be required.

10.4. SOLAR POWER PLANTS

10.4.1. Solar Energy—General Terms and Introduction

General Terms

Solar Constant. Solar constant is the energy from the sun, per unit time, received on a unit area of surface perpendicular to the radiation, in space, at the earth's mean distance from the sun. According to Thekaekara and Drummond (1971) the value of the solar constant is 1353 W/m^2 (1.940 Cal/cm^2 min, or 4871 kJ/m^2 hr.).

Beam Radiation. The solar radiation received from the sun without change of direction is called beam radiation.

Diffuse Radiation. It is the solar radiation received from the sun after its direction has been changed by reflection and scattering by the atmosphere.

Air Mass. It is the path length of radiation through the atmosphere, considering the vertical path at sea level as unity.

Zenith Angle. It is the angle between the beam from the sun and the vertical.

Solar Altitude. It is the angle between the beam from the sun and horizontal *i.e.*, (90-zenith angle).

Solar or Short-wave Radiation. It is the radiation originating from the sun, at a source temperature of about 6000°K and in the wavelength range of 0.3 to 3.0 μm.

Long-wave Radiation. Radiation originating from sources at temperatures near ordinary ambient temperatures and thus substantially all at wavelength greater than 3 μm.

Declination. It is the angular position of the sun at solar noon with respect to the plane of the equator (north positive).

Solar Energy—Introduction

The surface of the earth receives from the sun about 10^{14} kW of solar energy which is approximately five order of magnitude greater than currently being consumed from all resources. It is evident that sun will last for 10^{11} years. Even though the sun light is filtered by the atmosphere one square metre of the land exposed to direct sun light-receives the energy equivalent of about 1 H.P or 1 kW. However, this vast amount of solar energy reaching earth is not easily convertible and certainly is not "free".

There are two obvious obstacles to harnessing solar energy. *Firstly* it is not constantly available on earth. Thus some form of storage is needed to sustain a solar power system through the night and during periods when local weather conditions obscure the sun. *Second* the solar energy is diffused. Although the total amount of energy is enormous, the collection and conservation of solar energy into useful forms must be carried out over a large area which entails a large capital investment for the conversion apparatus.

Solar energy, therefore, most likely will be developed not because it is cheaper than alternative energy sources but because these alternative sources sooner or later (*i*) will be exhausted, (*ii*) will become increasingly more expensive, (*iii*) will continue to political and economical control by the nations possessing them and (*iv*) will produce undesirable yet incompletely understood environmental consequences, especially on large scale that will be required to meet projected demands even with controlled growth.

Solar energy has some good advantages in comparison to the other sources of power. Solar radiation does not contaminate environment or endanger ecological balance. It avoids major problems like exploration, extraction and transportation.

10.4.2. Collectors in Various Ranges and Applications

Following list gives the thermal applications of solar energy and possible temperature ranges :

1. **Long temperature**
(t = 100°C)
(*i*) Water heating
(*ii*) Space heating
(*iii*) Space cooling
(*iv*) Drying
... Flat plate

2. **Medium temperature**
(100 to 200°C)
(*i*) Vapour engines and turbines
(*ii*) Process heating
(*iii*) Refrigeration
(*iv*) Cooking
... Cylindrical Parabola

3. **High temperature**
(> 200°C)
(*i*) Steam engines and turbines
(*ii*) Stirling engine
(*iii*) Thermo-electric generator
... Parabolloid Mirror arrays

The above classification of low, medium and high temperature ranges is some what arbitrary. Heating water for domestic applications, space heating and cooling and drying of agricultural products (and industrial products) is generally at temperature below 100°C, achieved using flat plate collectors with one or two glass plate covers. Refrigeration for preservation of food products, heating for certain industrial processes, and operation of engines and turbines using low boiling organic vapours is possible at some what higher temperature of 100 to 200°C and may be achieved using focusing collectors with cylindrical-parabola reflectors requiring only one directional diurnal tracking. Conventional steam engines and turbines, stirling hot air engines, and thermoelectric generators require the solar collectors to operate at high temperatures. Solar collectors operating at temperature above 200°C generally consist of parabolloid reflector as an array of mirrors reflecting to a central target, and requiring two directional diurnal tracking.

The concentrators or focusing type collectors can give high temperatures than flat plate collectors, but they entail the following shortcomings/limitations.

1. Non-availability and high cost of materials required. These materials must be easily shapeable, yet have a long life ; they must be light weight and capable of retaining their brightness in tropical weather. Anodised aluminium and stainless steel are two such materials but they are expensive and not readily available in sufficient quantities.

2. They require direct light and are not operative when the sun is even partly covered with clouds.

3. They need tracking systems and reflecting surfaces undergo deterioration with the passage of time.

4. These devices are also subject to similar vibration and movement problems as radar antenna dishes.

Comparison between Flat plate and Focusing collectors :

1. The absorber area of a concentrator system is smaller than that of a flat-plate system of the same solar energy collection area and the *insolation intensity is therefore greater.*

2. Because the area from which heat is lost to the surroundings per unit of the solar energy collecting area is less than that for a flat plate collector and because the insolation on the absorber is more concentrated, the working fluid can attain higher temperatures in a concentrating system than in a flat-plate collector of the same solar energy collecting surface.

3. Owing to the small area of absorber per unit of solar energy collecting area, selective surface treatment and/or vacuum insulation to reduce heat losses and *improve collector efficiency are economically feasible.*

4. Since higher temperatures can be achieved, the focusing collector *can be used for power generation*.

5. *Little or no anti-freeze is required* to protect the absorber in a concentrator system whereas the entire solar energy collection surface requires anti-freeze protection in a flat-plate collector.

