with a shadow band (or occulting disc), to prevent beam radiation from reaching the sensing element, measures the diffused radiation only. Such an arrangement of shadow band stand (model: SBS) is shown in Fig. 4.7.

Fig. 4.6 *Pyranometer (Courtesy: Eppley Laboratory)*

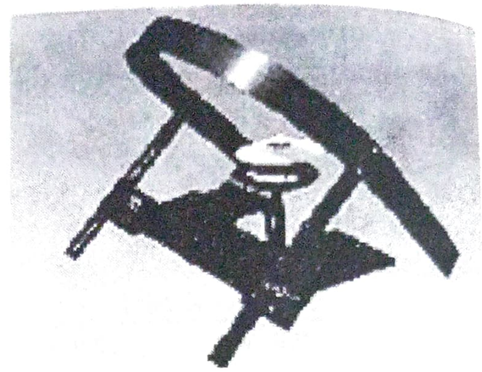


Fig. 4.7 *A pyranometer with shadow band (courtesy: Eppley Laboratory)*

Many inexpensive instruments are also available for measuring light intensity, including instruments based on cadmium-sulphide photocells and silicon photodiodes. These instruments give good indication of relative intensity but their spectral response is not linear, and thus they cannot be accurately calibrated.

4.7.2 Pyrheliometer

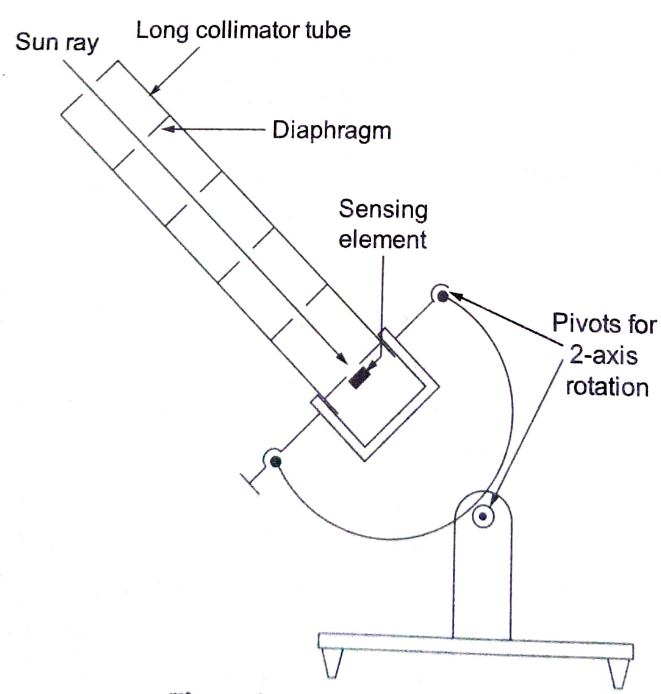


Fig. 4.8 *Pytheliometer*

The normal incidence pyranometer, shown in Fig. 4.8 uses a long collimator tube to collect beam radiation whose field of view is limited to a solid angle of 5.5° (generally) by appropriate diaphragms inside the tube. The inside of the tube is blackened to absorb any radiation incident at angles outside the collection solid angle. At the base of the tube a wire wound thermopile having a sensitivity of approximately 8 $\mu V/W/m^2$ and an output impedance of approximately 200 Ω is provided. The tube is sealed with dry air to eliminate absorption of beam radiation within the tube by water vapour. A tracker is needed if continuous readings are desired.

4.7.3 Sunshine Recorder

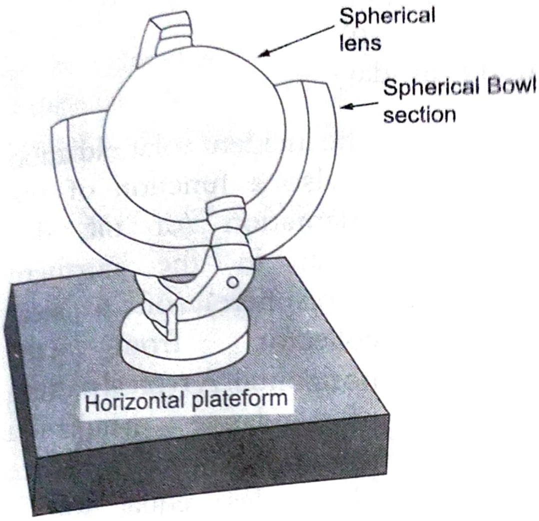


Fig. 4.9 *Sunshine recorder*

This instrument measures the duration in hours of bright sunshine during the course of a day. It essentially consists of a glass sphere (about [illegible] in diameter) mounted on its axis parallel to that of the earth, within a spherical section (bowl), as shown in Fig. 4.9. The bowl and glass sphere are arranged in such a way that the sun's rays are focused sharply at a spot on a card held in a groove in the bowl. The card is prepared from a special paper bearing a time scale. As the sun moves, the focused bright sunshine burns a path along this paper. The length of the trace thus obtained on the paper is the measure of the duration of the bright sunshine. Three overlapping pairs of grooves are provided in the spherical segment to take care of the different seasons of the year.

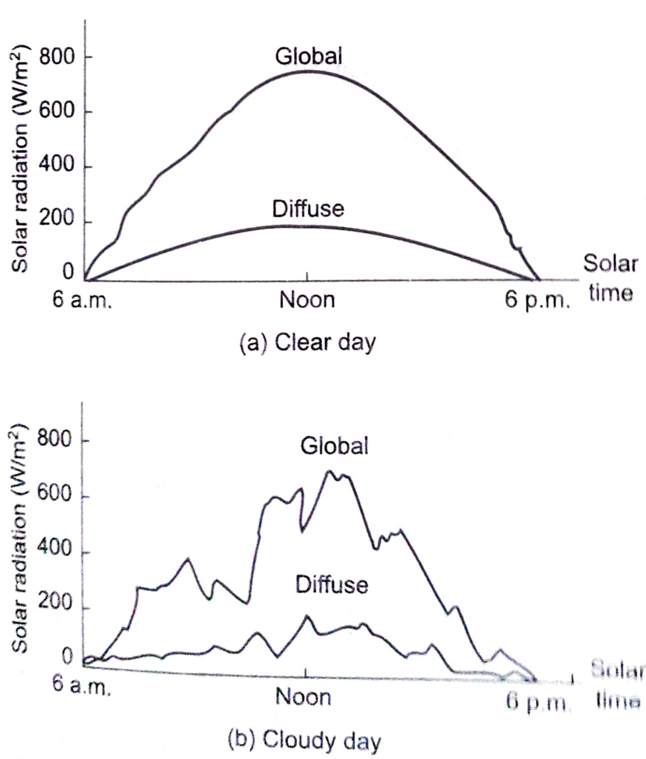


Fig. 4.10 Daily variation of global and diffuse radiation on topical (a) clear and (b) cloudy days on horizontal surface

SOLAR RADIATION DATA

4.8

The radiation data are mostly measured on a horizontal surface. Typical records of global and diffused radiation versus solar time on a horizontal surface for a clear day and partially cloudy day are shown in Fig. 4.10. Daily radiant energy is obtained from the area under the corresponding curve. The monthly average of the daily radiation is obtained by averaging over a span of the corresponding month and expressed in kJ/m²/day. An alternative unit for expressing solar radiation is langley per unit time, where one langley is equal to 1 cal/cm².

4.7.3 Sunshine Recorder

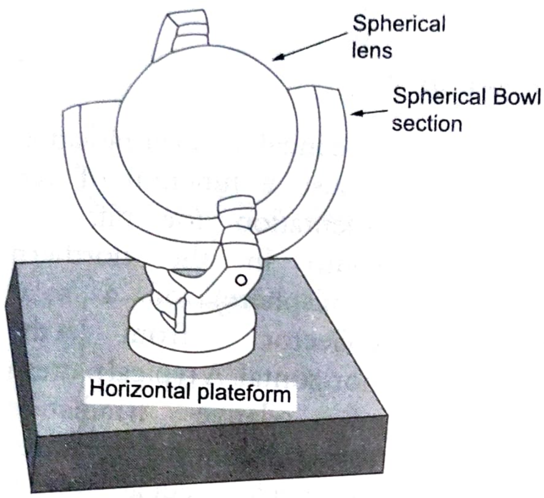


Fig. 4.9 *Sunshine recorder*

This instrument measures the duration in hours of bright sunshine during the course of a day. It essentially consists of a glass sphere (about 10 cm in diameter) mounted on its axis parallel to that of the earth, within a spherical section (bowl), as shown in Fig. 4.9. The bowl and glass sphere are arranged in such a way that the sun's rays are focused sharply at a spot on a card held in a groove in the bowl. The card is prepared from a special paper bearing a time scale. As the sun moves, the focused bright sunshine burns a path along this paper. The length of the trace thus obtained on the paper is the measure of the duration of the bright sunshine. Three overlapping pairs of grooves are provided in the spherical segment to take care of the different seasons of the year.

