mirror is tracked on two axes. The absorber surface temperature may be 400 to 1000°C. The concentration ratio (total mirror area divided by receiver area) may be 1500. Steam, air, or liquid metal may be used as working fluid. Steam is raised for the conventional steam power plant.

The technical data of an experimental solar power plant is given below:

1. Electric power output = 1.2 MW
2. Solar energy input = 5.5 MW
3. Heliostat field area = 1200 m^2
4. Tower height = 80 m
5. Working fluid = Water/steam

A total heliostat area of 0.5 km^2 is required for a power plant of 20 MW.

Useful solar energy output,

$$E = AI_b\,\eta, \text{ [W]}$$

where A = Total area (m^2)

I_b = Intensity of beam radiation (W/m^2)

η = Efficiency of heliostat field = 55 to 80%

Performance Analysis

The rate of useful heat output of central receiver,

$$Q_c = E\text{-}\Sigma\Delta E_l - \Sigma\Delta\, Q_l, \text{ [W]}$$

where E = Output of heliostat [W]

$\Sigma\Delta_{El}$ = Electrical losses [W]
(radiation losses due to reflection from the absorber surface)

$\Sigma\Delta Q_l$ = heat losses [W]
(due to conduction, convection and radiation in the receiver walls).

The rate of useful heat output is also equal to

$$Q_c = A_a\left[I_a - F_R U_c[T_{\text{in}} - T_a]\right]\text{[W]}$$

$$= \dot{m}\,(h_o - h_i)\text{ (W)}$$

The absorbed solar radiation flux,

$$I_a = \frac{(E - \Sigma \Delta E_l)}{A_a}$$

$$= I_b\, C\rho\, \tau\alpha \text{ (W/m}^2\text{)}$$

where I_b = Beam radiation intensity on heliostat surface (W/m^2)

C = Concentration ratio of heliostat-receiver system

ρ = Reflectivity of heliostat

γ = Intercept factor

τ = Transmissivity of transparent cover of absorber

α = Absorptivity of absorber surface

The efficiency,

$$\eta = \frac{Q_c}{E}$$

where E = useful solar radiation flux of heliostat [W].

8.10.3 Disk-Sterling Engine System

This system is useful for autonomous power generation.

A hot gas Sterling engine receives solar irradiation from a parabolic trough concentrator (disk). It has very high efficiency. Glass mirrors are used for radiation concentrator. The working fluid is hydrogen or helium for sterling engine.

The maximum pressure and temperature of the engine cycle are 20 MPa and 1000 K. A schematic diagram of a power plant is shown in Figure 8.17.

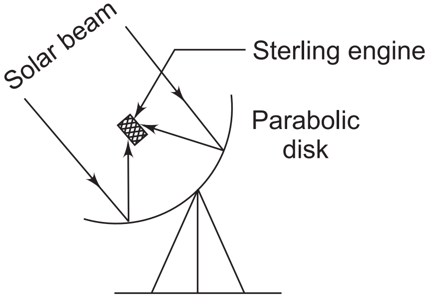


FIGURE 8.17 Disk-sterling engine power plant.

Typical specifications of such a system are given below:

1. Power output of Sterling engine = 50 kW
2. Cycle efficiency = 42%
3. Disk diameter = 17 m
4. Concentration ratio = 4000
5. Optical efficiency = 89%
6. Receiver diameter = 700 mm
7. Flux density = 800 kW/m^2
8. Cost = $ 2100/kW

8.10.4 Solar Chimney Power Plant

The air stream is heated by solar radiation absorbed by the ground and covered by a transparent cover. The hot air flows through the chimney, which gives the air a certain velocity due to pressure drop caused by chimney effect. The hot air flows through an air turbine to generate power. The schematic diagram of the plant is shown in Figure 8.18. This system could be categorized as semi-direct due to having a generator to convert mechanical energy, received from turbine, to electricity.

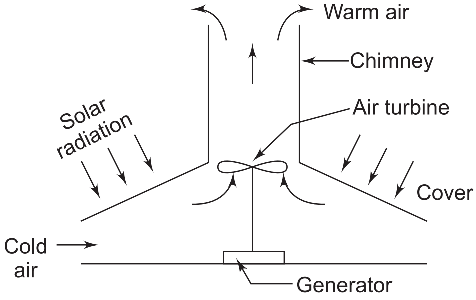


FIGURE 8.18 Chimney solar power plant.

The pressure difference due to chimney effect

$$\Delta p = gH\,(\rho_c - \rho_w),\ \ [\mathrm{N/m^2}]$$

where g = Acceleration due to gravity [9.81 m/s^2]

H = Chimney height [m]

ρ_c = Density of cold air (kg/m^3)

ρ_w = Density of warm air [kg/m^3]

The pressure energy is converted into kinetic energy of air.

The air velocity in the chimney,

$$V = \sqrt{2\frac{\Delta p}{\rho}}\,[\mathrm{m/s}]$$

The power output of air turbine is a function of air velocity and chimney area.

The plant efficiency,

$$\eta = \frac{p}{IA}$$

where P = Power output of air turbine [W]

I = Intensity of global solar radiation [W/m^2]

A = Area of ground receiving solar radiation [m^2]

Typical specifications of a chimney power plant in operation are:

1. Power output = 50 kW

2. Annual energy output = 42 MWh

3. Overall efficiency = 0.05%

4. Chimney height = 200 m

5. Radius of solar collector = 122 m

6. Chimney diameter = 10 m

7. Air velocity in chimney = 7.6 m/s

8.10.5 Solar Ponds

Solar ponds are also called solar salt ponds. Natural ponds convert solar radiation into heat, but the heat is quickly lost through convection in the pond and evaporation from its surface. A solar pond is designed to reduce convective and evaporative heat losses by reversing the temperature gradient with the help of nonuniform vertical concentration of salts. A greater salt concentration at the bottom causes bottom water to have greater density and remain at the bottom. It is also hotter. The solar energy is absorbed in deep layers and is usefully tapped.

The solar ponds are useful in two ways:

1. The conversion of solar energy to useful work as a result of the temperature difference between bottom and top layers of the pond.
2. The use of pond as thermal storage medium.

A solar pond is a combination of solar collector and storage medium. A schematic of an artificial solar pond and conversion system is shown in Figure 8.19.

The pond is divided into three layers:

1. *Top layer*: Low density convective layer.
2. *Central layer*: Nonconvective layer and contains the required salinity and density gradient with salinity greatest at the bottom.
3. *Bottom layer*: High-density salinity convective storage layer.

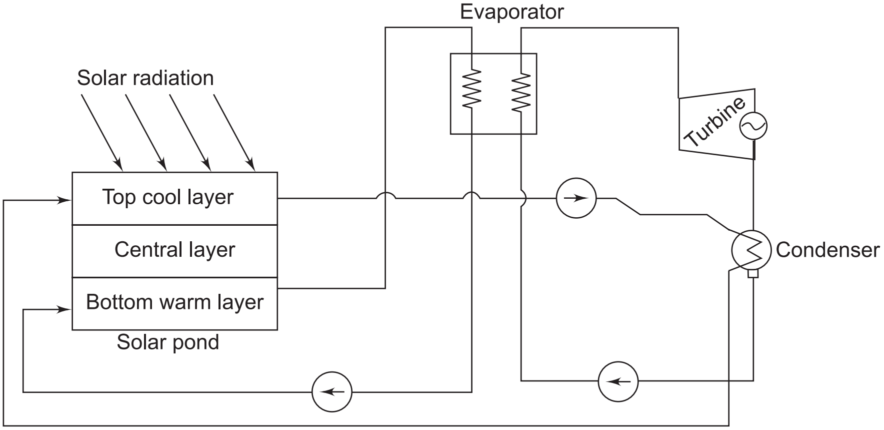


FIGURE 8.19 Solar pond power plant.