6. Out of the beam and diffuse solar radiation components, only beam component is collected in case of focusing collectors because diffuse component cannot be reflected and is thus lost.

7. *Costly orienting systems* have to be used to track the sun.

8. Non-uniform flux on the absorber whereas flux in flat-plate collectors is uniform.

10.4.3. Flat Plate Collectors

10.4.3.1. Description

Fig. 10.14 shows a Flat Plate Collector which consists of four essential components :

1. **An absorber plate.** It intercepts and absorbs solar radiation. This plate is usually metallic (Copper, aluminium or steel), although plastics have been used in some low temperature applications. In most cases it is coated with a material to enhance the absorption of solar radiation. The coating may also be tailored to minimise the amount of infrared radiation emitted.

A heat transport fluid (usually air or water) is used to extract the energy collected and passes over, under or through passages which form an integral part of the plate.

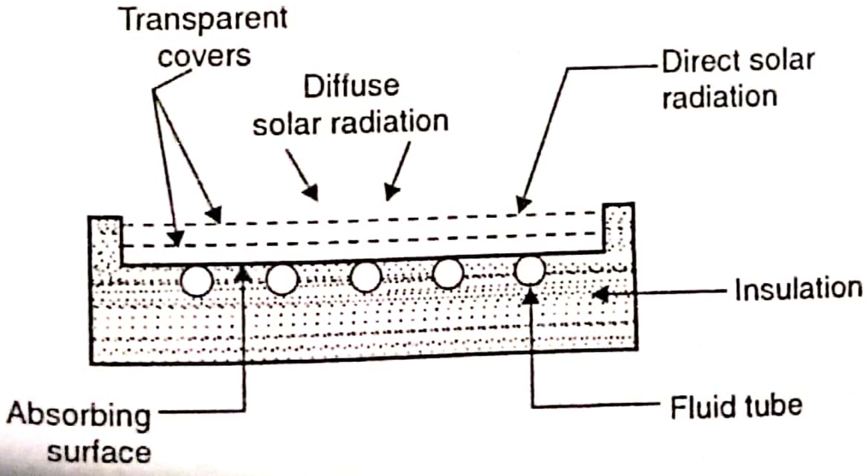

Fig. 10.14. Flat plate solar collector.

2. **Transparent covers.** These are one or more sheets of solar radiation transmitting materials and are placed above the absorber plate. They allow solar energy to reach the absorber plate while reducing convection, conduction and re-radiation heat losses.

3. **Insulation beneath the absorber plate.** It minimises and protects the absorbing surface from heat losses.

4. **Box like structure.** It contains the above components and keeps them in position.

Various types of flat plate collectors have been designed and studied. These include tube in plate, corrugated type, spiral wound type etc. Other criteria is single exposure, double exposure or exposure and reflector type. The collector utilizes sheets of any of the highly conducting material *viz.* copper, aluminium, or galvanized iron. The sheets are painted dead black for increasing the absorbtivity. The sheets are provided with one or more glass or plastic covers with air gap in between to reduce the heat transfer losses. The sides which are not exposed to solar radiation are well insulated. The whole assembly is fixed in air tight wooden box which is mounted on simple device to give the desired angle of inclination. The dimensions of collectors should be such as to make their handling easy. The collector will absorb the sun energy (direct as well as diffused) and transfer it to the fluid (air, water or oil) flowing within the collector. Basically, a flat plate collector is *effective* most of time, *reliable* for good many years and also *inexpensive.*

Use of flat mirrors in the flat plate collectors improves the output, permitting higher temperatures of operation. Side mirrors are used either at north and south edges or at east and west edges of the collector or a combination of both. The mirrors may be of reversible or non-reversible type.

10.4.3.2. Analysis

Consider an object exposed to sun radiations of intensity P, per unit area at the surface of the body. These radiations, will partly be absorbed by the body, while the remaining will be partly transmitted and rest reflected. If we take the incident radiations equal to unity, then, the absorbed, reflected, and transmitted parts of energy will add up to unity. There parts are called *absorption* co-efficient, *reflection* co-efficient and *transmission* co-efficient and represented by the symbols α, ρ and τ respectively.

Using the above symbols we can write

$$\alpha + \rho + \tau = 1 \qquad \text{...}(i)$$

The absorbed part of the solar radiations, which is equal to α is responsible for increasing the temperature of the body. However, the body also loses energy by conduction, convection and radiation. The equilibrium temperature of the body will be that at which the heat loses from the body are equal to the absorbed radiations. For analysis purposes, if we represent the body by a flat plate and assume that the convection and conduction loses are negligible to begin with, then at equilibrium temperature, the absorbed solar radiations should be equal to the radiation losses from the flat plate. The radiation losses are equal to $\varepsilon\sigma T^4$, where ε and T are the emission co-efficient and absolute temperature respectively of flat plate and σ is the Boltzman's constant.

Therefore, at equilibrium,

$$\alpha P = \varepsilon\sigma T^4 \qquad \text{...}(ii)$$

or

$$\frac{\alpha P}{\varepsilon} = \sigma T^4 \qquad \text{...}(iii)$$

From equation (*iii*), it is evident that comparatively higher equilibrium temperature will be obtained where the quantity $\frac{\alpha}{\varepsilon}$ *i.e.*, the ratio of absorption co-efficient to emission co-efficient of the flat plate is more. However, this has been demonstrated by an equation obtained under idealised condition. In the realistic conditions too, its nature will remain the same, but it will get modified by other influencing factors.