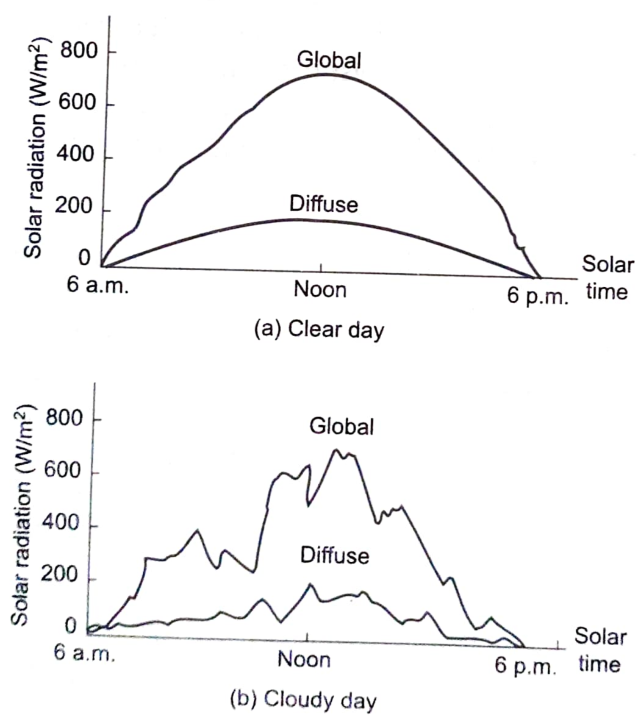


Fig. 4.10 *Daily variation of global and diffuse radiation on topical (a) clear and (b) cloudy days on horizontal surface*

SOLAR RADIATION DATA

4.8

The radiation data are mostly measured on a horizontal surface. Typical records of global and diffused radiation versus solar time on a horizontal surface for a clear day and partially cloudy day are shown in Fig. 4.10. Daily radiant energy is obtained from the area under the corresponding curve. The monthly average of the daily radiation is obtained by averaging over a span of the corresponding month and expressed in kJ/m^2-day. An alternative unit for expressing solar radiation is langley per unit time, where one langley is equal to 1 cal/cm^2.

Thus, solar radiation data are presented in three ways:

(i) Flow of energy per unit area per second, (kJ/m^2-s)
(ii) Flow of energy per unit area per hour, (kJ/m^2-h)
(iii) Flow of energy per unit area per day, (kJ/m^2-day)

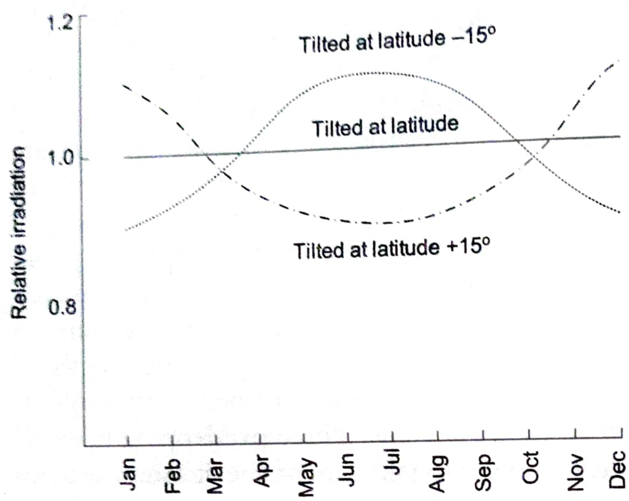


Fig. 4.11 *Relative irradiation at tilted surfaces throughout a year*

The incident solar radiation is also a function of the orientation (or tilt, due south in the northern hemisphere) of a solar collector from the horizontal. A typical pattern of relative irradiation throughout a year for three tilt angles, equal to: (i) latitude, (ii) (latitude –15°), and (iii) (latitude +15°) is shown in Fig. 4.11. The radiation pattern indicates favouring of a certain tilt during certain periods of the year. Therefore, seasonal adjustment of the tilt angle may result in enhanced radiation collection. However, the overall strategy changes from place to place and also on the type of application.

The maximum solar radiation is received on a collector surface placed normal to incident rays. But as the position of the sun in the sky changes throughout the day, the collector has to adjust itself continuously to collect maximum radiation. Therefore, maximum energy can be collected if the collector tracks the sun along two axes. However, providing for two-axis tracking is expensive and complicated. A compromising but less expensive option is to fix the collector at a suitable tilt and track the sun along a single axis only. The most cost-effective method with further compromise in the performance is to have a fix orientation for a collector and possibly with some arrangement for seasonal adjustments only.

For designing a solar system or for predicting the potential of any solar application at a location, we need monthly average, daily solar radiation data (both global and diffused) on a horizontal and possibly at certain positions of the tilt angle of the surface. These data are measured at certain measuring stations in a country (at present 16 locations in case of India) and computed for other locations. This record is produced in the form of charts and tables and an atlas is prepared to help in solar-systems design. The typical record of measured daily solar radiation data for New Delhi is shown in Tables C1, C2 and C3 in Appendix C.

5.1.3 Performance Indices

The important performance indices of a solar collector are (i) collector efficiency, (ii) concentration ratio, and (iii) temperature range. The performance of a solar collector is evaluated on the basis of these features.

Collector efficiency is defined as the ratio of the energy actually absorbed and transferred to the heat-transport fluid by the collector (useful energy) to the energy incident on the collector.

Concentration ratio (CR) is defined as the ratio of the area of aperture of the system to the area of the receiver. The aperture of the system is the projected area of the collector facing (normal) the beam.

Temperature range is the range of temperature to which the heat-transport fluid is heated up by the collector.

In flat-plate collectors, no optical system is utilized to concentrate the solar radiation and hence the concentration ratio is only 1. The temperature range is less than 100°C. Line focus collectors have CR up to 100 and a temperature range of the order of 150°C to 300°C. A concentration ratio of the order of thousands and temperature range of 500°C to 1000°C can be obtained by using point-focus collectors.

5.1.4 Liquid Flat-plate Collector

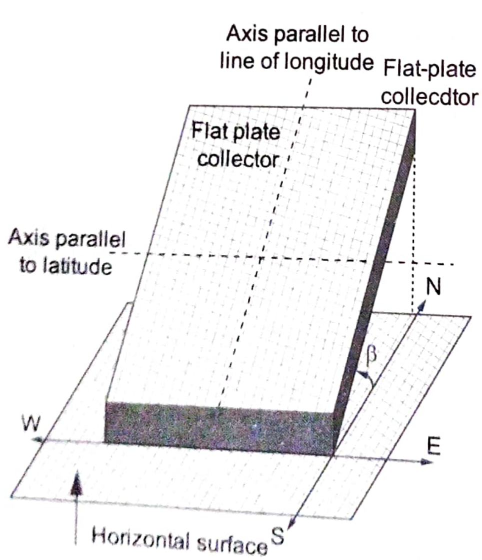


Fig. 5.2 *Positioning of flat-plate collector*

A flat-plate collector is placed at a location in a position such that its length aligns with the line of longitude and is suitably tilted towards south to have maximum collection. The positioning of the collector is shown in Fig. 5.2. The constructional details of a simple flat-plate collector are shown in Fig. 5.3. The basic elements in a majority of these collectors are:

(i) transparent cover (one or two sheets) of glass or plastic
(ii) blackened absorber plate usually of copper, aluminium or steel
(iii) tubes, channels or passages in thermal contact with the absorber plate—in some designs, the tubes form an integral part of absorber plate
(iv) weather tight, insulated container to enclose the above components