The bottom warm water is used as the heat source and top cool water as the heat sink. The hot bottom water is pumped through an evaporator and back to the bottom. An organic fluid is evaporated and drives a turbo-generator. The turbine exhaust is condensed and condensate is fed back to the evaporator. The cooling water for the condenser is taken from the cool layer of the pond.

Specifications: A leak-proof pond container is constructed. 330 kg of salt per square meter of pond area is added. The bottom layer can achieve a temperature of 93°C. The salinity gradient is maintained in the pond by injecting salt to the bottom layer and flushing the top layer with fresh water periodically. The efficiency is very low, but these plants have a large potential for tapping solar energy.

Applications. The main applications of solar ponds are:

1. Power generation
2. Space heating and cooling
3. Crop drying
4. Desalination
5. Process heat

Limitations: The main limitations are:

1. Need for large land area
2. Sunny climate
3. Availability of water
4. Availability of salt (brackish water)

A solar pond power plant of 5 MW capacity is in operation in Dead Sea, Israel.

8.11 DESIGN OF SOLAR THERMAL PLANTS

There are basically two types of solar thermal plants.

1. *Low Temperature Solar Plants*: These plants are used for various thermal applications such as swimming pool heating (pool water temperature of 23 to 28°C), hot water system (45 to 60°C), space heating (heating water to a temperature of 30 to 90°C), and refrigeration and space cooling (heat is supplied to the refrigerant vapor generator at 90 to 150°C). Domestic water heating

is the most widely used system. Solar air heaters are used for the drying of agricultural produce and the heating of green houses and buildings.

2. *High Temperature Solar Plants*: These plants are used for the generation of electricity by using thermodynamic cycle: Rankine cycle, Brayton cycle.

All solar thermal plants have the following systems/components:

1. Solar radiation data
2. Solar collector and receiver
3. Heat Transport system
4. Thermal Storage system

The detailed design of each system/component depends upon the specific applications.

8.12 HELIOSTATS

Central receiver solar power plants use heliostats.

1. These are reflecting mirrors to reflect the sun rays onto the receiver.
2. A heliostat consists of a mirror, mirror support structure, pedestal, foundations, and control and drive mechanism.
3. A glass heliostat is divided into 10 to 14 panels for ease of manufacture and transportation. The rectangular panels are 1.2 × 3.6 m with 1.5 to 3 mm thickness of low iron glass sheets to minimize absorption.
4. The cost of heliostats may be 45% of total capital cost of a solar thermal power plant.
5. Plastic heliostats have lower cost, lower mass but are lower in reflectance.
6. A north heliostat field is used for higher efficiency.
7. During normal operation, the heliostats are in sun-tracking mode.
8. Active reflected beam sensors are used to control the drive motors. Preprogrammed computer control can also be used.

8.12.1 Heliostat Losses

There are additional energy losses between the incident energy or the heliostat field and the receiver.

1. *Shadowing*: This is caused by one heliostat causing a shadow on the reflective surface of another at a certain time of the day.
2. *Cosine loss*: In order to adjust the angle of beam reflected to the receiver, the heliostat may not be perpendicular to the sun rays. The area of the solar flux intercepted by the heliostat is cosine of the angle between the surface and perpendicular to the beam.
3. *Blocking*: Reflected light from one heliostat may be partly blocked by back side of the other.
4. *Reflective loss*: Some radiation may be absorbed by the glass and silvering, and some may be scattered due to dirt on the mirror surface.
5. *Attenuation*: Absorption and scattering by water vapor, haze, fog, smoke, and particulates in the atmosphere between heliostat and receiver.

8.12.2 Receiver

1. Central receivers sit atop tall towers and receive radiation energy flux from 300 to 700 kW/m^2.
2. The receiver should intercept, absorb, and transport this energy to a heat-transfer fluid.
3. The panels of parallel tubes with headers at each end absorb the solar energy on their outside surface and conduct it to heat transfer fluid inside. The panels are supported at the top to allow thermal expansion downward.
4. The coolant tubes are 20 to 56 mm diameter and 1.2 to 6.4 mm thickness.

Receiver losses: The efficiency of a receiver is reduced due to following losses:

1. *Spillage*: The reflected rays may miss the receiver due to heliostat tracking errors, wind effects, steering back losses, and so on. These losses are less than 5% in a well-designed system.
2. *Reflection*: The energy scattered back from the receiver heat transfer surface can be minimized by painting these surfaces with high-absorptivity paint. These losses are less than 5% in a well-designed system.

3. *Convection*: There is a loss by wind convection from the hot surface of the receiver.
4. *Radiation*: There are radiation losses from the hot receiver surface to the environment. The convection and radiation losses can be 5% to 15%.
5. *Conduction*: About 1% energy is lost due to conduction of heat to structural members, insulation, and so on.

8.12.3 Heat Transport System

The heat transport system is composed of primary coolant piping, pumps, and so on. The primary coolant may or may not be same as power plant working fluid.

1. *Water-Steam*: Steam may be generated at 70 to 140 bar and 540 to 600°C as in a once-through boiler or drum-type boiler. It is an extension of conventional technology to solar system.
2. *Liquid Metal*: Liquid metals have low vapoor pressures and hence, low-operating pressure. Sodium may be used as single-phase coolant up to 540°C as used in a fast-breeder nuclear reactor.
3. *Molten Salts*: Molten salts also have low vapor pressures, high volumetric heat capacities, and high freezing temperatures. Nitrate salt mixtures can be used for solar central receiver systems.
4. *Gases*: Air and helium can be used up to 840°C. These can be used to generate steam for a Rankine cycle or may be used directly in a Brayton-cycle power plant gas turbine of open type (with air) or in a closed cycle (with helium) or a combined cycle.
5. *Heat Transfer Oil*: Low corrosive properties and low vapor pressures of some oils can be used as the primary coolant of raising steam in a boiler. However, the danger of decomposition of oil and fouling of piping can cause operational problems.

8.13 THERMAL ENERGY STORAGE

In order to take care of intermittency of solar energy availability and to fill up the gap between power demand and supply of a power plant, there is a need for an energy storage system. There are basically two types of energy storage systems:

1. Electrical storage-like batteries, super conducting coils, pumped hydro, compressed air, flywheel, and so on.
2. Thermal storage including sensible heat, latent heat, and chemical reaction.

Various energy storage systems are classified in Figure 8.20. At present, a thermal single-phase energy storage system is cost-effective due to the location of most solar power plants.