The collectors for which ratio is equal to unity are called **'Neutral collectors'** and those for which the ratio is greater than unity are called **'Selective collectors'.**

The amount of energy collected, however, does not depend on $\frac{\alpha}{\varepsilon}$ ratio. It primarily depends on higher value of α. So to obtain higher energy collection, one should use such flat plate where absorption co-efficient is as high as possible.

A flat plate painted black is placed on a well insulated base. If it is exposed to solar radiations where $P = 800$ W/m^2, a typical summer value for a tropical region, we obtain from equation (*iii*) the equilibrium temperature as 70°C. Inspite of the simplifications here, it is a fair estimate of the temperature reached by a black plate left for a time in the tropical sun.

This method can be refined by including the convection losses and the energy gain as a result of absorption of diffused radiations by the flat plate.

If P' is the intensity of the diffused radiations and α' the absorption co-efficient, then equation (*ii*) becomes

$$\alpha P + \alpha' P' = h_c(T - T_a) + \varepsilon\sigma T^4 \qquad ...(iv)$$

This is valid, where the base is insulated, hence conduction losses are neglected. Here T_a is the atmospheric temperature and h_c is the convection heat transfer co-efficient.

10.4.4. Focusing (or Concentrating) Collectors

The main types of focusing or concentrating collectors are as follows :

1. Parabolic trough collector
2. Mirror strip collector
3. Fresnel less collector
4. Flat plate collector with adjustable mirrors
5. Compound parabolic concentrator.

Fig. 10.15 (*a*) shows the principle of the parabolic trough collector which is often used in focusing collectors. Solar radiation coming from the particular direction is collected over the area of

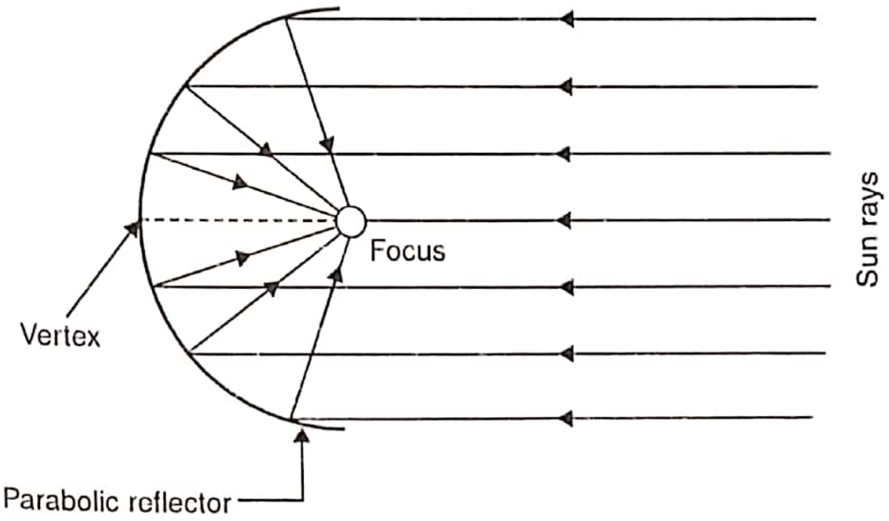

Fig. 10.15. (*a*) Cross-section of parabolic trough collector.

reflecting surface and is concentrated at the focus of the parabola, if the reflector is in the form of a trough with parabolic cross-section, the solar radiation is focused along a line. Mostly *cylindrical parabolic concentrators* are used in which absorber is placed along focus axis [Fig. 10.15. (*b*)].

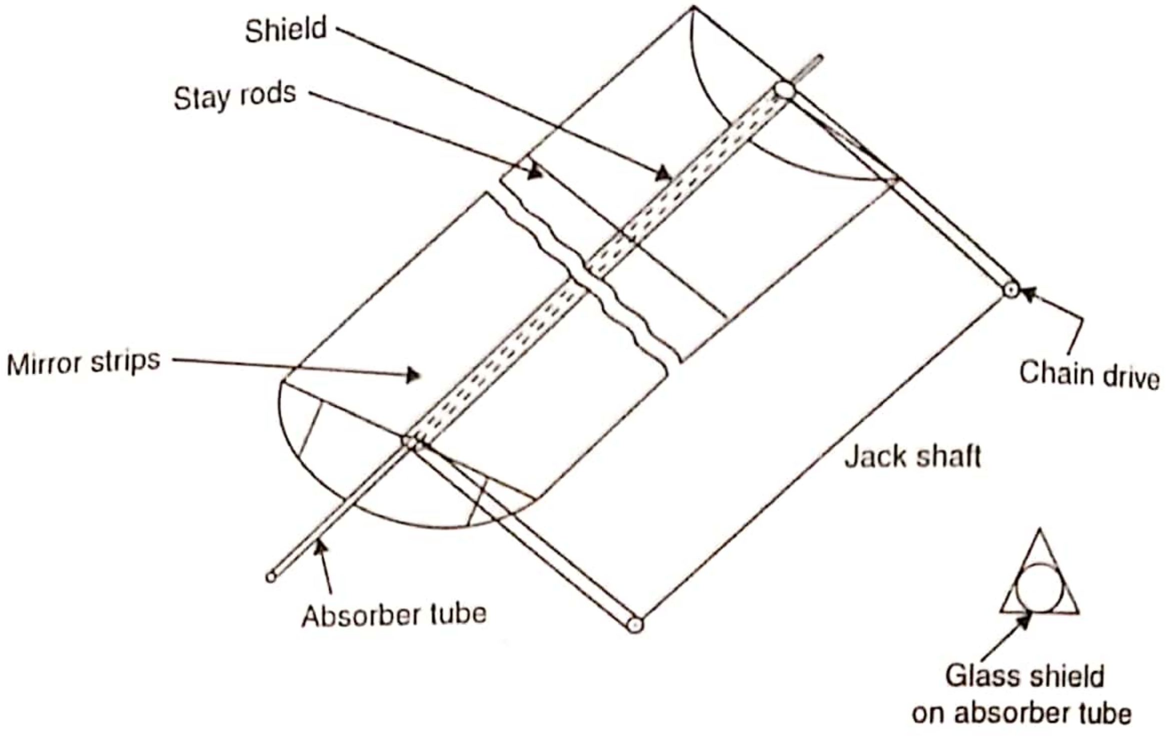

Fig. 10.15. (*b*) Cylindrical parabolic system.