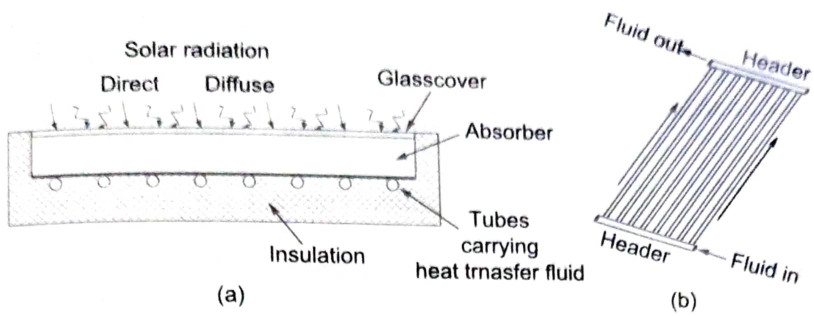
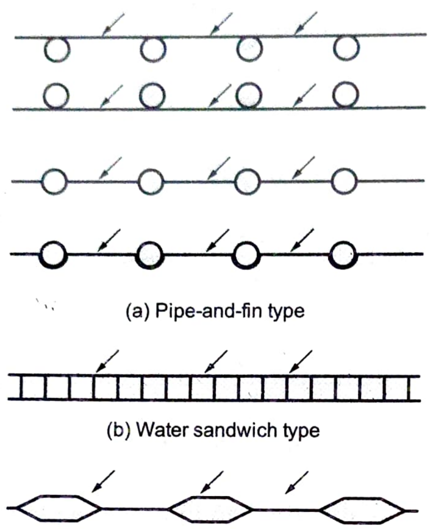


Fig. 5.3 *Construction of flat-plate collector*

A liquid, most commonly water, is used as the heat-transport medium from the collector to the next stage of the system. However, sometimes a mixture of water and ethylene glycol (antifreeze mixture) is also used if the ambient temperatures are likely to drop below 0°C during nights. As solar radiation strikes on a specially treated metallic absorber plate, it is absorbed and raises the plates temperature. The absorber plate is usually made from a metal sheet ranging in thickness from 0.2 to 1 mm. The heat is transferred to the heat-transfer liquid circulating in the tube (or channels), beneath the absorber plate and in intimate contact with it. The metallic tubes range in diameter from 1 to 1.5 cm. These are soldered, brazed, welded or pressure bonded to the absorber plate with a pitch ranging from 5 to 12 cm. In some designs, the tubes are bonded to the top or are in line and integral to the absorber plate. Some of these arrangements are shown in Fig. 5.4. Header pipes, which are of slightly larger diameter of typically 2 to 2.5 cm, lead the water in and out of the collector and distribute to tubes. The metal that is most commonly used, both for the absorber plate, the tubes and the header pipes, is copper, but other metals and plastics have also been tried. In the bottom and along the side walls, thermal insulation provided by a 2.5 to 8-cm thick layer of glass wool prevents heat loss from the rear surface and sides of the collector. The glass cover permits the entry of solar radiation as it is transparent for incoming short wavelengths but is largely opaque to the longer infrared radiation reflected from the absorber. As a result, the heat remains trapped in the airspace between the absorber plate and glass cover in a manner similar to a green house. The glass cover also prevents heat loss due to convection by keeping the air stagnant. The glass cover may reflect some 15% of incoming solar radiation, which can be reduced by applying anti-reflective coating on the outer surface of the glass. The usual practice is to have one or two covers with spacing ranging from 1.5 to 3 cm. Plain or toughened glass of 4 to 5-mm thickness is the most favoured material. Transparent plastics may also be used in place of glass but they often offer inferior performance as compared to glass. Most plastics are not as opaque to infrared radiation as glass. Also, their transparency for incoming solar radiation decreases with aging. The life of a plastic material is short when exposed to sunrays as it breaks down and cracks develop over a span of time.



(a) Pipe-and-fin type

(b) Water sandwich type

(c) Semi-water-sandwich type

Fig. 5.4 *Cross-sections through collector plates*

A variety of absorber-plate designs have been developed as shown in Fig. 5.4. These absorber plates can be broadly divided into three basic types depending on the extent of wetted area relative to the absorbing surface area.

(i) Pipe-and-fin Type Here, the liquid flows only in the pipe and hence they have a comparatively low wetted area and liquid capacity.

(ii) Rectangular or Cylindrical Full-sandwich Type In this, both the wetted area and water capacity are high.

(iii) Roll-bond or Semi-sandwich Type It is an intermediate between the above two types.

The best choice depends on the particular application. For low-temperature requirements, such as warming of a swimming pool, the plastic, full water-sandwich plate may be the most appropriate. For domestic and industrial applications, high temperatures are required and hence the pipe-and-fin-type plate may be more suitable.

5.1.5 Liquid Flat-plate Collector Efficiency

The instantaneous collection efficiency of a flat-plate solar collector is det as follows:

$$\eta_i = \frac{\text{useful heat gain}}{\text{solar radiation incident on the collector}} = \frac{q_u}{A_p\, I_T} \tag{5.1}$$

where q_u = useful heat gain (i.e., rate of heat transfer to the working fluid)

A_p = area of absorbing plate

I_T = instantaneous radiation energy incident on the collector face (kW/m^2)

The above expression is also valid for calculating the hourly collecting efficiency. In that case, q_u will be taken as useful heat gain in one hour and I_T as the energy incident on the collector face in one hour (kJ/m^2-h).

An energy balance on the absorber plate yields the following equation:

$$q_u = A_p\, S - q_L \tag{5.2}$$

cover. This requires continuous cleaning of the cover, which is not possible in a practical situation. Cleaning is generally done once in a few days. For this reason, it is recommended that the incident flux be multiplied by a correction factor which accounts for the reduction in intensity because of accumulation of dust. In general, a correction factor from 0.92 to 0.99 seems to be indicated.

5.1.6 Flat-Plate Air-Heating Collector (Solar Air Heater, Solar Air Collector)

A solar air-heating collector is similar to a liquid flat-plate collector with a change in the configuration of the absorber and tube (riser), as shown in Fig. 5.6. The value of the heat-transfer coefficient between the absorber plate and the air is low. For this reason, the surfaces are sometimes roughened or longitudinal fins are provided in the air-flow passage. Corrugated, V-shaped, matrix, etc., are some of the other variations of shapes of the absorber plate. The principal applications of these collectors are drying for agricultural and industrial purposes, and space heating.

It has the following advantages over a liquid flat-plate collector:

- It is compact, simple in construction and requires little maintenance.
- The need to transfer thermal energy from the working fluid to another fluid is eliminated as air is used directly as the working fluid.
- Corrosion is completely eliminated.
- Leakage of air from the duct is less severe.
- Possibility of freezing of working fluid is also eliminated.
- The pressure inside the collector does not become very high.

The major disadvantages of air collectors are the following:

- A large amount of fluid is to be handled due to low density. As a result, the electrical power required to blow the air through the system can be significant if the pressure drop is not kept within prescribed limits.
- Heat transfer between the absorber plate and air is poor.
- There is less storage of thermal energy due to low heat capacity.

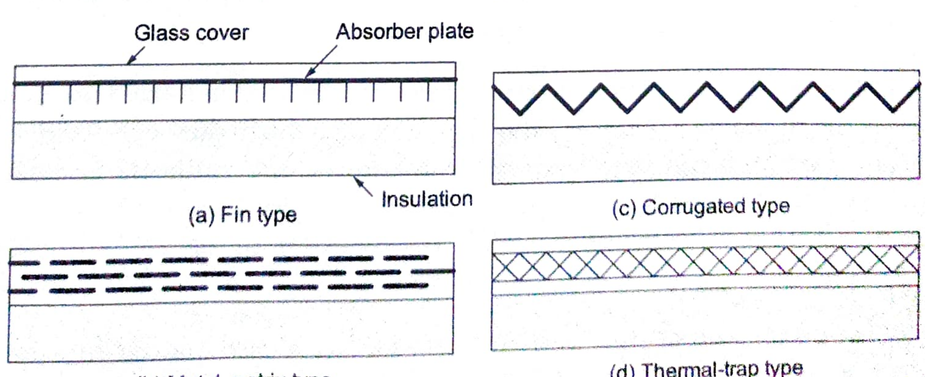


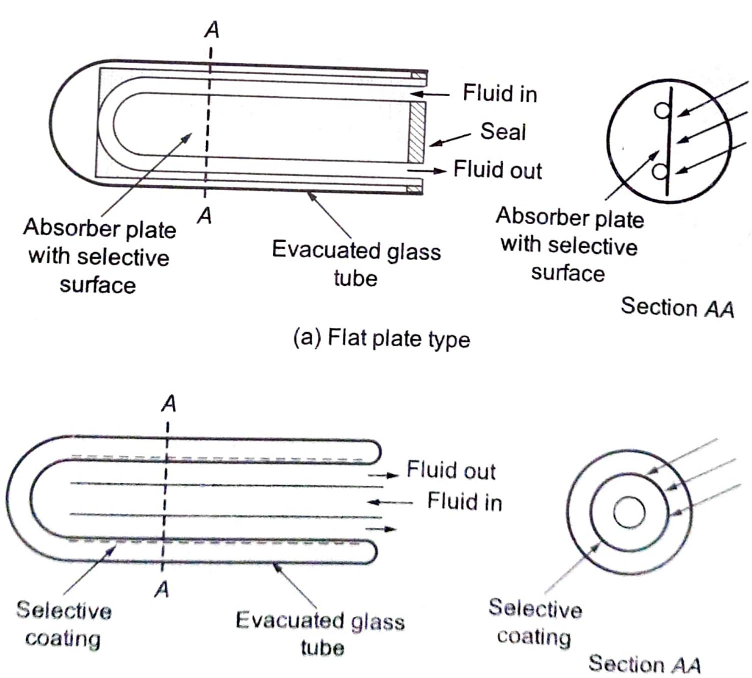
Fig. 5.6 *Various types of flat-plate air heating collector*

