RENEWABLE ENERGY POWER PLANTS

(Course Code:21ME652)

Department of Mechanical Engineering
JSS Academy of Technical Education, Bangalore-560060

MODULE 2

Solar Radiation Geometry: Flux on a plane surface, latitude, declination angle, surface azimuth angle, hour angle, zenith angle, solar altitude angle, expressions for the angle between the incident beam and the normal to a plane surface (No derivation) local apparent time, apparent motion of sun, day length, numerical problems.

Solar Thermal Systems: Flat plate collector, Evacuated Tubular Collector, Solar air collector, Solar concentrator, Solar distillation, Solar cooker, Thermal energy storage systems, Solar Pond, Solar Chimney (Tower). Solar Photovoltaic Systems: Introduction, Solar cell Fundamentals, Characteristics and classification, Solar cell: Module, panel and array construction

Module -2

Solar Radiation Geometry:

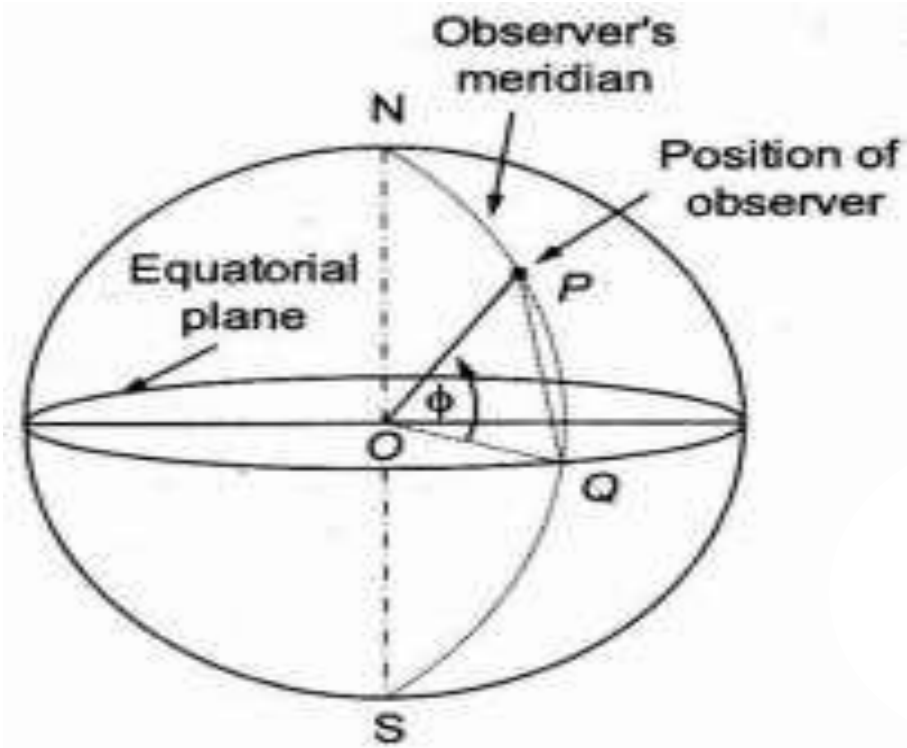


Figure 2 .11: Latitude

- **Latitude (Angle of Latitude) (Ø):** The latitude of a location on the earth's surface is the angle made by the radial line joining the specified location to the centre of the earth with the projection of this line on the equatorial plane as shown in the Figure 2.11.
- **Declination angle, (d):** It is the angle made by the line joining the centers of the sun and earth with the equatorial plane as shown in Figure 2.12. The angle of declination varies when earth revolves around the sun .