10.4.5. Solar Pond Technology

Refer to Fig. 10.16.

The vertical configuration of salt-gradient solar pond normally consists of following *three zones* :

1. Adjacent the surface there is a *homogeneous convective zone* that serves as a buffer zone between environmental fluctuations at the surface and conductive heat transport from the layer below. This is the *upper convective zone* (UCZ).

2. At the bottom of the pond there is another convective zone, the lower convective zone or LCZ. This is the layer with the *highest salt concentration* and where the high temperatures are built up.

3. For given salinites and temperatures in the upper and lower convective zones, there exists a stable *intermediate gradient zone*. This zone keeps the two convective zones apart and gives the solar pond its unique thermal performance. This intermediate zone provides excellent insulation for the storage layer, while simultaneously transmitting the solar radiation. To maintain a solar pond in this non-equilibrium stationary state, it is necessary to replace the amount of salt that is transported by molecular diffusion from the LCZ to the UCZ. This means that salt must be added to the LCZ, and fresh water to the UCZ whilst-brine is removed. The brine can be recycled, divided into water and salt (by solar distillation) and returned to the pond.

The major heat loss occurs from the surface of the solar pond. This heat loss can be prevented by spreading a plastic grid over the pond's surface to prevent disturbance by the wind. Disturbed water tends to lose heat transfer faster than when calm.

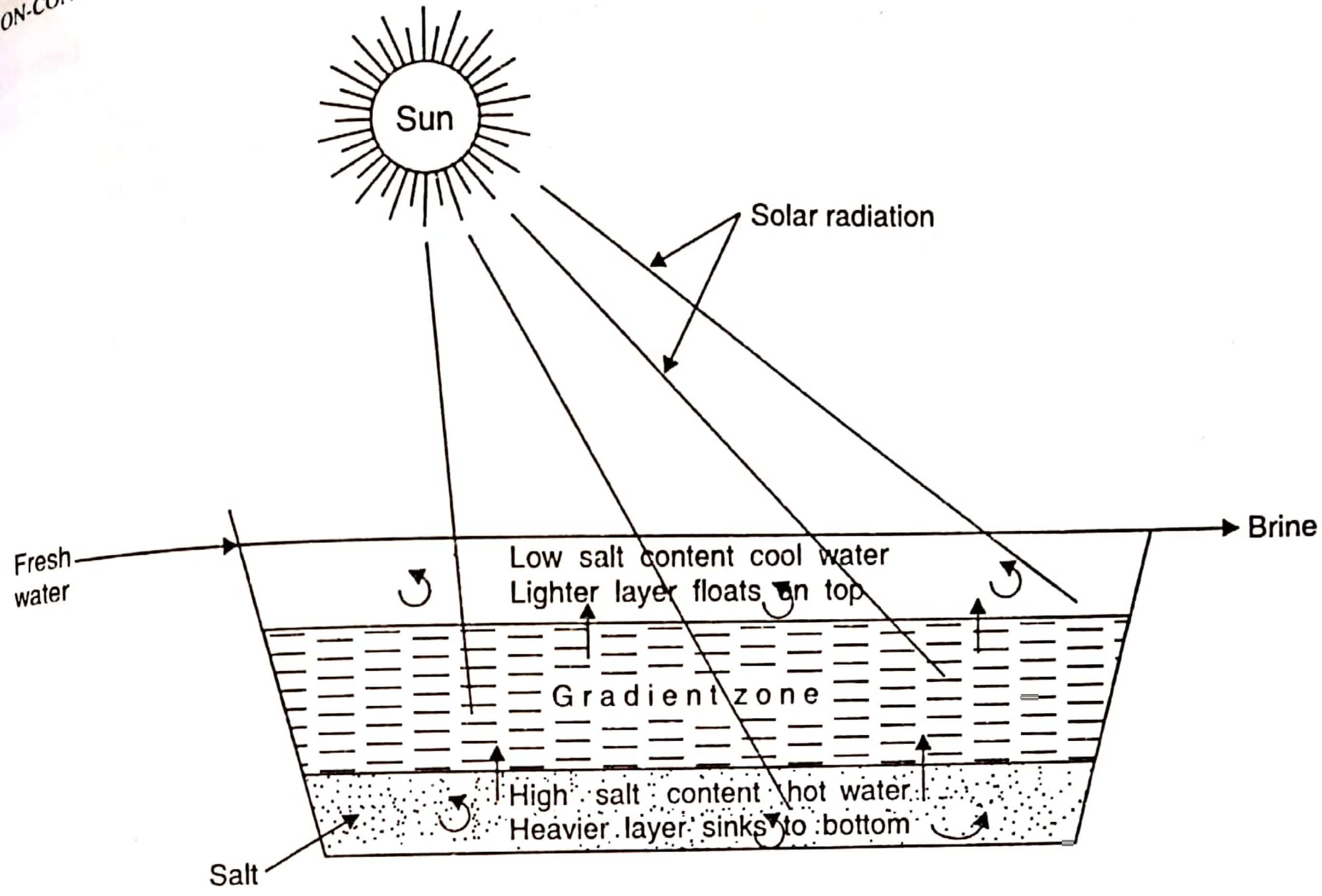

Fig. 10.16. Principle of solar pond.