5.1.7 Evacuated Tube Collector

The performance of a flat-plate collector can be improved by suppressing or reducing the heat lost from the collector by convection and conduction. This is done by having vacuum around the absorber. As a consequence, it becomes essential to use a glass tube as the cover because only a tubular surface is able to withstand the stresses introduced by the pressure differences as a result of vacuum. The collector consists of a number of long tubular modules stacked together.

A number of designs have been developed and some of them are commercially available. In the simplest design, each module consists of a metal absorber plate with two fluid tubes housed in an evacuated, cylindrical glass tube as shown in Fig. 5.7(a). The absorber plate has a selective surface coating on it. The two tubes are joined at the other end inside the glass cover and form a "U" path for the fluid, with one tube acting as the inlet tube while the other as the outlet tube. A glass to metal seal is provided between the absorber tubes and the end cover of the vacuum tube. Also, special precaution is required to reduce thermal contact between the absorber tubes and the outer tube though the seal.

In another design shown in Fig. 5.7(b), the metal to glass seal is avoided by using three concentric tubes with the space between the outer two tubes, which are made from glass, being evacuated. The outer surface of the middle tube acts as the absorbing surface and has a selective surface coating on it. The liquid flows in through the innermost tube and flows out through the annulus between this tube and the middle tube.



(a) Flat plate type

(b) Concentric tube type

Fig. 5.7 *Various designs of evacuated tube collectors*

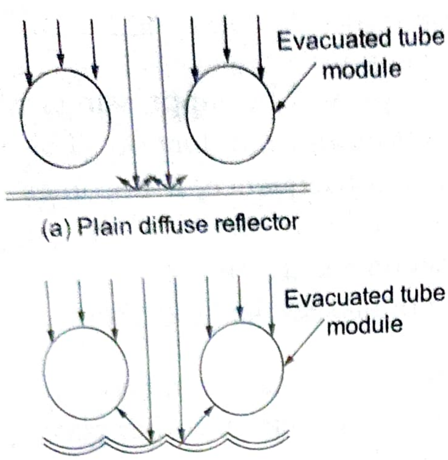


Fig. 5.8 *Layout of evacuated tube modules with reflectors*

Two types of layouts are used for the evacuated tube modules in a collector. In one type, the modules are stacked side by side without a gap between them. In another one, a spacing of a few centimetres is kept between the modules and a back reflector is used. The back reflector may be a plane white surface to act as a diffuse reflector or a curved surface acting as a specular reflector. The cross-sectional view of both these arrangements is shown in Fig. 5.8.

The level of evacuation required for suppression of convection and conduction can be calculated from basic heat-transfer theory. With increasing the level of evacuation, reduction of heat loss first occurs because of reduction of the Rayeigh number. When the Rayleigh number is further reduced below the lower threshold of convection, the heat transfer occurs because of conduction only. When the pressure is reduced to 10^{-3} torr, the conduction heat transfer is also completely suppressed. A vacuum of the order of 10^{-3}–10^{-4} torr is easily achievable.

Evacuated tube collectors are very expensive compared to conventional flat-plate collectors. Thus, it is possible to consider them only for high fluid temperatures in a range 100 to 130°C.

5.1.8 Modified Flat-Plate Collector (Flat-Plate Collector with Booster Mirrors)

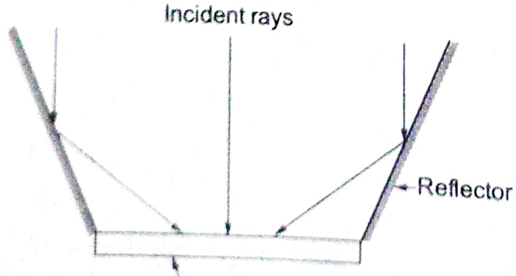


Fig. 5.9 *Modified flat-plate collector*

By providing plane reflectors at the edges of a flat-plate collector to reflect additional radiation into the receiver, the concentration of solar radiation can be increased. These mirrors are also called booster mirrors. The concentration ratio of these concentrators has a maximum value of 4. Such a design (V-trough) is aligned in the east–west direction and requires periodic tilt adjustment. Different optimum depth to base width ratio and cone angles are possible depending on the frequency of seasonal tilt adjustment. The schematic diagram is shown in Fig. 5.9.

Active solar thermal system
Solar collector

5.1.9 Compound Parabolic Concentrator (CPC)

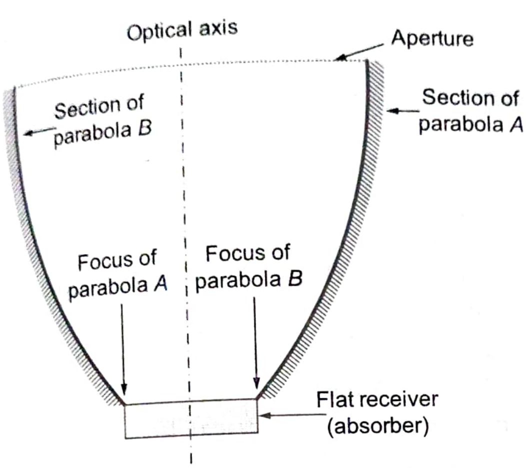


Fig. 5.10 *Compound parabolic concentrator*

A compound parabolic concentrator (shown in Fig. 5.10) consists of two parabolic mirror segments, attached to a flat receiver. The segments are oriented such that the focus of one is located at the bottom end point of the other in contact with the receiver. It has a large acceptance angle and needs to be adjusted intermittently. Rays in the central region of the aperture reach the absorber directly whereas those near the edges undergo one or more reflections before reaching the absorber. The concentration ratio achieved from this collector is in the range of 3–7.

5.1.10 Cylindrical Parabolic Concentrator

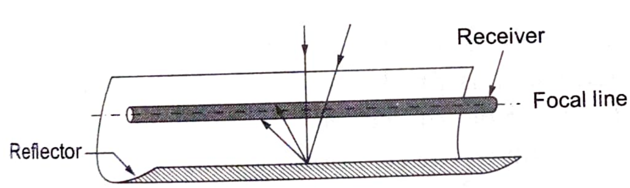


Fig. 5.11 *Cylindrical parabolic concentrator*

It consists of a cylindrical parabolic trough reflector and a metal tube receiver at its focal line as shown in Fig. 5.11. The receiver tube is blackened at the outside surface to increase absorption. It is rotated about one axis to track the sun. The heat-transfer fluid flows through the receiver tube, carrying the thermal energy to the next stage of the system. This type of collector may be oriented in any one of the three directions: east–west, north–south or polar. The polar configuration intercepts more solar radiation per unit area as compared to other modes and thus gives the best performance. The concentration ratio in the range of 5–30 may be achieved from these collectors.

5.1.11 Fixed-mirror Solar Concentrator

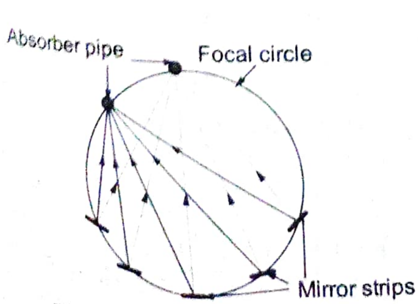


Fig. 5.12 *Fixed mirrors solar concentrator*

Due to practical difficulty in manufacturing a large mirror in a single piece in a cylindrical parabolic shape, long narrow mirror strips are used in this concentrator. The concentrator consists of fixed mirror strips arranged on a circular reference cylinder with a tracking receiver tube as shown in Fig. 5.12. The receiver tube is made to rotate about the centre of curvature of the reflector module to track the sun. The image width at the absorber is ideally the same as the projected width of a mirror element; the concentration ratio is approximately the same as the number of mirror strips.