There are two types of thermal storage systems suitable with solar systems:

1. Single-tank or thermocline storage system
2. Dual-tank or hot-cold storage system.

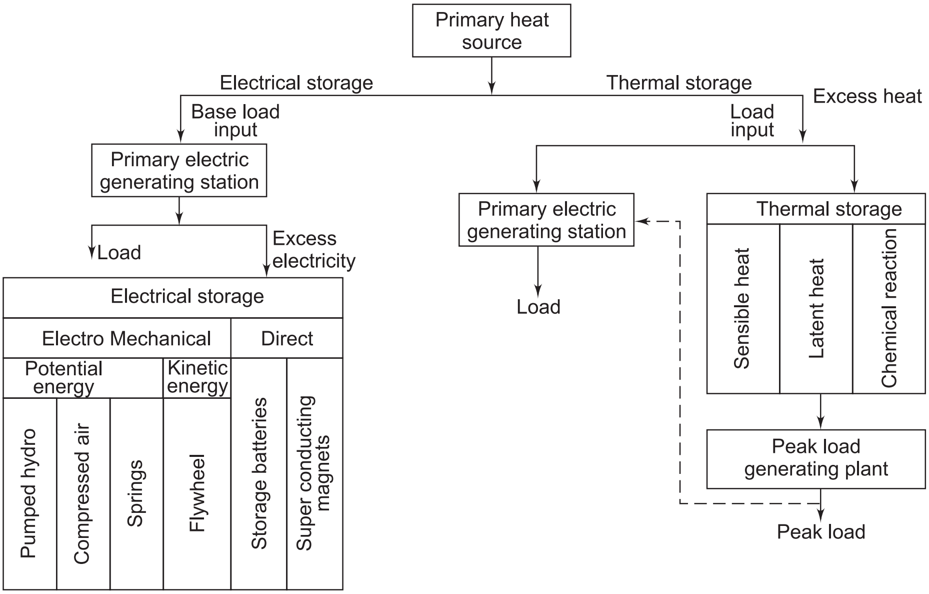


FIGURE 8.20 Energy storage systems.

8.13.1 Thermocline Storage System

The hot primary coolant is passed through a packed bed consisting of rocks and oil. The packed bed is heated and cooled. Coolant is returned to the solar collector for reheating. During times of need, the direction of fluid flow is reversed. The primary coolant is admitted at the bottom of the storage tank which gets heated by extracted heat from the packed bed and hot fluid goes to the power plant. The storage utilization factor is 0.8 for liquid-solid systems.

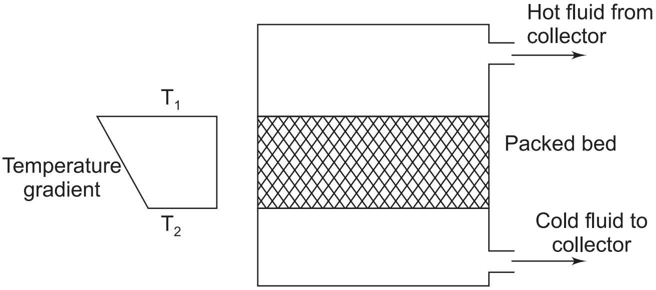


FIGURE 8.21 Thermocline storage system.

8.13.2 Hot-Cold System

The storage system consists of two well-insulated tanks with necessary pumps, valves, and piping. The storage fluid is either sodium molten salt or oil. The tanks are made of austenitic stainless steel. During storage of extra energy, cold liquid is pumped out of the cold tank, heated in the receiver, and returned to the hot tank. During extraction of energy, the hot liquid is drawn from the hot tank, used in raising steam in the steam generator, and returned to cold tank. The amount of sensible energy stored varies by changing the liquid levels in the tanks.

The thermal energy storage capacity (density) depends upon the storage media. Some typical values of energy storage density for an operating temperature range of 550°C to 565°C are given below:

Sodium : 0.08 MWh/m^3
Molten salt (Nitrate) : 0.22 MWh/m^3
Rock (25% void factor) : 0.15 MWh/m^3.

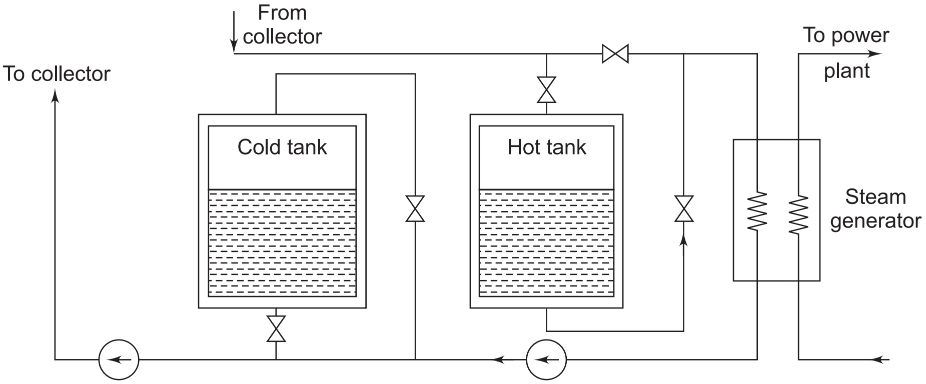


FIGURE 8.22 Hot-cold thermal storage system.

The storage utilization factor is the fraction of stored energy that can be extracted within maximum and minimum temperature limits of storage media. This value is in excess of 0.98. The storage sizing can be made to supply enough thermal energy together with direct thermal power from receiver to operate the power plant continuously 24 hours per day. Sizing depends upon many conflicting factors:

- Variations in daily and seasonal load demands
- Cloud conditions
- Availability of back-up power
- Cost

The cost of storage capacity will include cost of additional heliostats and large receivers to fill the storage system.

8.14 LIMITATION OF SOLAR ENERGY

Immense solar energy is available free of cost. Its potential is huge. But the nature of solar energy has certain limitations that affect the engineering design of the equipment and system and reduce cost effectiveness.

1. *Low Flux Density*: Large surfaces are needed to collect solar energy of low flux density for large-scale utilization resulting in increased cost of delivered energy. When the sun is directly overhead on a cloudless day, 10 m^2 of surface could theoretically provide energy at 10% efficiency of collection at the rate of 1 kW. Most of the human-made solar collectors can convert only direct

energy efficiently and the position of the sun, thick clouds, and anthropogenic pollution let less energy pass and scatter the energy back into space and the percentage of diffuse energy increases.

2. *Intermittency of Solar Energy*: Solar energy has a regular daily cycle due to the turning of the earth around its axis, a regular annual cycle due to inclination of the earth axis with the plane of the ellipse and due to the motion of the earth around the sun, and is also unavailable during periods of bad weather. The diffuse and cyclic nature of the source introduce special problems in storage and distribution of the energy, restrict the areas of application, and need supplementation from other sources.

3. *Global Distribution of Solar Energy*: The global distribution of solar energy does not favor the industrial parts of the world but may be of help to industrially developing countries located in the favorable radiation belt. The greatest amount of energy is available in the continent desert areas around 25°N and 25°S of the equator and falls off toward both the equator and the poles. Mostly, these are flat deserts that are practically unusable for agriculture or any type of industrial development. These regions have little or no water which can create special problems in the generation of thermal electric power.

4. *Cost Effectiveness*: Although solar energy is essentially free, there is a definite cost effectiveness associated with the utilization whereas for conventional energy sources, the processing cost has traditionally been borne by large industries which borrow money from a bank and then charge the consumer for each unit of energy used. Solar energy installations, especially for low-temperature applications in home heating and cooling are the total responsibility of the user. As a result of this shift in the economic risk, a solar energy installation appears to the users as a huge additional investment that they personally must make in advance before deriving any benefit from it. Solar energy must be viewed as a long-term investment, and its cost must be prorated just like the cost of fossil fuels. Acceptance of this view is necessary to assess the cost effectiveness of solar energy. Also government incentives could help with the technology penetration.

5. *Energy Intensive*: Much of the construction materials used for collecting and converting solar radiation are themselves very energy intensive. For example, large quantities of aluminium, steel, copper, concrete, glass, and plastics are needed, all of which require large quantities of energy for conversion from ore to finished products and in constructing the systems is a large fraction of the net energy generated during the life of the plant. This

fraction is in most cases bordering on the unacceptable limits, except in special cases where solar energy is uniquely suited.