Due to the excessively high salt concentration of the LCZ, a *plastic liner* or impermeable soil must be used to *prevent infiltration* into the nearby ground water or soil. The liner is a factor that increases the *cost* of a solar pond. A site where the soil is naturally impermeable, such as the base of a natural pond or lake, or can be made impermeable by compaction or other means, will allow considerably lower power costs.

The optical transmission properties and related collection efficiency vary greatly and depend on the following :

(*i*) Salt concentration.

(*ii*) The quantity of suspended dust or other particles.

(*iii*) Surface impurities like leaves or debris, biological material like bacteria and algae.

(*iv*) The type of salt.

It becomes obvious that much higher efficiencies and storage can be achieved *through the utilization of refined or pure salt* whenever possible, as this *maximizes optical transmission*.

The solar pond is an effective collector of diffuse, as well as direct radiation, and will gather useful heat even on cloudy or overcast days. Under ideal conditions, the pond's absorption efficiency can reach 50% of incoming solar radiation, although actual efficiencies average about 20% due to heat losses. Once the lower layer of the pond reaches over 60°C the heat generated can be drawn off through a heat exchanger and used to drive a low temperature organic Rankine cycle (ORC) turbine. This harnesses the pressure differentials created when a low boiling point organic fluid (or gas) is boiled by heat from the pond *via* a heat exchanger and cooled by a condenser to drive a turbine to generate electricity. The conversion efficiency of an organic Rankine cycle turbine driving an electric generator is 5—8% (which mean 1—3% from insolation to electricity output).

10.4.6. Low Temperature Thermal Power Generation

10.4.6.1. Solar pond electric power plant

A low temperature thermal electric power production scheme using solar pond is shown schematically in Fig. 10.17. The energy obtained from a solar pond is used to drive a Rankine cycle heat engine. Hot water from the bottom level of the pond is pumped to the evaporator where the organic working fluid is vapourized. The vapour then flows under high pressure to the turbine where it expands and work thus obtained runs an electric generator producing electricity. The exhaust vapour is then condensed in a condenser and the liquid is pumped back to the evaporator and the cycle is repeated.