5.1.12 Linear Fresnel Lens Collector

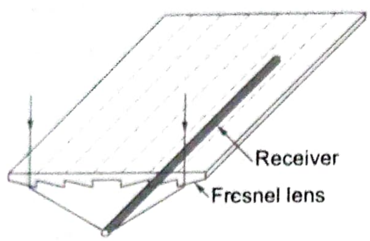


Fig. 5.13 *Linear Fresnel lens collector*

In this collector, a Fresnel lens, which consists of fine, linear grooves on the surface of the refracting material (generally optical quality plastic) on one side and flat on the other side, is used. The angle of each groove is designed to make the optical behavior similar to a spherical lens. The beam radiation, which is incident normally, converges on the focal line, where a receiver tube is provided to absorb the radiation. A concentration ratio of 10 to 30 may be realized which yields temperatures between 150 to 300°C. The construction of this type of collector is shown in Fig. 5.13.

5.1.13 Paraboloidal Dish Collector (Scheffler Solar Concentrator)

Fig. 5.14 *Paraboloidal dish collector (Scheffler solar concentrator)*

When a parabola is rotated about its optical axis, a paraboloidal shape is produced. Figure 5.14 shows the details of this type of collector. Beam radiation is focused at a point in the paraboloid. This requires two-axis tracking. It can have a concentration ratio ranging from 10 to few thousands and can yield a temperature up to 3000°C. Paraboloidal dish collectors of 6–7 m in diameter are commercially manufactured.

5.1.14 Hemispherical Bowl Mirror Concentrator

It consists of a hemispherical fixed mirror, a tracking absorber and a supporting structure as shown in Fig. 5.15. All rays entering the hemisphere after reflection cross the paraxial line at some point between the focus and the mirror surface. Therefore, a linear absorber pivoted about the centre of curvature of the hemisphere intercepts all reflected rays. The absorber is to be moved so that its axis is always aligned with solar rays passing through the centre of the sphere. This requires two-axis tracking. The absorber is either driven around a polar axis at a constant angular speed of 15 degrees

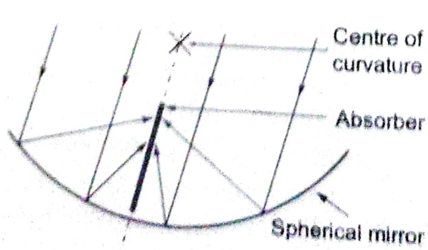


Fig. 5.15 *Hemispherical mirror concentrator*

hour or adjusted periodically during the day. This type of concentrator gives lesser concentration, owing to spherical aberration, than that obtained in paraboloidal concentrator.

5.1.15 Circular Fresnel Lens Concentrator

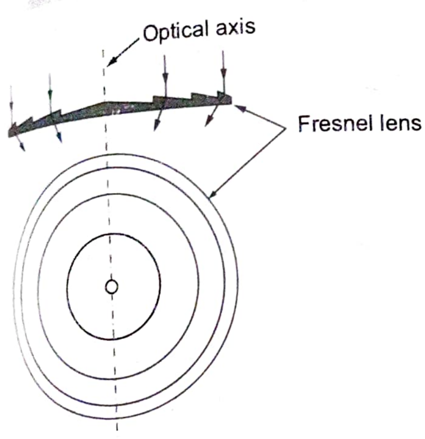


Fig. 5.16 *Circular Fresnel lens*

These lenses are generally used where high flux is desired, such as with silicon solar cells or with gallium arsenide solar cells as receiver. Figure 5.16 shows the construction of a circular Fresnel lens. It is divided into a number of thin circular zones. The tilt of each zone is so adjusted that optically, the lens approximates a thin spherical lens. The concentration ratio may be as high as 2000, but is less than that obtained from a paraboloidal reflector. In solar-cell applications, tracking is required to keep the small solar image centered on the receiver.

5.1.16 Central Tower Receiver

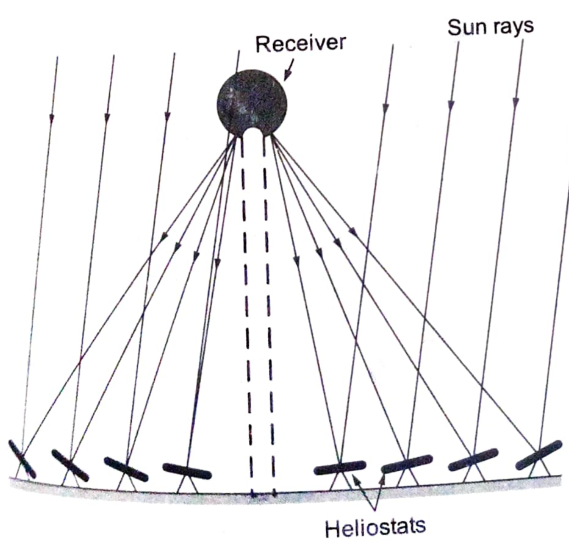


Fig. 5.17 *Central tower receiver*

In a central tower receiver collector, the receiver is located at the top of a tower. Beam radiation is reflected on it from a large number of independently controlled, almost flat mirrors, known as *heliostats*, spread over a large area on the ground, surrounding the tower. Thousands of such heliostats track the sun to direct the beam radiation on the receiver from all sides. The heliostats together act like a dilute paraboloid of very big size. Concentration ratio of as high a value as 3000 can be obtained. The absorbed energy can be extracted from the receiver and delivered at a temperature and pressure suitable for driving turbines for power generation. The schematic view of a central tower receiver is shown in Fig. 5.17.

SOLAR WATER HEATER

5.2 The details of the most common type of solar water heater are shown in Fig. 5.18. A tilted flat-plate solar collector with water as a heat-transfer fluid is used. A thermally insulated hot-water storage tank is mounted above the collector. The heated water of the collector rises up to the hot water tank and replaces an equal quantity of cold water, which enters the collector. The cycle repeats, resulting in all the water of the hot water tank getting heated up. When hot water is taken out from the hot water outlet, the same is replaced by cold water from a cold-water make up tank fixed above the hot water tank. The scheme is known as *passive heating scheme*, as water is circulated in the loop naturally due to thermo-siphon action. When the collector is fixed above the level of the hot-water tank, a pump is required to induce circulation of water in the loop and the scheme will be known as active (or forced) solar thermal system. An auxiliary electrical emersion heater may be used as a back-up for use during cloudy periods. In average Indian climatic conditions, a solar water heater can be used for about 300 days in a year. A typical 100-litres per day (LPD) rooftop solar water heater costs approximately Rs. 18,000–21,900 (year 2008) and delivers water at 60–80 °C. It has a life span of 10–12 years and a payback period of 2–6 years.

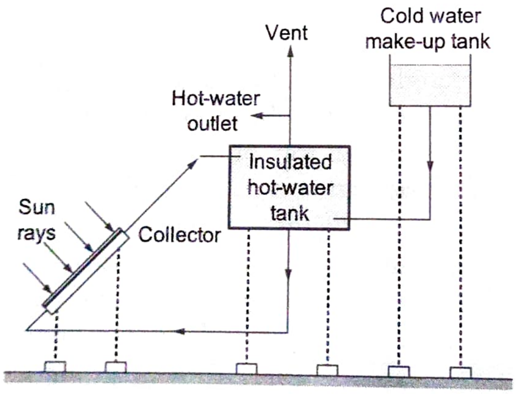


Fig. 5.18 *Solar water heater*

In other schemes, the hot water from the collector delivers heat to service water through a heat exchanger. In this scheme, an anti-freeze solution may be used as the heat-transport medium to avoid freezing during cold nights.

SOLAR PASSIVE SPACE-HEATING AND COOLING SYSTEMS

5.3 Solar energy is also used for heating or cooling a building to maintain a comfortable temperature inside. Passive systems do not require any mechanical device and make use of the natural process of convection, radiation and conduction for transport of heat. Use of passive heating/cooling systems puts restrictions on the building design to make possible the flow of heat naturally. Such a specially designed building is called a *solar house*. The technology for passive cooling is much less developed than that for passive space heating. Natural passive cooling may not always be sufficient to meet the requirement and at peak load, auxiliary means may also be needed, but it greatly reduces the load on the air-conditioner plant.