6. *Environmental Pollution*: Solar energy systems are relatively emission free during operation. However, extracting raw materials, manufacturing, maintenance, and recycling of system components are major emission contributors. The mining of large quantities of mineral ores, the processing of these ores into the finished material, the manufacturing of equipment, and construction of the plants are the processes that generate their own pollution, as well as health and occupational safety risks. In addition, the low efficiency of these plants results in large heat rejection, hence producing thermal pollution.

EXERCISES

1. Prove that direct solar energy can meet the needs of the entire population of the world.
2. What is a solar constant? What is the difference between extra-terrestrial and terrestrial solar radiation? Give reasons for the difference.
3. How can the amount of solar radiations falling on a tilted flat surface be estimated?
4. Describe the construction of different types of solar collectors. Discuss the various materials used.
5. How is performance of a flat plate solar collector evaluated?
6. Compare the performance of various types of solar collectors. How is focusing accomplished in paraboloid disk collector?
7. Describe a solar water-heating plant.
8. What are various types of solar thermal power plants? Discuss in detail.
9. Describe the construction and performance of a solar-tower power plant.
10. Write notes on:
    (*a*) Sterling engine system
    (*b*) Solar chimney system
11. Describe the principle and application of solar ponds.
12. Give a detailed classification of energy storage systems. Describe thermocline and hot-cold thermal storage systems.

13. Describe the application of solar energy for the following rural applications:
(*a*) Solar cooking
(*b*) Solar refrigeration
(*c*) Solar water pumping

14. What are the main limitations of solar thermal energy? How do these limitations affect its widespread utilization?

15. Define various solar angles and their effects on the collection of solar radiations on a tilted flat surface.

16. How is the optical efficiency of a solar collector estimated?

APPENDIX I

SOLAR THERMAL POWER STATIONS

(*a*) Operational

No.	Name of country	Total Installed Capacity (MW)	Largest Plant Capacity (MW)	Type of Technology	Remarks
1.	United States	506	354	Parabolic Trough	
2.	Spain	1954.8	150	Parabolic Trough	
3.	UAE	100	100	Parabolic Trough	
4.	Algeria	25	25	ISCC	
5.	Egypt	20	20	ISCC	
6.	Morocco	20	20	ISCC	
7.	Iran	17.25	17	ISCC	
8.	Italy	5	5	Parabolic Trough	
9.	Thailand	5	5	Parabolic Trough	
10.	Australia	9	9	Fresnel Reflector	
11.	India	2.5	2.5	Solar Power Tower	
12.	Germany	1.5	1.5	Solar Power Tower	
13.	China	2.5	1.5	Solar Power Tower	
14.	France	0.25	0.25	Fresnel Reflector	
Total operational capacity = 2668.6 MW					

(*b*) Under Construction

No.	Name of Country	Total Installed Capacity (MW)	Largest Plant Capacity (MW)	Type of Technology	Remark
1.	United States	1290	370	Solar Power Tower	
2.	Morocco	160	160	Parabolic Trough	
3.	Israel	121	121	Parabolic Trough	
4.	Spain	500	100	Parabolic Trough	
5.	India	100	50	Parabolic Trough	
6.	China	128.5	50	Solar Power Tower	
7.	South Africa	150	100	Solar Power Tower	
8.	France	1.4	12	Fresnel Reflectors	
Total = 2450.9					

(*c*) Plants Announced

No.	Name of Country	Total Installed capacity (MW)	Largest Plant Capacity (MW)	Type of Technology	Remarks
1.	United States	4508	500	Parabolic Trough	
2.	Spain	1080	200	Parabolic Trough	
3.	China	2000	2000	Solar Power Tower	
4.	Morocco		1840	Unknown	
5.	Israel	192	120	Parabolic Trough	
6.	Chile	100	100	Unknown	
7.	Iran	72	72	Parabolic Disk	
8.	South Africa	50	50	Parabolic Trough	
9.	Italy	30	30	Parabolic Trough	
10.	Mexico	14	14	ISCC	
Total = 8046					

CHAPTER 9

NUCLEAR FUSION ENERGY

9.1 INTRODUCTION

Of all the currently known available sources, only nuclear and solar energy have the potential of supplying large amounts of power within the available time frame. These two sources can complement each other to meet the demand economically and safely. However, considerable technical and economic problems must be solved before large-scale utilization of these sources can become possible.

Energy is produced in the sun and stars by continuous fusion reactions. Fusion of light nuclei to form a heavy nucleus releases large amounts of energy by converting the mass balance (heavy nucleus is lighter than sum of masses of light nuclei) to energy ($E = mc^2$). If the controlled fusion of light elements is carried out on our planet, enough energy can be generated to meet all the energy requirements of future generations.

The primary common fuels for fusion are isotopes of hydrogen (^{1}H); deuterium (^{2}H or D), and tritium (^{3}H or T). A hydrogen atom nucleus has one proton, whereas that of deuterium has one proton and one neutron, and the nucleus of tritium has one proton and two neutrons. Deuterium is naturally available in seawater, but tritium is unstable (has a half-life of more than 12 years). There is one atom of deuterium for about every 6500 atoms of ordinary hydrogen in sea water. The total energy content of deuterium as fossil fuel is about 100 MWh of energy per gram of deuterium. This is about 10 million times more than released per gram in the combustion of fossil fuels. The entire amount of world energy consumption of 6×10^{13} kWh per year could be supplied by the fusion of only 600 metric tons of deuterium.

The amount of deuterium in the world oceans would be enough to sustain the present total world energy requirement for 100 million years. Nuclear fusion would indeed present an ultimate solution of humankind's energy needs for all the years to come.

A nuclear fusion reaction can occur when two atomic nuclei (D and T) approach very close to each other at velocities at least large enough to overcome their mutual electrolytic repulsion called *Coulomb barrier*, which is inversely proportional to particles electric charges through Coulomb's constant. In order to achieve the high speed for the nuclei, fusion reaction must occur at very high temperature, about 150-200 million degrees Celsius. To do this, a plasma, a fourth state of matter like an ionized gas should be created inside a nuclear fusion reactor in an extremely controlled environment. Controlling and maintaining a plasma for any practical length of time is the main hurdle of fusion technology along the path to perfecting nuclear fusion. Therefore, there is problem of confinement of fusion. There are other essential difficulties (like superconducting magnets, advanced vacuum systems, and thermal and radioactive insulations) lying to be overcome before this future energy source can be put into use. The performance of a nuclear fusion power plant is measured by the ratio of power (or energy) produced to the power used (mainly to maintain the gas/plasma in steady state), the so-called *fusion energy gain factor* or *Q-value*. A Q-value of 1 would indicate a balance of energy, at ideal condition. Usually a Q-value of minimum 5 is considered engineering or practical value.

Fusion research is indeed being taken seriously by the major industrial nations. There are serious efforts by individual countries as well as combined effort by consortium of countries. It is almost certain that large practical fusion power plants will be built in the twenty-first century. Once this technology is developed, an almost unlimited supply of energy will be available for the world's needs ushering in a better living standard for the humankind all over the world. Examples of these projects and efforts are; JET (Joint European Torus, 16.1 MW, Q = 0.67, 1984), ITER (The International Thermonuclear Experimental Reactor, "The Way" in Latin, 500 MW, Q = 10, by 2025), proposed commercial power plat EU-DEMO (500 MW, Q = 30-50, by 2031). An introduction to this technology is summarized in a YouTube™ video (*https://www.youtube.com/watch?v=mZsaaturR6E*).