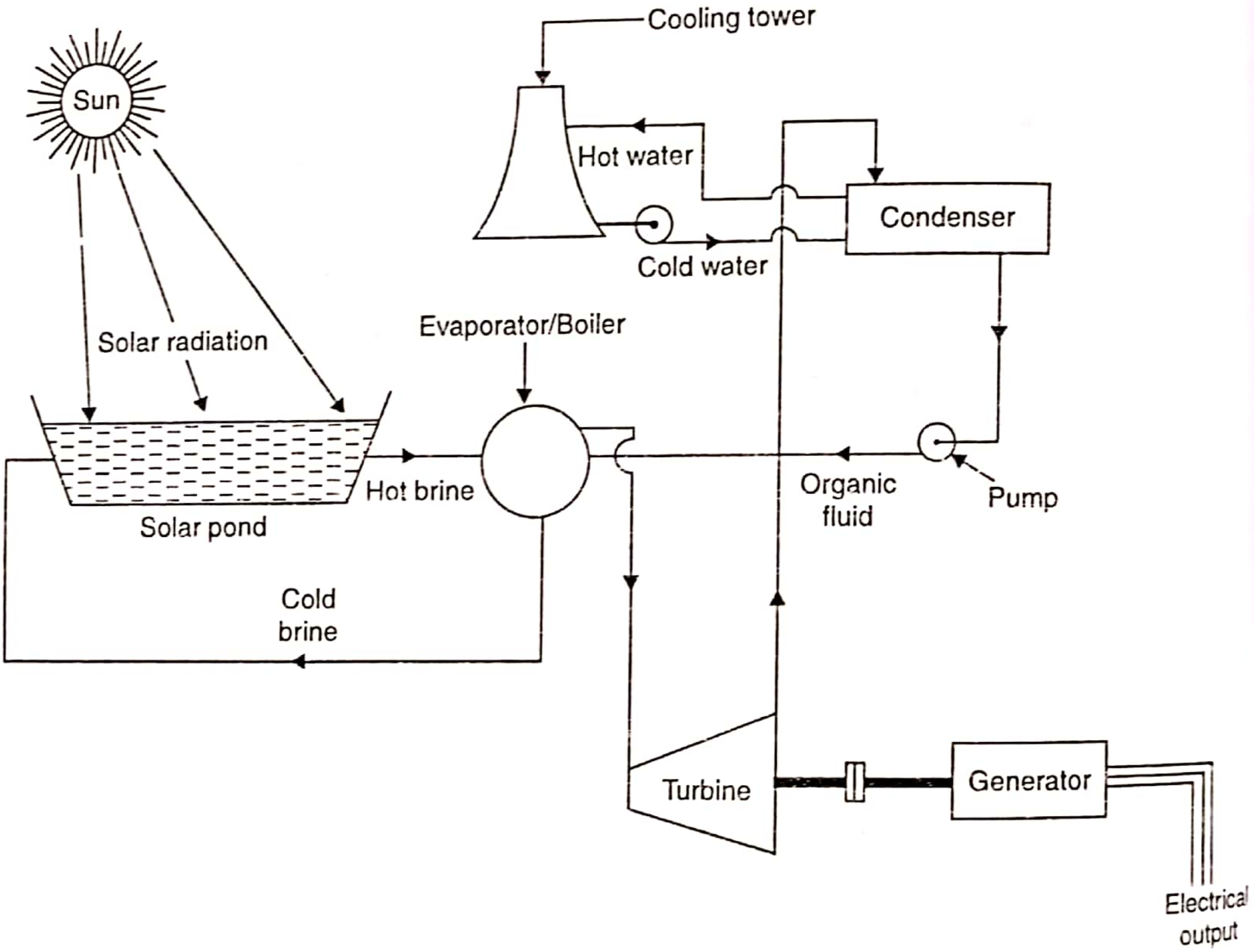

Fig. 10.17. Solar pond electric power plant.

In Australia a 2000 sq. m. solar pond equipped with a 20 kW engine has been installed.

10.4.6.2. Low temperature solar Power Plant

Fig. 10.18 shows a schematic diagram of a low temperature solar power plant. In this system an array of flat plate collectors is used to heat water to about 70°C and then this heat is used to boil butane in a heat exchanger. The high pressure butane vapour thus obtained runs a butane turbine which in tern operates a hydraulic pump. The pump pumps the water from well which is used for irrigation purposes. The exhaust butane vapour (from butane turbine) is condensed with the help of water which is pumped by the pump and the condensate is returned to the heat exchanger (or boiler).

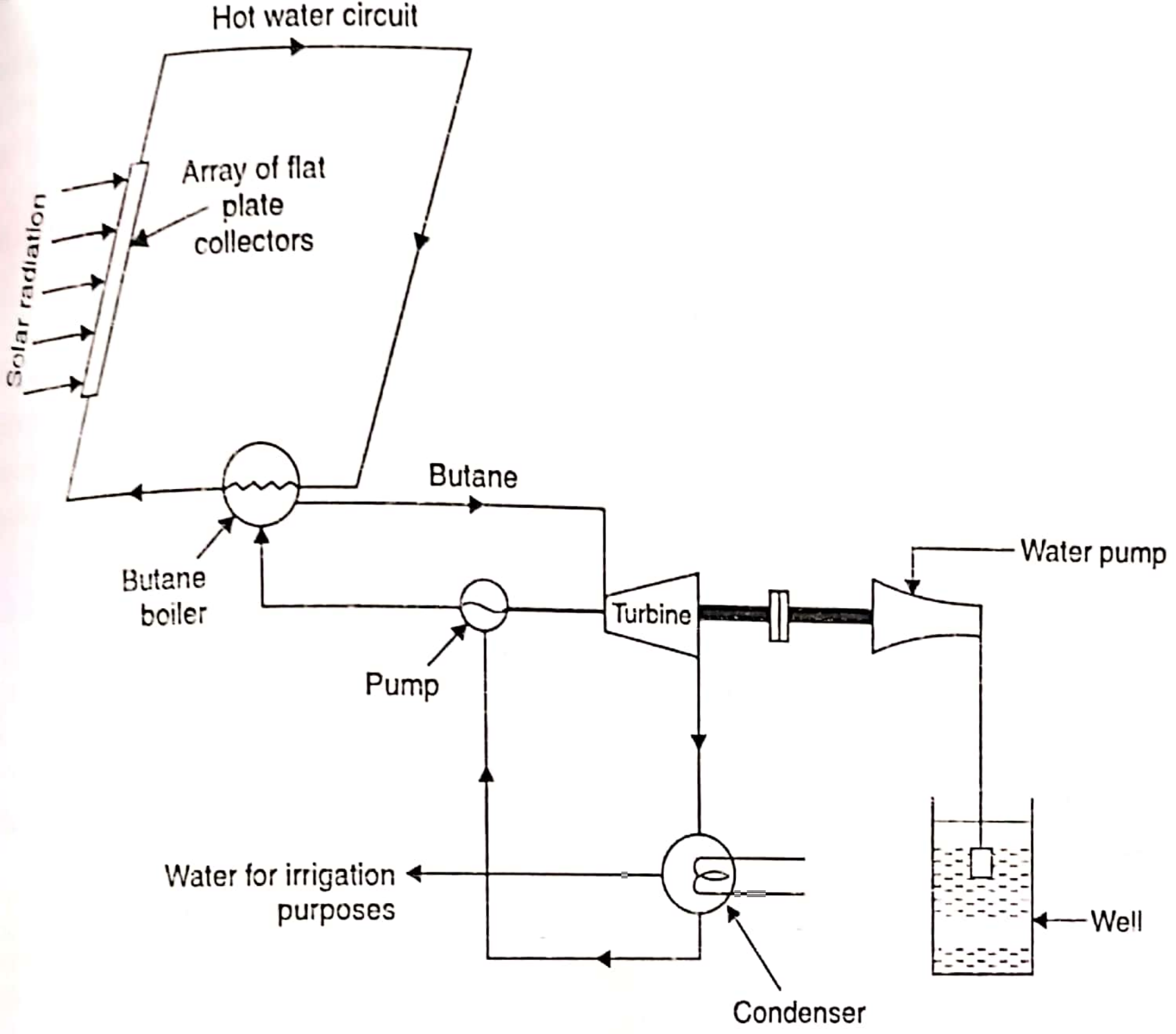

Fig. 10.18. Low temperature solar power plant.