Active solar thermal

Active heating/cooling systems employ mechanical devices, e.g., pumps, blowers, etc., to circulate the working fluid for transportation of heat and, therefore, a special building design is not necessary as required in the case of passive heating. Nevertheless, careful building design and insulation is desirable and will be less expensive than an additional heating/cooling load due to poor design.

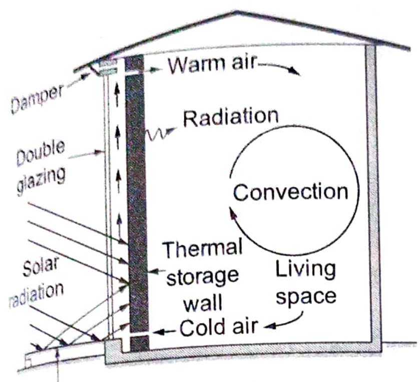


Fig. 5.19 *Solar space heating*

A solar passive space-heating system is shown in Fig. 5.19. The south-facing thick wall, called *Trombe Wall* is made of concrete, adobe, stone or composites of brick blocks and sand, designed for thermal storage. In order to increase the absorption, the outer surface is painted black. The entire south wall is covered by one or two sheets of glass or plastic with some air gap (usually 10–15 cm) between the wall and inner glazing. Solar radiation after penetration through the glazing is absorbed by the thermal storage wall. The air in the air gap between the glazing and the wall thus gets heated, rises up and enters the room through the upper vent while cool air from the room replaces it from the bottom vent. The circulation of air continues till the wall goes on heating the air. Thus, the thermal wall collects, stores and transfers the heat to the room. Heating can be adjusted by controlling the air flow through the inlet and outlet vents by shutters. Opening the damper at the top of the glazing allows the excess heat to escape outside, when heating is not required.

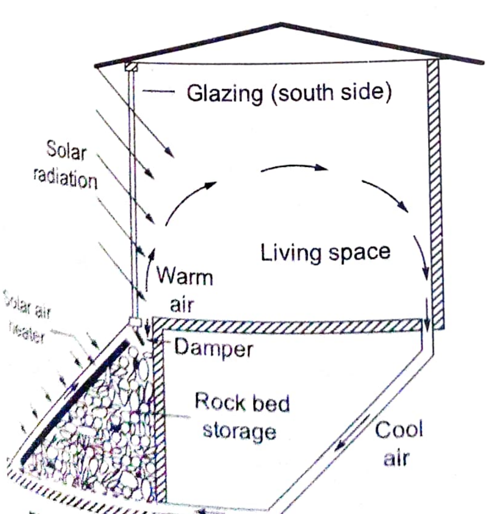


Fig. 5.20 *Solar space heating with rock bed storage*

Sometimes, a reflective horizontal surface is also provided to make available the additional radiation for thermal storage. A movable insulation cover (not shown in the figure) is also sometimes used to cover the glaze to reduce the heat loss from the storage wall to outdoors during night. In some models, the thermal storage wall is made up of water drums stacked over one another to increase the thermal storage capacity. In another variation, the thermal storage mass is provided above a metallic roof of the building instead of a wall.

In Fig. 5.20, another variation of a solar space-heating system is shown. Here a collector cum-rock-bed storage system is integrated with the apartment. During daytime when direct gain through the glaze is sufficient, the hot air from the air heater (collector) is not allowed to enter the room. The available thermal energy is stored in the rock bed to be used later, preferably during night.

For natural cooling, the first and best approach is to reduce unnecessary thermal loads entering the building. For example, (i) direct sunlight entering the building, which can be reduced by use of sun breakers or shading the windows, walls, roof etc., (ii) conduction of heat through building elements, which can be reduced by proper thermal insulation, and (iii) infiltration of outside warm air, which can be reduced by proper sealing. The techniques, generally used for passive cooling of the buildings include (i) shading, (ii) ventilation, (iii) evaporation, (iv) radiation, (v) ground coupling and (vi) dehumidification.

The shading method prevents heating from the direct sun light entering the house. In the ventilation method, warm air is driven out and cool outside air is sucked inside by utilizing the chimney effect. The evaporation method is effective in dry regions, where cooling is maintained by utilizing the internal heat to evaporate water. A pond may be used above a thin roof to maintain cooling below it. A desert cooler is another example of evaporative cooling. In radiation cooling, black plastic water bags kept over a metal roof are exposed to the sky at night. Nocturnal radiation cools the water during night. This water absorbs heat from the space below it and keeps it cool. During daytime, the roof is covered by a thermal insulating sheet to prevent heating of water due to solar radiation. A ground coupling system makes use of the fact that in summer the ground temperature is always lower than the air temperature. The lower temperature of the ground can be used for cooling a building by partially sinking it into the ground.

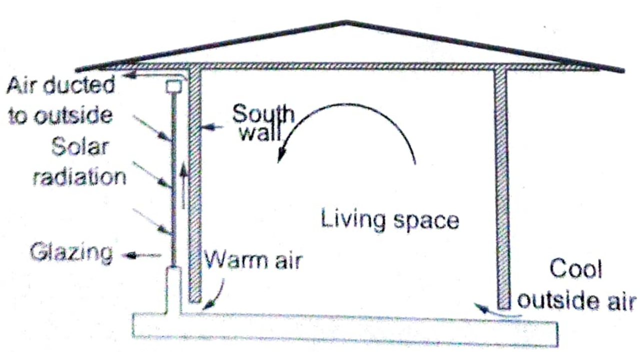


Fig. 5.21 *Solar passive cooling through ventilation*

Figure 5.21 shows the scheme of solar passive cooling through ventilation. This scheme utilizes solar 'chimney effect' and is effective where outside temperatures are moderate. Solar radiation is allowed to heat up the air between the glazing and the interior south wall. The heated air rises up, is ducted outside and the warm air from the room is drawn into this space due to the natural draught thus produced. As a result, cool outside air enters the room from the bottom air vent on the other side of the room.

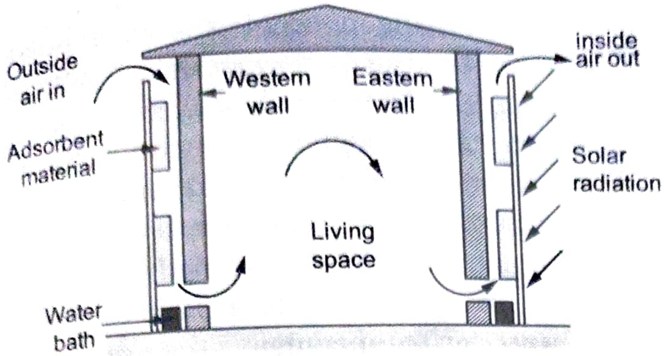


Fig. 5.22 *Solar passive cooling through dehumidification*

In a dehumidification system, the moisture content of the air in the room is reduced and cooling is maintained by adsorption and evaporation. The east- and west-facing walls of a specially designed house are provided with solid adsorbent materials and water baths. Air circulation is maintained using a 'chimney effect' as shown in Fig. 5.22.

In the morning when the east wall is heated by solar radiation, the air gets heated, rises up and is ducted outside. Due to the natural draught thus produced, air is drawn inside from the west side. The incoming west-side air first gets dried up by a solid adsorbent material, is evaporatively cooled by passing over water baths and then enters the room. The hot air going out through the east-facing wall regenerates the solid adsorbent material. In the evening when the west wall is heated up by the sun, a reversal of air flow occurs and the functions of east and west walls reverse.

5.4 SOLAR INDUSTRIAL HEATING SYSTEMS

Solar active heating systems are used for several industrial-process heat requirements. The process heat in various industries is generally supplied in the form of (i) process hot water, (ii) hot air, and (iii) process steam.

A hot-air solar heating system is shown in Fig. 5.23. Thermal energy is transported from the collector through hot air and is utilized for process heat. The excess heat is stored in a rock-bed thermal storage to be used later when solar radiation is not available. Auxiliary heating augments the supply when the heat supplied by the collector or storage is not sufficient. The used air is passed through a heat exchanger to recover the heat from the exhaust air to raise the initial temperature of fresh air entering the collector.