9.2 PRINCIPLE OF FUSION PROCESS

Energy is produced in the sun and stars by the following continuous fusion reactions:

$$4\,{}_{1}\mathrm{H}' \rightarrow {}_{2}\mathrm{H}_{e}^{4} + 2\mathrm{e}^{\circ}{}_{+1}$$

Four nuclei of hydrogen fuse in a series of reactions to yield one nucleus of helium and positrons. There is a decrease of 0.7% in the mass of four hydrogen nuclei or about $0.007 \times 4 = 0.028$ amu, or atomic mass unit. One amu is defined as 1/12 the mass of an atom of carbon 12, or about 1.66×10^{-27} kg. The energy corresponding to the change in mass is calculated from Einstein's Equation.

$$\Delta E = \Delta m C^2, \text{ [J]}$$

where Δm = Change in mass, [kg]

C = Velocity of light

$= 3 \times 10^8$ m/s

$$\Delta E = 9 \times 10^{16}\ \Delta \mathrm{m}$$

$$1\ \text{amu} = 1.66 \times 10^{-27}\ \text{kg}$$

$$\Delta E\ (\text{in } J) = 1.49 \times 10^{-10}\ \Delta \mathrm{m}\ (\text{in amu})$$

or $$\Delta E\ (\text{in MeV}) = 931\ \Delta \mathrm{m}\ (\text{in amu})$$

The energy released per nuclear reaction will be 25.7 MeV. The heat produced in these reactions maintain temperatures of the order of several million degrees in the core of the sun and stars which serves to trigger and sustain succeeding reactions.

9.2.1 Artificial Fusion Reaction

The four-hydrogen reaction shown above requires, on an average, billions of years for completion. On earth, artificial fusion reaction may be accomplished when two light atoms fuse into a larger one as there is much greater probability of two particles colliding than of four. In order to cause artificial fusion reaction, the following problems must be solved:

1. The positively charged nuclei must be accelerated to high kinetic energies in order to overcome the electrical repulsive forces.

2. The temperature must be raised to hundreds of millions of degrees resulting in a plasma.
3. The plasma must be prevented from contacting the walls of the container.
4. The plasma must be confined for a certain period of time (of the order of a seconds) at a minimum density.
5. The fusion heat must be converted to electricity.
6. All operational problems of a fusion power plant must be solved.

9.2.2 Thermonuclear Fusion

There are several possible reactions between the nuclei of light elements that can be the basis for controlled thermonuclear fusion. These reactions along with energy released per reaction are given in Table 9.1.

Table 9.1 Fusion Reactions

No.	Reactants	Products	Energy per reaction, MeV	Energy per gram kWh
1.	D + D	T + P	4.0	22,000
2.	D + D	$He^3 + n$	3.2	27,000
3.	T + D	$He^4 + n$	17.6	94,000
4.	$He^3 + D$	$He^4 + P$	18.3	94,000

The following symbols have been used in the table:

$D = {}_1H^2$ = Deuterium

$T = {}_1H^3$ = Tritium

$n = {}_0n^1$ = Neutron

$p = {}_1p' = {}_1e^\circ$ = Proton

$1\ \text{MeV} = 1.602 \times 10^{-3}$ J.

Reaction number 3 is the most favourable reaction which is self-sustaining at a temperature of 50×10^6 K releasing 17.6 MeV per reaction. The first two $D + D$ reactions occur at 500×10^6 K and release less energy (2.2 MeV and 4.0 MeV) The fourth reaction releases very high energy (18.3 MeV), but requires very high temperatures of 1000×10^6 K for fusion reaction.

The basic raw materials for the $D + T$ reaction is water for deuterium and tritium. Deuterium in the form of heavy water (D_2O) is extracted from water on a large scale at a moderate cost. Tritium does not occur abundantly in nature. It can, however, be produced in a lithium "breeding blanket" that surrounds the plasma core of the fusion reactor. Lithium can be extracted from sea water at low cost.

There are two processes used for plasma confinement:

1. Magnetic confinement
2. Inertia confinement

These processes are described in following sections.

9.3 TOKAMAK FUSION REACTOR

The fusion reactor with magnetic confinement is called Tokamak reactor, which in Russian means toroidal magnetic chamber. A schematic diagram of a Tokamak fusion reactor is shown in Figure 9.1.

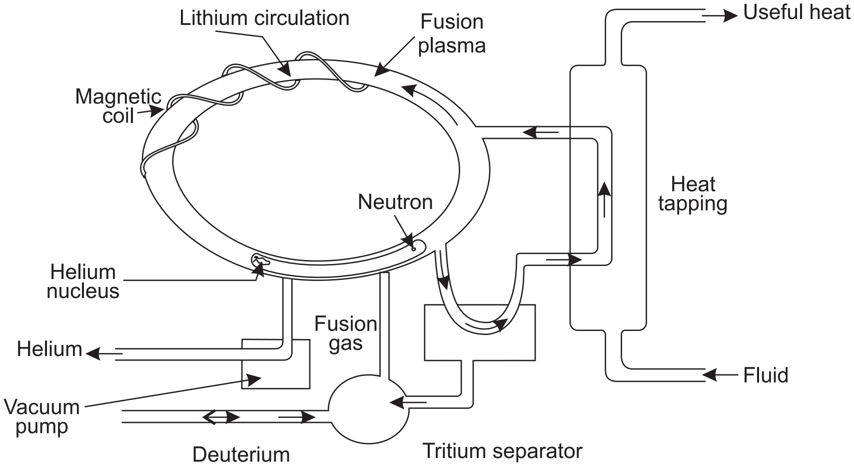


FIGURE 9.1 Tokamak fusion reactor.

The plasma is contained inside an evacuated tube of about 4m. The surrounding vacuum wall through which 14 MeV neutrons from the plasma pass, is maintained at about 750°C. Outside this wall are two concentric regions, *i.e.*, the lithium breeder modulator and magnetic shield. Tritium is manufactured in the lithium blanket. Large cryogenic superconducting magnets of 7 to 8 m in diameter maintain the magnetic field.

The breeding of tritium takes place as follows:

$$^{6}\text{Li} + n \rightarrow \text{He} + \text{T} + 4.78\ \text{MeV}.$$

The heavy helium isotope ^{6}Li acts as breeding material and moderator

The design parameters of a projected fusion reactor are given below:

1. Thermal fusion power = 800 MW
2. Larger plasma radius = 6.3 m
3. Smaller plasma radius = 2.05 m
4. Toroidal field strength on axis = 6 Wb/m^2
5. Plasma current = 25-30 MA
6. Neutron wall loading = 0.7 MW/m^2
7. Triple product $(n\ t\ T) = 7 \times 10^{18}$ Me VS/m^2.

where, T is the plasma temperature of the order of 10^{8} K, t is the confinement time of 0.1s and n is the plasma density of the order of 10^{20} l/m^3. The triple product is the index for positive energy balance on net release of energy. Enough fusion reactions per unit time must occur in the reactor.

9.4 INERTIAL CONFINEMENT REACTOR

Inertia confinement fusion (ICF) is like creating a tiny "star." Take a hollow, spherical plastic capsule, a pellet, about two millimeters in diameter. Fill it with 150 micrograms of a mixture of deuterium and tritium. Take a laser that for about 20 billionths of a second can generate 500 trillion watts and focus all that laser power onto the surface of the pellet for ten billionths of a second.