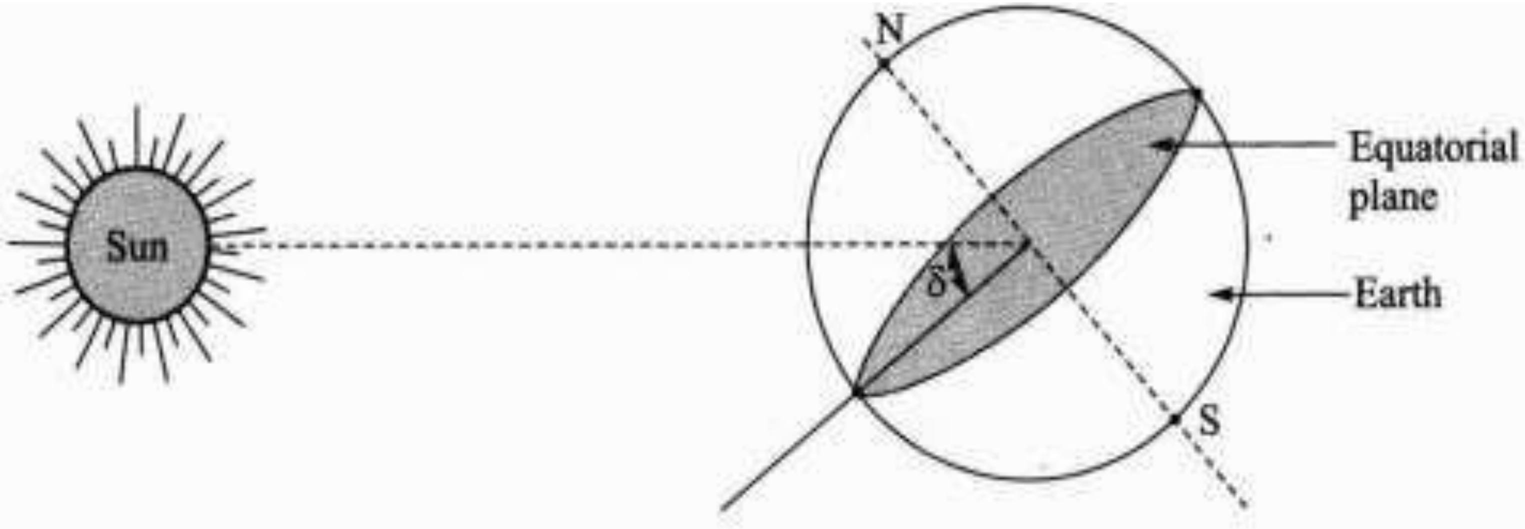


Figure 2 .12 Declination angle

Declination is the direct consequence of earth's tilt and It would vary between 23.5° on June 22 to – 23.5° on December 22. On equinoxes of March 21 & Sept 22 declination is zero.

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

Where n is the day of the year.

- It has a maximum value of 23.45° when the earth achieves a position in its orbit corresponding to 21st J u n e and has a minimum value of -23.45° when the earth is in orbital position corresponding to 21st December.
- The angle of declination is taken positive when it is measured above the equatorial plane in the northern hemisphere. The angle of declination is given by the equation.
- $\delta = 23.45 \times \sin[360/365\ (284+n)]$, Where 'n' is the number of days from January 1.

- **Hour angle, (w):** The hour angle at any instant is the angle through which the earth has to turn to bring the meridian of the observer directly in line with sun ray's. It is an angular measure of time.
- It is the angle in degree traced by the sun in one hour with reference to the twelve noon of the location.

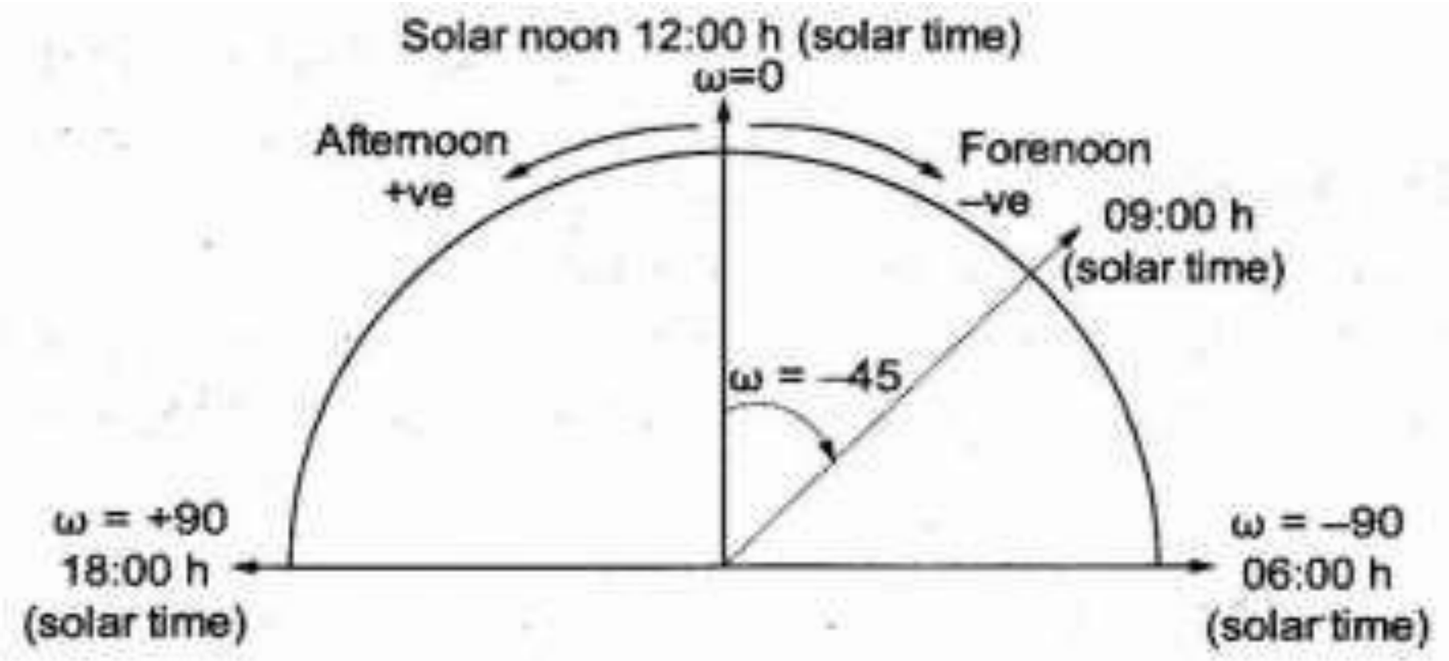
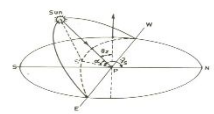