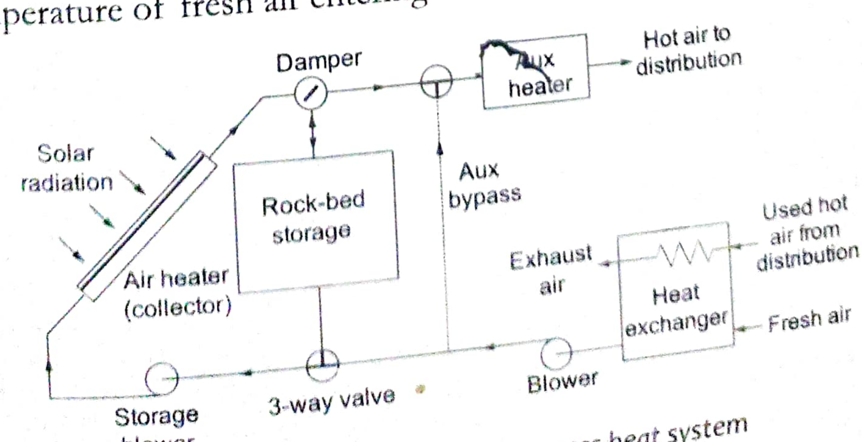


Fig. 5.23 *Hot-air industrial-process heat system*

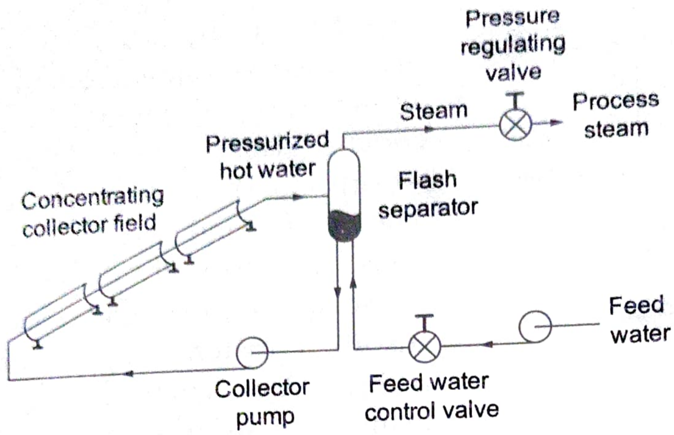


Fig. 5.24 *Solar-process steam system*

Figure 5.24 shows a solar process steam system. Pressurized water is circulated through a concentrating collector to prevent boiling. The high-pressure heated water is throttled and flash separated in a flash separator. To maintain the necessary liquid level in the flash tank, boiler feed water is injected into the pump suction. The saturated steam obtained from the flash separator is recirculated through the collector field and distributed for use. A pressure regulator valve regulates the pressure.

5.5 SOLAR REFRIGERATION AND AIR-CONDITIONING SYSTEMS

Solar energy can also be used in air conditioning (cooling for comfort) and refrigeration (cooling for preserving food). There are several ways of using solar energy for cooling purpose. However, one based on absorption cycle cooling is most widely used at present. The principle of absorption refrigeration was first demonstrated by Faraday in 1825. Thus, this is one of the oldest cycles for producing refrigeration effect, which differs fundamentally from the conventional vapour compression cycle in the method for compressing the refrigerant.

In absorption-cycle cooling systems two working fluids, a refrigerant and an absorbent–refrigerant solution, are used. The absorbent–refrigeration combination is so chosen that the absorbent has a high affinity for the refrigerant and at the same temperature, the vapour pressure of the refrigerant is higher than that of the absorbent. The absorbent cooling is based on the principle that the refrigerant can be bound by a liquid or solid solvent, known as the absorbent to release heat during absorption, while it absorbs heat during evaporation (and thus produces cooling effect). Though a large number of refrigerant–absorbent combinations are possible, the two most common and commercially tried combinations are LiBr–water (LiBr as absorbent and water as refrigerant) and aqua–ammonia (water as absorbent and ammonia as refrigerant). In the former, the absorbent is a solid (a salt), whereas in the later it is a liquid. The performance of a cooling cycle is judged from its *COP (coefficient of performance)*, which is defined as the ratio of amount of cooling produced to the energy input.

There are four major components in an absorption cycle cooling system: generator, condenser, evaporator and absorber. Cooling can be produced continuously or intermittently. An intermittent refrigerator is compact, simple in operation and

The main advantages of the aqua–ammonia absorption system are (i) it can provide both air conditioning and refrigeration, (ii) the refrigerant has low molecular weight and therefore, a high heat of vaporization, and (iii) the absorbent (water) is non-toxic and inexpensive. The disadvantages are (i) as the absorbent (water) is volatile, a rectifier unit is required to separate and drain it out, (ii) a comparatively high pumping power is required to pump working fluid from absorber pressure to the generator pressure, and (iii) ammonia is inflammable and toxic. Therefore, special precautions are required in its use.

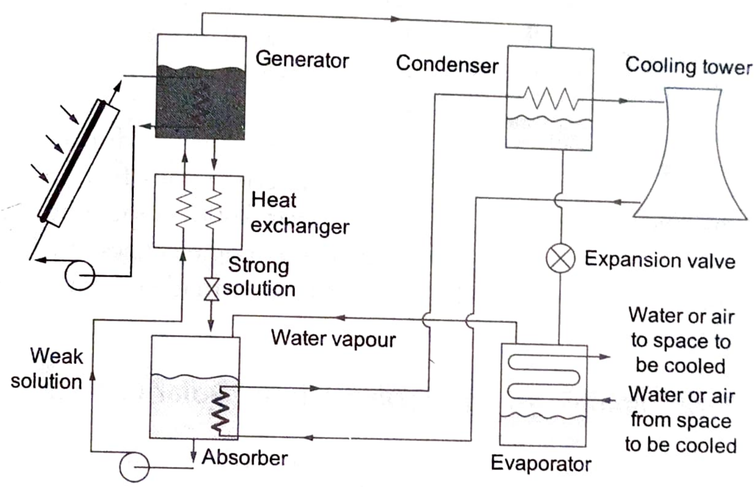


Fig. 5.26 *LiBr–H_2O absorption cooling system*

5.6 SOLAR COOKERS

Thermal energy requirements for cooking purpose forms a major share of the total energy consumed, especially in rural areas. A variety of fuels like coal, kerosene, cooking gas, firewood, dung cakes and agricultural wastes are used to meet the requirements. Fossil fuel is a fast-depleting resource and needs to be conserved. Firewood for cooking causes deforestation and cow dung, agricultural waste, etc., may be better used as good fertilizers. Harnessing solar energy for cooking purposes is an attractive and relevant option. A variety of solar cookers have been developed, which can be clubbed in four types of basic designs: (i) box type solar cooker, (ii) dish-type solar cooker, (iii) community solar cooker, and (iv) advanced solar cooker.

5.6.1 Box-Type Solar Cooker

The construction of the most common box-type solar cooker is schematically shown in Fig. 5.27. The external dimensions of a typical family-size (4 dishes) box-type cooker are 60 cm × 60 cm × 20 cm. This cooker is simple in construction and operation. An insulated box of blackened aluminum contains the utensils filled with food material. The box receives direct radiation and also reflected radiation from a reflector mirror fixed on the inner side of the box cover hinged to one

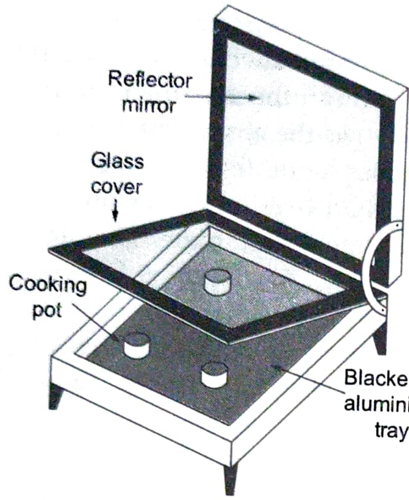


Fig. 5.27 *Box-type solar cooker*

side of the box. The angle of the reflector can be adjusted as required. A glass cover consisting of two layers of clear-window glass sheets serves as the box door. The glass cover traps heat due to greenhouse effect. The maximum air temperature obtained inside the box is around 140–160°C. This is enough for cooking boiling-type food-stuffs slowly in about 2–3 hours. It is capable of cooking 2 kg of food and can save up to 3–4 LPG cylinder fuel in a year. Electrical backup is also provided in some designs for use during non-sunshine hours. Its cost varies from Rs 1,800 to Rs 2,800 (year 2008) depending on the type, size, quality and electrical backup facility. A more affordable, folding-type model of solar cooker made of cardboard material has also been developed.