In this process the pellet and its deuterium–tritium fuel will be compressed to a density 100 times that of solid lead and heated to more than 100 million degrees Celsius—hotter than the center of the sun. These conditions are just those required to initiate thermonuclear fusion, the energy source of stars. By following our recipe, we would make a miniature star that lasts for a tiny fraction of a second. During its very short lifetime, it will produce energy the way the stars and the sun do, by nuclear fusion. The Q-value of the reaction is 10-100.

No magnetic confinement is needed for ICF. Lawrence Livermore National Laboratory in the United States performs research and development in this area.

9.5 FUTURE NUCLEAR FUSION POWER PLANT

The thermal energy generated from fusion reactor can be transferred to traditional power plants. For example, the fusion reactor can be coupled to a triple Rankine cycle using potassium, diphenyl and steam as working fluids. A binary vapor power cycle consisting of a potassium topping cycleand a conventional steam cycle is shown in Figure 9.2. The tritium recovery system is also shown.

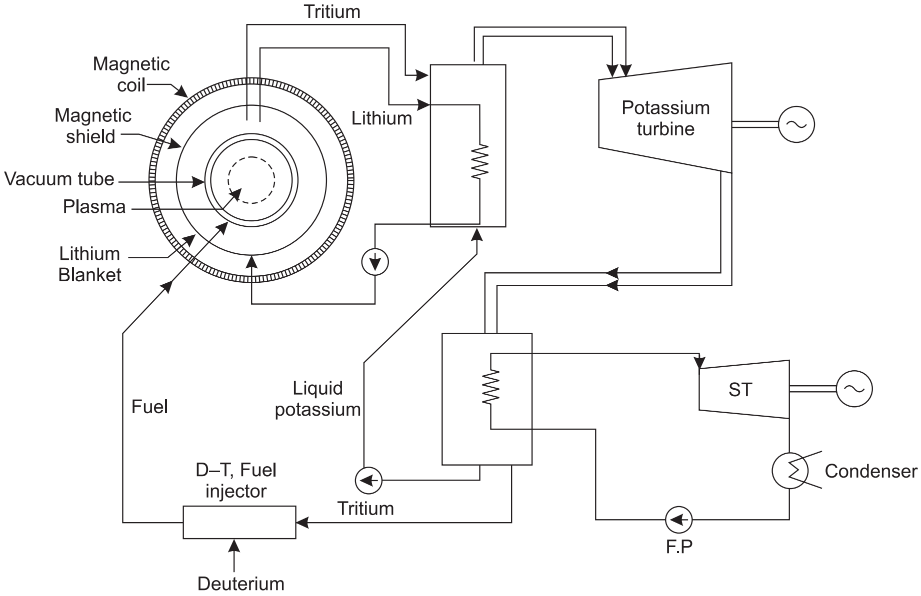


FIGURE 9.2 D-T fusion power plant.

9.6 ADVANTAGES OF FUSION ENERGY

The main attractions of fusion energy, when commercially available, will be as follows:

1. The supply of deuterium is inexhaustible.
2. No radio-active waste is produced.
3. It is very safe to operate, although some radioactive leak exists.
4. High conversion efficiency (60%) can be achieved.
5. Low heat rejection per kW of electricity generated to atmosphere.
6. No enriched materials is employed, hence limited risk of proliferation.
7. No risk of chain reaction or meltdown, plasma cools down within seconds.
8. Energy cost ($/kWh) is comparable to that of nuclear fission technology.

EXERCISES

1. What is fusion reaction? What are the main fusion reactions? Which one is the most favorable reaction and why?
2. Describe Tokamak reactor system for power generation. What are the main design parameters of an experimental fusion reactor?
3. Prove that nuclear fusion energy is the future energy.
4. Describe a D-T fusion reactor power plant with the help of a flow diagram.
5. What are the advantages of nuclear fusion energy? What are the main problems hindering further progress?

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CHAPTER 10

HYDROGEN ENERGY

10.1 INTRODUCTION

Electrical energy is the most convenient form of energy because it can be easily and relatively safely controlled, transported, and converted into heat and work at high efficiencies. The only shortcoming of electrical energy is that the technology to store it in large quantities is not readily available nor economically viable.

One of the options for alternative energy of the future is hydrogen energy, which can also be easily stored in addition to other qualities of electrical energy. But it is highly inflammable and special handling precautions are needed during its production, transportation, storage, and utilization. Hydrogen is a secondary fuel that is produced by utilizing energy from a primary source. Water and solar energy are freely and abundantly available in nature on earth. Hydrogen can be produced from water by using solar energy, through electrolysis process, or through steam processing of natural gas. Hydrogen can be stored as gas underground or in high-pressure cylinders (approximately 35-70 MPa). It can also be stored in liquid form at low temperatures (boiling point approximately −253°C). There are a few metals and alloys which form solid hydrides with hydrogen (such as MgH_2, $NaAlH_4$, $LiAlH_4$, LiH, $LaNi_5H_6$, $TiFeH_2$, and palladium hydride). The hydrogen can be recovered by heating metal hydrides, depending on the bond strength. Thus, metal hydrides provide a possible means for hydrogen storage in solid form. Hydrogen can be similarly transported as gas through pipes or storage cylinders or as liquid hydrogen or as metal hydrides.

Hydrogen has the highest energy content per unit mass, approximately 130 MJ/kg (gasoline 45 MJ/kg). Its combustion process is non-polluting, and it can be used in fuel cells to produce electricity and useful heat. A H_2-O_2 fuel cell liberates energy and water as the sole material product for the use of spacecraft passengers. Hydrogen has been used as fuel for space crafts also, due to its high specific-energy value. It can be used as motor vehicle fuel in urban transportation where air pollution problems are critical.

The simplest practical way to obtain hydrogen from water is its electrolysis using electricity. The latter can be generated from renewable energy sources like solar energy, wind energy, and geothermal energy.

Hydrogen has huge market. However, enormous capital investment is required for its production, distribution, and storage. Special design precautions are needed for the safe operation of equipment and systems. This presents essential obstacles in the quick introduction of hydrogen.

10.2 PRODUCTION OF HYDROGEN

Hydrogen can be produced from fossil fuels, electrolysis of water, and solar energy.

10.2.1 From Fossil Fuels

The conventional hydrogen production processes are shown in Figure 10.1.

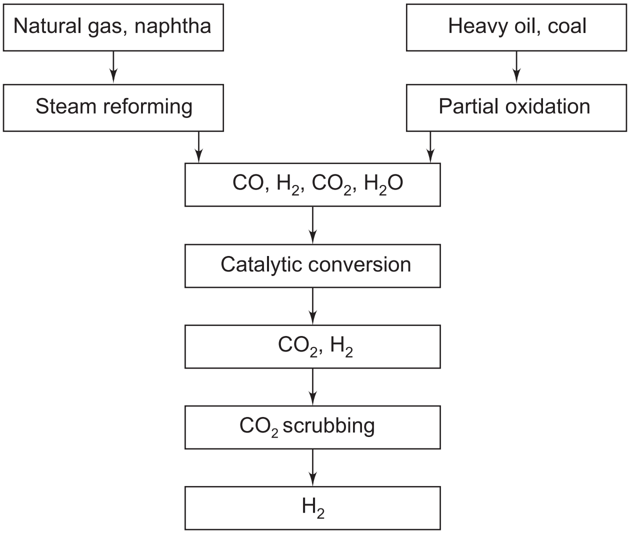

FIGURE 10.1 Flow diagram of hydrogen gas production from fossil fuels.