Figure 2 .13: Hour angle

- Figure 2.13. The earth completes one rotation (360°) in 24 hours. Hence one hour corresponds to 15° of earth's rotation.
- As at solar noon the sun rays in line with local meridian or longitude, the hour angle at that instant is zero. The hour angle is given by the equation.
- **w = [Solar time - 12] * 15°**
- **Inclination or Altitude angle, (α):** The angle between the sun's ray and its projection on a horizontal surface is known as the inclination angle, as shown in the Figure 2.14.
- **Zenith angle, (θ_z):** It is an angle between sun's ray and the perpendicular to the horizontal plane i.e. angle between the beam and the vertical as shown in Figure 2.14.

It is Complementary angle of Sun's Altitude angle $\Theta_z = \pi/2 - \alpha$



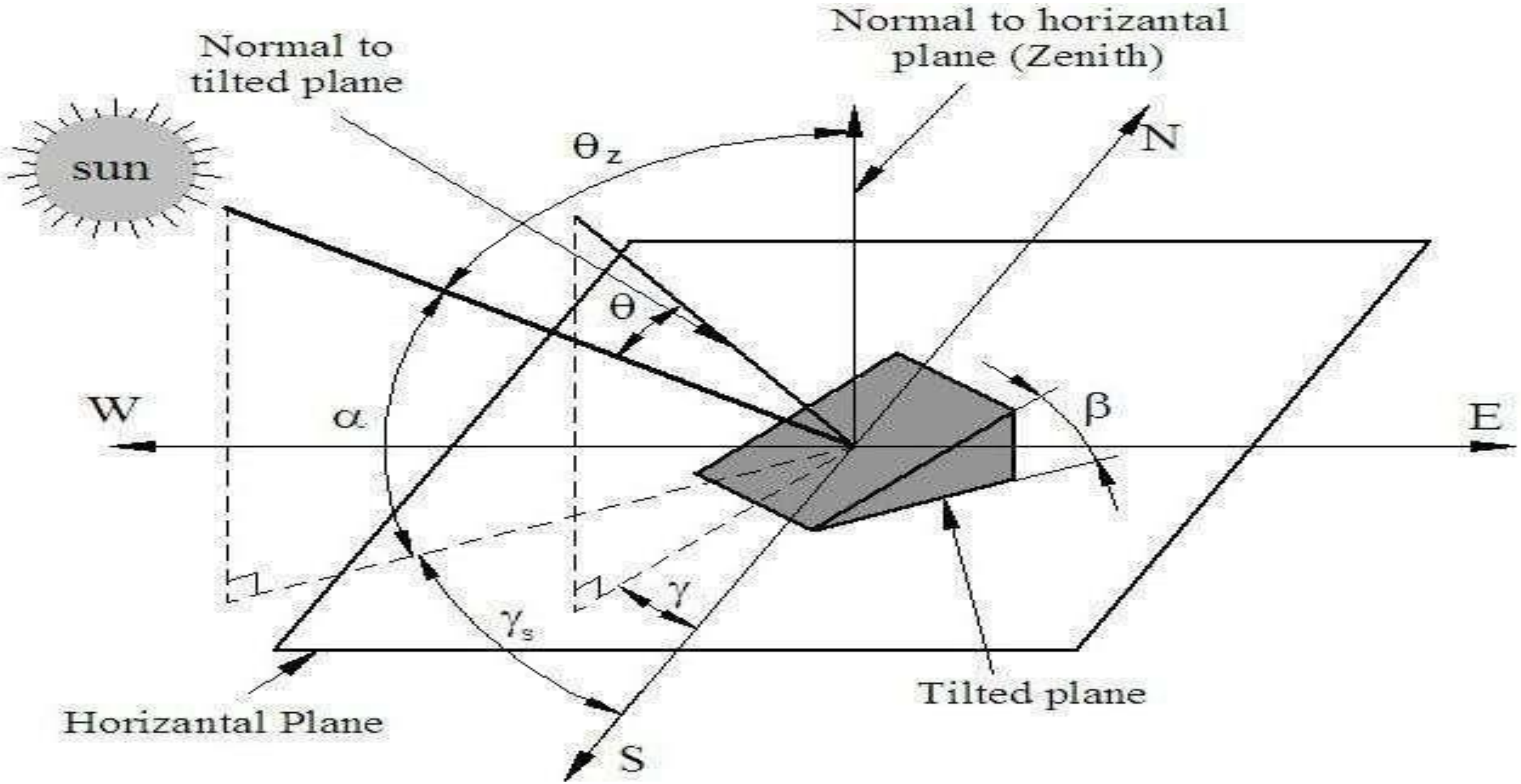


Figure 2.14 Solar radiation geometry

- **Solar Azimuth angle, (γ_s):** It is the angle on a horizontal plane, between the line due south and the projection of the sun's ray on the horizontal plane. It is taken as positive when measured from south towards west.
- **Surface Azimuth angle, (γ):** It is the angle in the horizontal plane, between the line due south and the horizontal projection of the normal to the inclined plane surface (flat plate collector) as shown in Figure 2.14. It is taken as positive when measured from south towards west.