10.4.7. Medium Temperature Systems Using Focusing Collectors

A circular or rectangular parabolic mirror can collect the radiation and focus it on to a small area, a mechanism for moving the collector to follow the sun being necessary. Such devices are used for *metallurgical research* where *high purity and high temperatures are essential*, an example being

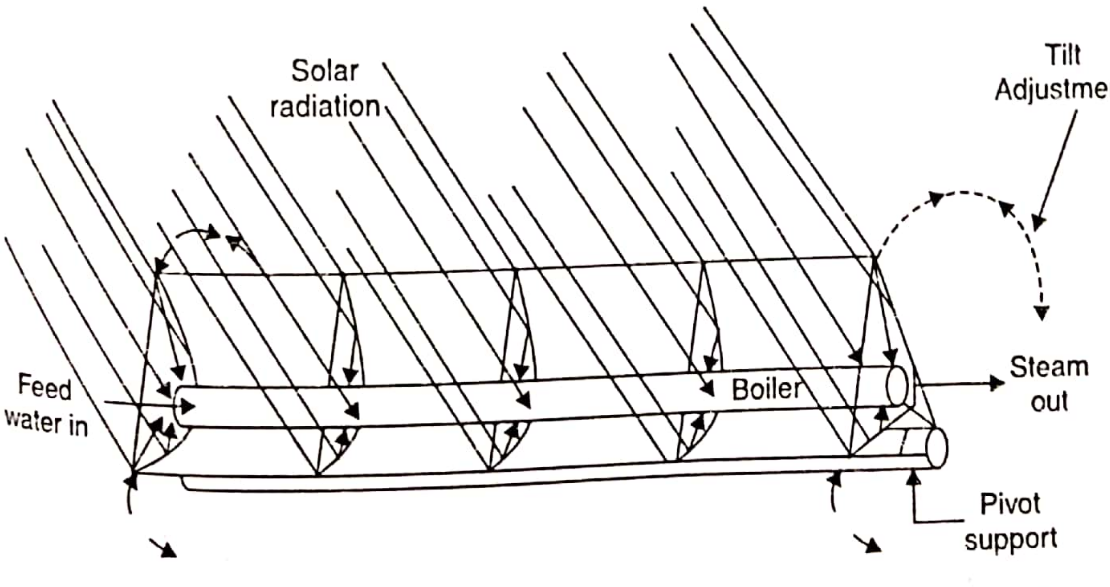

Fig. 10.19. Concave solar energy collector focuses sun's rays on boiler at focal point.

a 55 m diameter collector giving about 1 MW (th) at Mont Louis in Pyrenees. Smaller units having 20 m diameter reflector can give temperatures of 300°C over an area of about 50 m^2. The collector efficiency is about 50%. On a small scale, units about 1 m diameter giving temperatures of about 300°C have been used for cooking purposes.

Fig. 10.19 shows a concave solar energy collector focusing sun's rays on boiler at a focal point. Generation of steam at 250°C could give turbine efficiencies up to 20-25 per cent.

10.4.8. High Temperature Systems—Solar Farm and Solar Power Plant

For a large scale production of process-heat the following two concepts are available :

1. **The solar farm.** It consists of a whole field covered with parabolic trough concentrators.
2. **The solar tower.** It consists of a central receiver on a tower and a whole field of tracking.

In case of a '*solar farm*' temperature at the point of focus can reach several hundred degrees celsius. Fig. 10.20 shows a solar tower system.

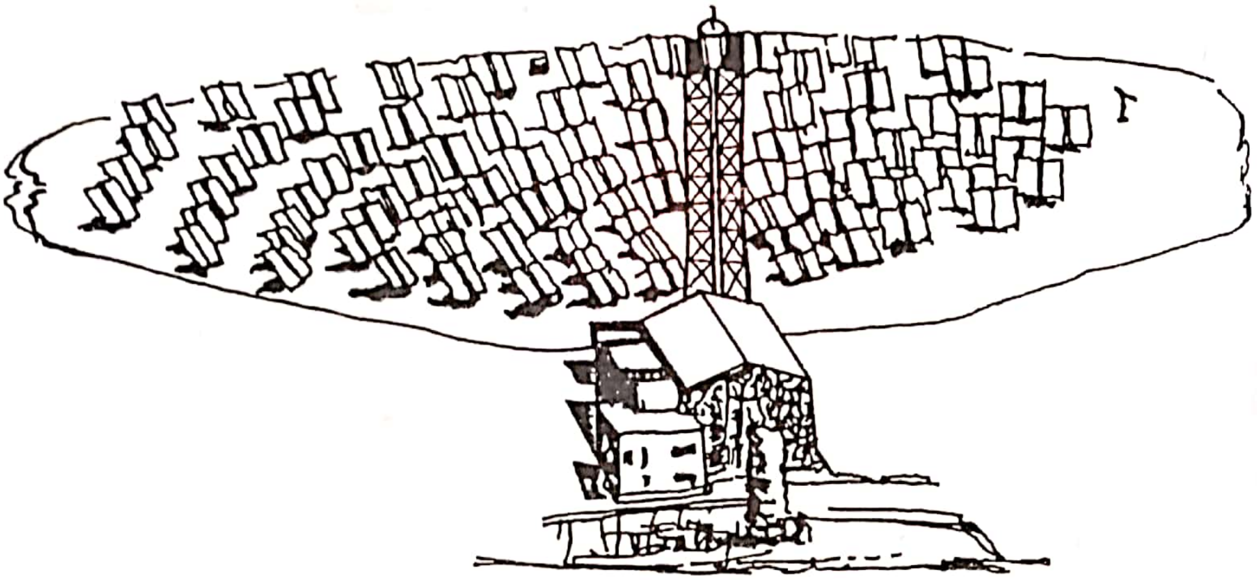

Fig. 10.20. Solar tower system.