(*i*) Natural Gas/Naphtha

1. The natural gas or naphtha is reformed with steam at 900°C to produce a mixture of gases by the following reaction:

$$C_mH_n + mH_2O \rightarrow m\,CO + \left(m + \frac{n}{2}\right)H_2$$

The gas produced has the following composition:

No.	Component	Composition in % Age by Volume
1.	H_2	68
2.	CO	10
3.	CH_4	10
4.	CO_2	10
5.	N_2	2

2. The CO present is converted into CO_2 by a two-stage catalytic conversion process:

first stage process at 300 – 500°C

second stage process at 200°C.

$$CO + H_2O(\text{steam}) = CO_2 + H_2$$

3. Methane (CH_4) is converted into CO_2 by the following reactions:

$$CH_4 + H_2O = CO + 3H_2 - 205\ \text{kJ/mol.}$$

$$CH_4 + 2H_2O = CO_2 + 4H_2 - 164\ \text{kJ/mol.}$$

4. Finally, CO_2 is removed by scrubbing process and H_2 is obtained as product gas.

5. The energy content of H_2 product gas is 75–80% of natural gas. The cost of H_2 is comparable with that of electricity on a similar basis.

(*ii*) Coal and Heavy Oil

1. Coal or heavy oil undergo partial oxidation or gasification at 1400°C with oxygen as gasifying medium.

2. The CO present is converted into CO_2 by a two-stage catalytic conversion process.
3. CO_2 is removed by scrubbing and H_2 is obtained as product gas.
4. The energy content of H_2 product gas is 55 to 60% of raw coal. The cost of H_2 product gas is higher than produced from natural gas if lignite or hard coal is used as feedstock.

10.2.2 By Water Electrolysis

The principle of operation of an alkaline water electrolysis cell is shown in Figure 10.2.

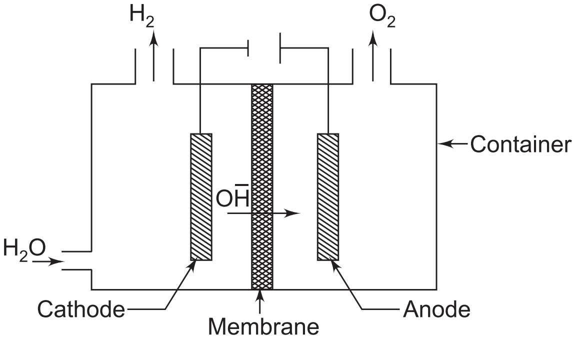

FIGURE 10.2 Alkaline cell water electrolysis.

Hydrogen is produced by electrolytic dissociation of water.

1. Cathode reaction:

$$4H_2O + 4\bar{e} \rightarrow 2H_2 \uparrow + 4O\bar{H}$$

2. Anode reaction:

$$4OH^- \rightarrow O_2 \uparrow + 2H_2O + 4\bar{e}$$

3. Total reaction:

$$2H_2O + \text{Energy} \rightarrow 2H_2 + O_2$$

The energy requirement is 3.5 kWh/m^3 of hydrogen produced.

The following electrolysis processes are available:

1. Alkaline electrolysis
2. Membrane electrolysis
3. High-temperature steam electrolysis

10.2.3 Solar Energy Methods

Hydrogen can be produced using solar radiation by the following processes:

1. Biophotolysis
2. Photoelectrolysis

(*i*) *Biophotolysis*: Hydrogen can be produced by using green algae's ability to generate hydrogen gas from water and sunlight. The green algae are plants and can be harvested quickly and with relatively minimum costs. They should be kept in an anaerobic (oxygen-free) environment free from sulphur.

(*ii*) *Photoelectrolysis*: Hydrogen and oxygen gases are liberated at the cathode and anode respectively by decomposition of water when both the electrodes are subjected to sunlight. It is an attractive method of producing hydrogen as the process is intermittent. There is no need for storage of gas.

10.3 HYDROGEN STORAGE AND DISTRIBUTION

10.3.1 Hydrogen Storage

There are five principle methods that have been considered for storage of hydrogen.

1. *Compressed gas storage*: Hydrogen is conveniently stored for many applications in high-pressure cylinders. The method is rather expensive and bulky.
2. *Liquid storage*: Liquid hydrogen is stored in cryogenic storage in vacuum insulated or super-insulated storage tanks. The liquid hydrogen fuel as rocket propellant in the space programs is stored in large tanks.
3. *Line pack system*: It can vary the pressure in the transmission and distribution system.

4. *Underground storage*: The hydrogen gas can be stored underground in depleted oil and gas fields or in aquifer systems. This is the cheapest way to store large amounts of hydrogen for subsequent distribution.
5. *Metal hydrides*: Hydrogen can be stored as metal hydrides in chemically bound form. A few metals and alloys form solid compounds by direct reaction with hydrogen gas. The metal hydrides can be transported in solid form. When the hydride is heated, hydrogen is released for use.

10.3.2 Hydrogen Transportation

1. *Transmission pipelines*: Long-distance hydrogen-gas transmission pipelines of lengths greater than 90 km must be supplied with booster compressors. Therefore, the cost of transmitting hydrogen by pipelines must include cost of piping, compressors, and power consumption by compressors. Another problem with hydrogen transmission is hydrogen embrittlement of pipeline materials and seals penetration.
2. *Double-walled insulated tanks*: Hydrogen in bulk can be transported and distributed as liquid in double-walled insulated tanks. Distribution of liquid hydrogen by pipelines, jacketed with liquid nitrogen can also be considered.
3. *Solid metal hydride*: Hydrogen can also be transported as a solid metal hydride. The main drawback is the heavy weight of hydride relative to its hydrogen yield.

10.3.3 Safety Precautions

Hydrogen is highly inflammable and explosive and can lead to fire and serious accidents. Hydrogen flame is invisible. The production, storage, and distribution of hydrogen require special precautions as outlined below.

1. The system should be designed to withstand the explosion pressures.
2. The system should be designed to withstand pressure surges.
3. Proper explosion-relief system must be provided.
4. Flame traps, flame suppressors, explosion-relief devices, and rapid-closing devices must be used.

5. The design, manufacture, and storage should follow the Petroleum Act and Conservation Act. The former has gone through variations in different legislatures, it is an act to regulate interests in petroleum in relation to frontier lands, to amend the oil and gas production.

10.4 PROPERTIES OF HYDROGEN

Hydrogen has the following properties that make it an attractive alternative energy source and at the same time more challenging.

1. Hydrogen is a light gas at room temperature and pressure (STP). Its density is 0.08988 g/L, only 1/4th of that of air and 1/9 that of natural gas.
2. Hydrogen can be liquefied at –253°C, at atmospheric pressure. The liquid hydrogen has a specific gravity of 0.07 which is 1/10th that of gasoline.
3. The standard heating value of hydrogen gas is 12.1. MJ/m^3 compared to 38.3 MJ/m^3 of natural gas.
4. The heating value of liquid hydrogen is 120 MJ/ kg or 8400 MJ/m^3 as compared to 44 MJ/kg or 32000 MJ/m^3 of aviation petrol. The specific energy of hydrogen liquid is superior to gasoline on mass basis, but inferior on volume basis.
5. The flame speed of hydrogen when burning in air is much greater than of natural gas. A 50% hydrogen-air flame speed is approximately 150 m/min.
6. The ignition energy of hydrogen to initiate combustion is less than that for natural gas.
7. Detonation can occur between hydrogen-air mixture between 18% and 59%. The internal combustion engines on hydrogen fuel can work from very rich (excess fuel) to very lean (excess air) mixture. The adjustment of air fuel ratio is less critical than for gasoline engine.
8. Mixture of hydrogen and air are compressible over a wide range of composition. The flammability limits are from 4% to 74% by volume of hydrogen in air at ordinary temperatures.
9. The combustion of hydrogen with oxygen from air results in release of energy and water as by-product.
10. The burning process of hydrogen is pollution free, when the oxidant is pure.