- **Slope or Tilt angle, (β):** It is the angle between the inclined plane surface (flat plate collector) and the horizontal plane as shown in Figure 2.14. It is taken to be positive for the surface sloping towards south.

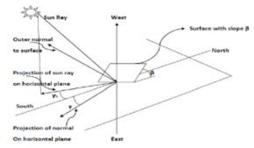


Fig.1.6 surface azimuth angle and solar azimuth angle

Meridian:

- Meridian is the imaginary line passing through a point or place on earth and north and south poles of the earth'.

- **Angle of incidence, (ɵ):** The angle of incidence for any surface is defined as the angle formed between the direction of the sun ray and the line normal to the surface as shown in Figure 2.14.

- **General equation for cos ɵ:** cos ɵ = [sin Ø (sin δ cos β + cos δ cos γ cos ω sin b) + cos Ø (cos δ cos ω cos β - sin δ cos γ sin β) + cos δ sin γ sin ω sin β].

- Where,

θ	:	Angle of incidence
Ø	:	Angle of latitude
δ	:	Angle of declination
γ	:	Surface azimuth angle
β	:	Tilt angle

1. *For a vertical surface: $\beta = 90°$:*

$$\cos\theta = \sin\text{Ø}\cos\delta\cos\gamma\cos\omega - \cos\text{Ø}\sin\delta\cos\gamma + \cos\delta\sin\gamma\sin\omega$$

Note: ($\sin 90° = 1$, $\cos 90° = 0$)

2. *For a horizontal surface: $\beta = 0°$: $\theta = \theta_Z$ (Zenith angle)*

$$\cos\theta = \cos\theta_Z = \sin\text{Ø}\sin\delta + \cos\text{Ø}\cos\delta\cos\omega$$

Note: ($\sin 0° = 0$, $\cos 0° = 1$)

Also,

$$\cos\theta = \cos\theta_z = \sin\alpha \left(\text{since } \theta_z = \frac{\pi}{2} - \alpha\right)$$