In case of central receiver "*solar tower*" concentrators, temperature can reach thousands of degrees celsius, since a field of reflectors (heliostats) are arranged separately on sun-tracking frames to reflect the sun on to a boiler mounted on a central tower (Fig. 10.21, 10.22).

With both systems ('solar farm' and 'solar tower'), *a heat transfer fluid or gas is passed through the point or line of insolation concentration to collect the heat and transfer it to the point of use. Such heat can be used either directly in industrial or commercial processes or indirectly in electricity production via. steam and a turbine.*

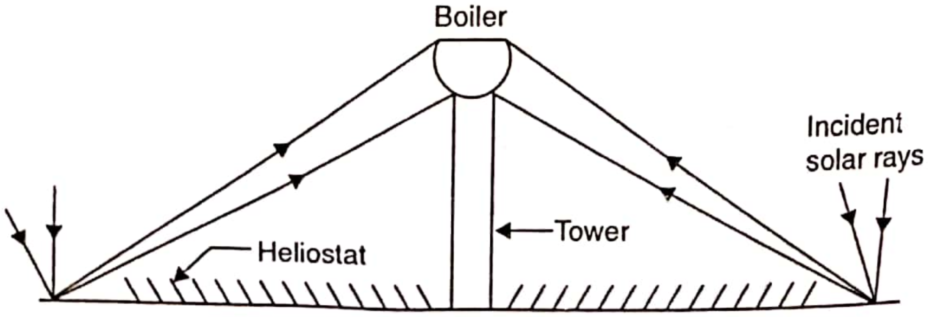

Fig. 10.21

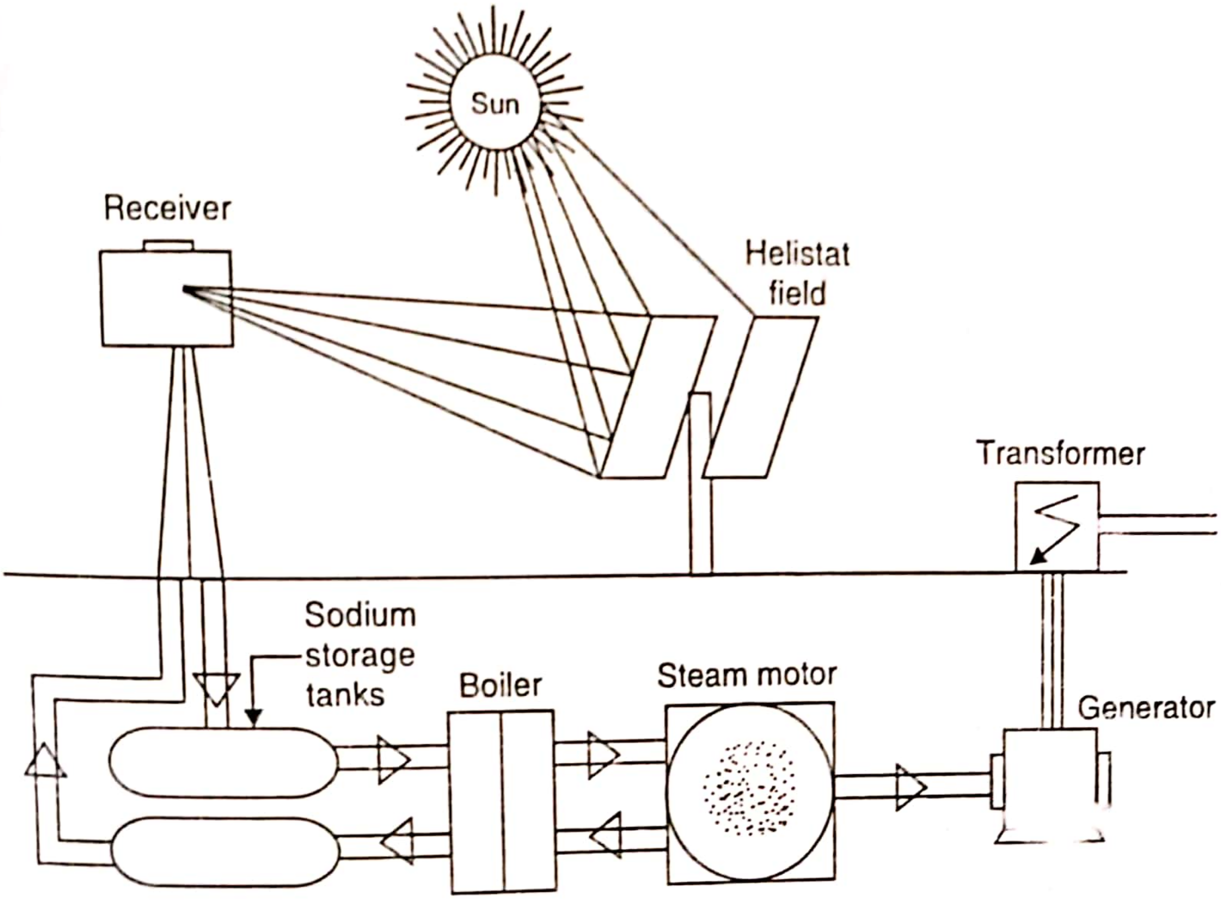

Fig. 10.22. Diagram of solar tower power plant.

The solar technologies such as the above two systems that produce very hot water or steam are currently still under development and, in general, these technologies are not cost competitive with conventional power sources such as oil or gas.