5.6.2 Paraboloidal Dish-type (Direct Type) Solar Cooker

A specially designed paraboloidal reflector surface concentrates the beam radiation at its focus, where a cylindrical brass vessel containing food material is placed. A commercial dish-type solar cooker, SK 14, developed by EG solar, an NGO of Germany, and being manufactured in India is shown in Fi[illegible]28. The vessel directly receives the concentrated solar radiation. The ref[illegible]s periodically adjusted to track the sun. A fairly high temperature of abou[illegible] can be obtained and a variety of food requiring boiling, baking and frying[illegible] cooked for 10–15 persons. It can save on fuel for up to 10 LPG cylinders a[illegible] on full use. The cooking time is approximately 20–30 minutes. The approx[illegible] cost of the cooker is Rs 8,500 (year 2008).

Fig. 5.28 *Paraboloidal dish-type solar cooker Source: MNES Annual Report*

5.6.3 Community Solar Cooker

Community solar cookers have been developed for indoor cooking. A community solar cooker has a large automatically tracked paraboloidal reflector standing outside the kitchen. The reflector reflects the sun's rays into the kitchen through an opening in its north wall. A secondary reflector further concentrates the rays on to the bottom of the cooking pot, which is painted black. It can cook all types of food for about 40–50 people and can save up to 30 LPG cylinders in a year with optimum use.

In another design of a community solar cooker, large number of automatically tracked paraboloidal reflectors are installed in series and parallel combinations and generate steam for cooking in a community kitchen. It can cook food for thousands of people in a short time depending upon its capacity. It is normally installed in conjunction with a boiler that may also use conventional fuel when necessary.

5.6.4 Advanced Solar Cooker

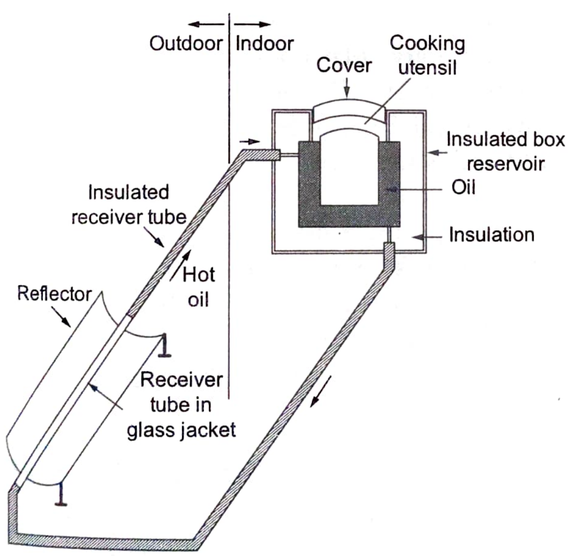


Fig. 5.29 *Advanced solar cooker*

The main disadvantage of the above cookers is that there is no provision for storing thermal energy; hence, cooking is possible only when the sun is available (unless an auxiliary source is also available). An advanced type cooker has been designed to overcome these difficulties. The cooker is schematically shown in Fig. 5.29. Basically, it consists of two parts: (i) an outdoor, parabolic cylindrical reflector of a size, typically 3 m× 2 m × 0.5 m, and (ii) an indoor, insulated hot-box reservoir of a size typically 0.4 m× 0.4 m × 1.2 m, kept at a level higher than the collector. Oil is used as a heat-transport fluid from the collector to hot-box reservoir. The oil in the receiver tube rises up due to natural convection after absorbing heat from the reflector and stores it in the reservoir. The reflector has an equatorial mounting with adjustments for seasonal variation of the sun or an arrangement for automatic solar tracking using a simple clock mechanism. The temperature at the top of the reservoir on sunny days reaches 150°C and rarely falls below 100°C even during nights. All types of cooking, except those which require frying and roasting, can be done with this cooker. Some other variations in the basic design such as use of a large hemispherical bowl-type collector, use of a heat exchanger to raise steam from heated oil for steam cooking are also possible. Such types of solar cookers are especially useful as large-size community cookers for military camps, temples, ashrams, gurdwaras and hostels.

There are four principal ways of cooking: (i) boiling, (ii) baking, (iii) frying, and (iv) roasting. Box-type cookers are suitable for boiling and baking. Paraboloidal dish-type cookers are suitable for boiling, baking and frying as higher temperatures are achieved. Advanced type cookers can perform boiling and baking only but have the advantage of thermal storage and indoor use. The major reasons for non-acceptability of a solar cooker are: (i) it is too expensive for individual family ownership, (ii) it is incompatible with traditional cooking practices, (iii) it requires comparatively more time and the menu has to be preplanned, (iv) it is to be used outdoors (except community and advance cookers), and (v) cannot be used during nights and cloudy days (except advanced cooker).

A 15-m diameter community solar cooker has been developed at the Centre for Scientific Research (CSR), Auroville (Pondicherry). Around 600 kg of steam per day could be generated from this bowl, which is sufficient to cook two meals for about 1000 people. A very large community solar cooker has recently been installed at Tirumala Tirupathi Devasthanam at AP, under the demonstration scheme of the Ministry of Non-conventional Energy Sources. This is said to be the largest solar cooker in the world and is used for cooking food for 15,000 devotees daily. It has 106 automatic solar-concentration collectors (Scheffler solar concentrator), each of 9.2 sq. m diameter, produce 4000 kg of steam daily at 180°C and 10 kg/cm^2 for steam cooking. The system is expected to save 1,18,000 litres of diesel annually. The total cost of the system is Rs 110 lakhs (year 2003). So far about 5,55,000 box-type and 2000 dish-type solar cookers have been sold in the country. About 100 community solar cookers with steam cooking have been installed in the country.

5.7 SOLAR FURNACES

A solar furnace is an ideal tool to study the chemical, optical, electrical and thermodynamic properties of the materials at high temperatures. It is basically an optical system in which solar radiations are concentrated over a small area. It has two main components: (i) a concentrator, and (ii) a single piece of a large-sized heliostat or a system of a large number of small heliostats. The basic principle is shown in Fig 5.30. The large number of heliostats direct solar radiation onto a paraboloidal reflector surface. The heliostats are adjusted such that they direct the radiation parallel to the optical axis of the paraboloid. Accurate sun tracking is required for this purpose. The concentrators focus the incoming rays at the target placed at their focii.

Active solar thermal collector

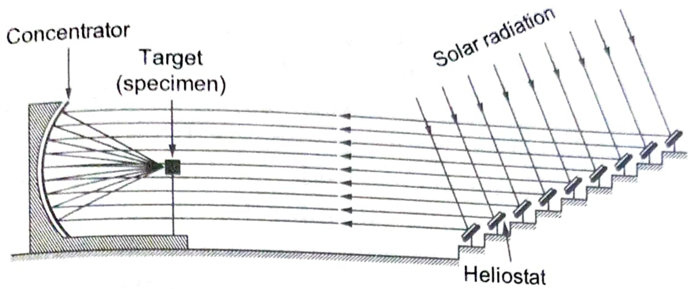


Fig. 5.30 *Solar furnace*

There is another possible configuration of a solar furnace, where the optical axis is vertical. A large heliostat directs the radiation upwards and the concentrator reflects it downward at its focus. In this arrangement, the unmelted portion of a specimen forms a crucible to hold the melted portion and is suitable for fusion studies.

There are few solar furnaces in countries like France, USA, Germany and Russia for scientific study. One of the world's largest solar furnace of 1000 kW output was installed at Odeillo, Font–Romeo, France in 1970. It has 63 heliostats, each 7.5 m × 6 m in size. The parboloidal concentrator is 40 m high, 54 m wide and 13 m above the ground level with a focal length of 18 m. Temperatures obtained are in the range of about 3,500°C.

Some of the advantages of a solar furnace are (i) heating without contamination, (ii) easy control of temperature, (iii) simple working, (iv) high heat flux obtainable, (v) continuous observation possible, and (vi) absence of electromagnetic field. In spite of the many advantages of solar furnaces, these have not become popular in industries due to the following reasons:

(i) Their use is limited to sunny days and that too for 4–5 hours only.
(ii) Their cost is high.
(iii) Very high temperatures are obtained only over a very small area.

5.8 SOLAR GREENHOUSE

A greenhouse is an enclosure where proper environment is provided for growth and production of crops, vegetable and flower plants under adverse climatic conditions. By controlling the environment, a particular vegetable or flower can be grown throughout the year. The design of a greenhouse depends on local climatic conditions. In cold countries, winter greenhouses provide supplementary heat to maintain adequate temperature during the cold months when solar insolation is low. In tropical countries, the solar insolation and ambient temperatures are quite high and therefore summer greenhouses are used to maintain low temperatures inside and allow just sufficient sunlight for photosynthesis. Greenhouses for arid zones are designed to conserve water resources. Although, there is slight variation in the environmental needs of each variety of plant for best production, basically