10.5 APPLICATIONS OF HYDROGEN ENERGY

The possible areas of use of hydrogen in near future are as follows:

1. *Production of Useful Heat*

(*i*) High-temperature combustion of hydrogen with oxygen or air
(*ii*) Low-temperature flameless catalytic combustion with extremely low NO_x emissions

2. *Power Generation*

(*i*) Direct steam generation in reactors
(*ii*) High temperature and membrane fuel cells

3. *Cogeneration of Heat and Electricity*

(*i*) Combined cycle power plants
(*ii*) Internal combustion engine-based cogeneration plant

4. *Automotive and Aircraft Fuel*

(*i*) Environment friendly fuel for motor vehicles
(*ii*) Aircraft fuel

5. *Energy Storage*

(*i*) Compressed hydrogen storage under high pressure
(*ii*) Metal hydrides

6. *Synthesis of Fuel*

(*i*) Raw material to produce methanol, ammonia, or hydrocarbon using carbon dioxide or nitrogen from air
(*ii*) Raw materials for manufacture of gaseous fuels

10.6 HYDROGEN ENERGY FOR AIR AND SURFACE TRANSPORT

The favorable properties of hydrogen make it a promising fuel for air and surface transport.

10.6.1 Jet Fuel

The high-energy density 33.3 to 39.4 kWh/kg of liquid hydrogen against 12.7 kWh/kg of conventional jet fuel is the main advantage in air transportation where hydrogen energy can be used. Although volume of liquid hydrogen would be greater than regular fuel, but this could be accommodated on a large aircraft. The cold liquid hydrogen can also be used directly or indirectly for cooling engine and airframe surfaces of high-speed aircrafts. Liquid hydrogen may be the only practical fuel for hypersonic aircrafts when developed. Because of smaller total weight, it may be possible to achieve shorter take-off runs, steeper climbing path, smooth engine thrust and less noise production.

The favorable diffusion properties and high thermal conductivity of hydrogen help to use shorter combustion chambers. Wide range of ignition for H_2–O_2 mixtures (5 to 75%) by volume of hydrogen helps better control of engine operation especially under peak load conditions and reductions in NO_x emission.

The heat required to vaporize hydrogen for the engines can be obtained from certain outer-skin of the wings and fuselage. This helps to cool the boundary layer. The laminar boundary layer so developed helps to reduce drag and fuel consumption.

The main problems are economic production of hydrogen, infrastructure for fueling of aircrafts, and setting of bulky hydrogen tanks in the aircraft body.

10.6.2 Road Vehicles

The use of hydrogen fuel in engines of automobiles, buses, trucks, and farm machinery can help conserve petroleum products and reduce atmospheric pollution. A mixture of hydrogen gas and air of constant ratio is introduced into the manifold of the engine. The engine speed and power are controlled by varying the quality of mixture entering the cylinder with the help of a throttle valve. In another design, hydrogen gas under pressure can be directly injected into the engine cylinder through a valve and air is admitted through another intake valve. The spark advance must be retarded because of higher speed of the flame of hydrogen in air. The engine emission will not contain carbon monoxide and hydrocarbon because the only product of combustion is H_2O. In order to control NO_x emission, the cylinder exhaust containing H_2O is injected to reduce combustion temperature.

Storage of hydrogen as compressed gas or metal hydrides for the vehicles is a disadvantage of hydrogen fuel because of lesser energy density per unit volume and the weight of metal hydrides is also excessive.

Alternatively, hydrogen can be used as vehicle fuel in fuel cells. The electricity generated in the fuel cells can be utilized to drive electric motors for propelling the vehicle. Several commercially available vehicles are now accessible, although in limited markets. For example, Toyota™ Mirai, Honda™ Clarity, and the Mercedes-Benz™ F-Cell.

10.7 HYDROGEN ENERGY FOR POWER GENERATION

There is a great potential for use of hydrogen as fuel for power generation, due to mainly reduced emissions.

10.7.1 Central Power Plants

The plants working on natural gas can be changed to hydrogen-fired plants without significant technological changes. These plants may be combined-cycle power plants with gas and steam turbines or cogeneration plants with gas turbines and internal combustion engines. Hydrogen-fired plants compared to gas-fired plants have lower capital cost and higher efficiency.

Hydrogen fuel has higher combustion speed (approximately 3 m/s) and flame temperature as compared to natural gas (approximately 0.3 m/s). Higher combustion speed results in unstable combustion, and higher flame temperature leads to higher NO_x emissions.

10.7.2 Autonomous Power Plants

Hydrogen fueled fuel cells can be used for domestic power generation as well as industrial power generation. Alkaline fuel cells can be used for production of electricity from pure hydrogen and oxygen. Fuel cells with acid electrolytes can be operated with impure hydrogen and hydrocarbon. High-temperature fuel cells with molten carbonate electrolytes operating at 600°C are advanced generation fuel cells for electricity and heat production in cogeneration plants. Another type, is the solid-oxide fuel cell which operates close to 1000°C.

10.8 MISCELLANEOUS APPLICATIONS

1. Hydrogen can be used for domestic cooking replacing liquid propane gas (LPG). The burner design must be changed with bigger holes and an air supply system to take care of greater flame speed and low specific energy per unit volume when hydrogen is used as fuel.
2. Hydrogen can be used in radiant space heating with flameless combustion on a catalytic surface. In this case, combustion temperature is low with negligible NO_x formation.
3. Hydrogen has many advantages over industrial gases for production of heat and other uses in industry, such as metallurgical industry, chemicals, pharmaceuticals, petroleum, food, and electronics.

10.9 ADVANTAGES AND LIMITATIONS OF HYDROGEN ENERGY

10.9.1 Advantages

1. Hydrogen has very attractive properties and can be a future source of energy.
2. It is abundant on earth in compounds.
3. It can be manufactured without harm to the environment.
4. It has good storage properties.
5. It is readily convertible to other forms of energy.
6. It can replace electricity, natural gas, synthetic gas, etc.

10.9.2 Limitations

Following are limitations for the use of hydrogen energy:

1. There is a need for considerable research and development in many areas of hydrogen technology.

2. Production of hydrogen by photosynthesis of water using energy requires research and development work.
3. Similarly, production of hydrogen by blue algae and by certain bacterial species requires further research.
4. The technology of storage of hydrogen through metal hydrides and non-metal hydrides has still to be perfected.
5. The practice of production, storage, and utilization of liquid hydrogen needs further development work.
6. There is a need for development of suitable engines and burners to utilize hydrogen as a fuel.

EXERCISES

1. What are the different methods of hydrogen production? Explain in brief.

2. Discuss the main problems and technologies available for storage and distribution of hydrogen.

3. What are the properties of hydrogen as fuel? Write briefly about the utilization of hydrogen energy.

4. Discuss briefly the role of hydrogen fuel for the following:
   (*a*) Power generation
   (*b*) Air and surface transport

5. What are the areas where research and development efforts are needed to make sure that hydrogen becomes a future source of energy?

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