3. *Surface facing south: $\gamma = 0°$:*

$$\cos\theta = \sin\text{Ø}\,(\sin\delta\cos\beta + \cos\delta\cos\omega\sin\omega) + \cos\text{Ø}\,(\cos\delta\cos\omega\cos\beta - \sin\delta\sin\beta)$$

Therefore $\cos\theta = \sin\delta\sin(\text{Ø} - \beta) + \cos\delta\cos\omega\cos(\text{Ø} - \beta)$

4. *Vertical surface facing south: $\beta = 90°$, $\gamma = 0°$:*

$$\cos\theta = \sin\text{Ø}\cos\delta\cos\omega - \cos\text{Ø}\sin\delta$$

Day Length: At the time of sunset or sunrise the zenith angle $\theta_z = 90^o$, we obtain sunrise hour angle as

$$Cos\ \omega s = -\frac{Sin\phi Sin\delta}{cos\phi\ Cos\delta} = -tan\phi\ tan\delta$$

$$\omega s = Cos^{-1}\{-\tan\phi\ tan\delta\}$$

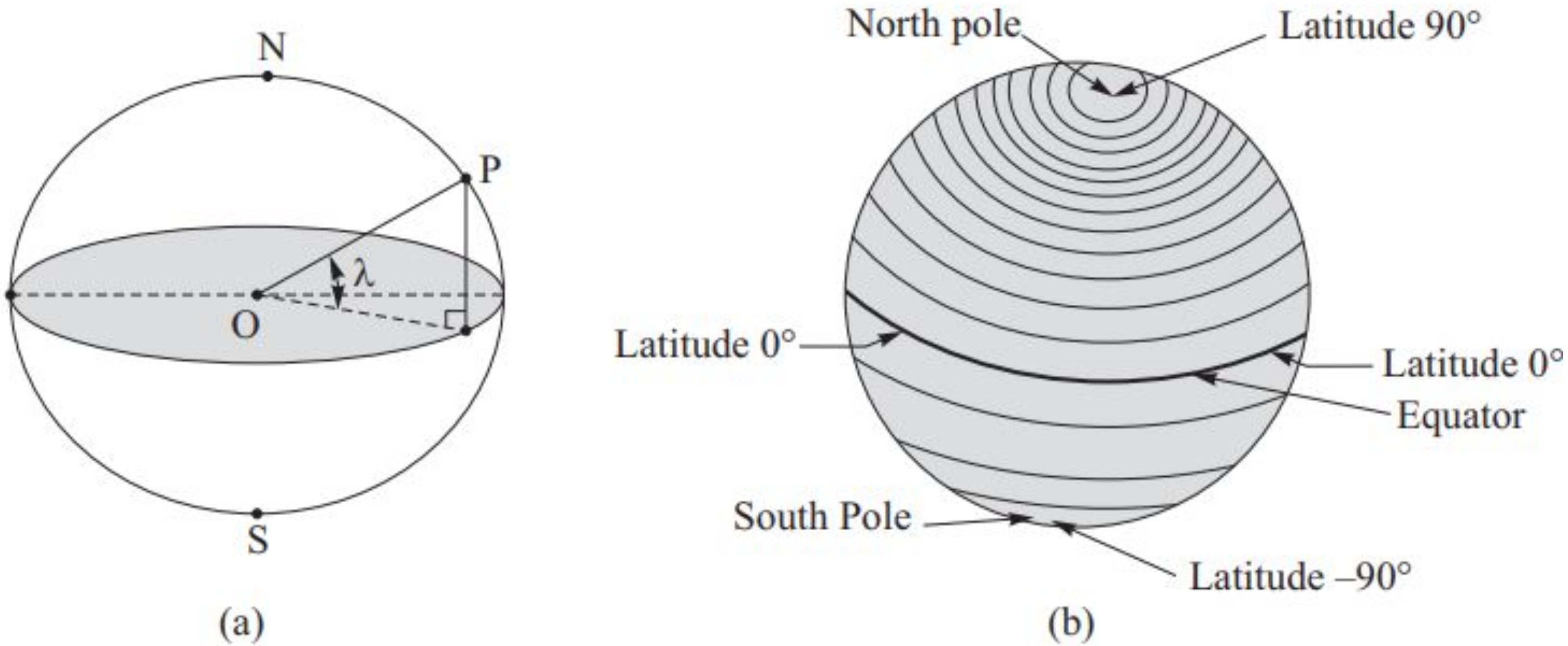
Since 15^0 of the hour angle are equivalent to 1 hour

The day length(hrs) is given by

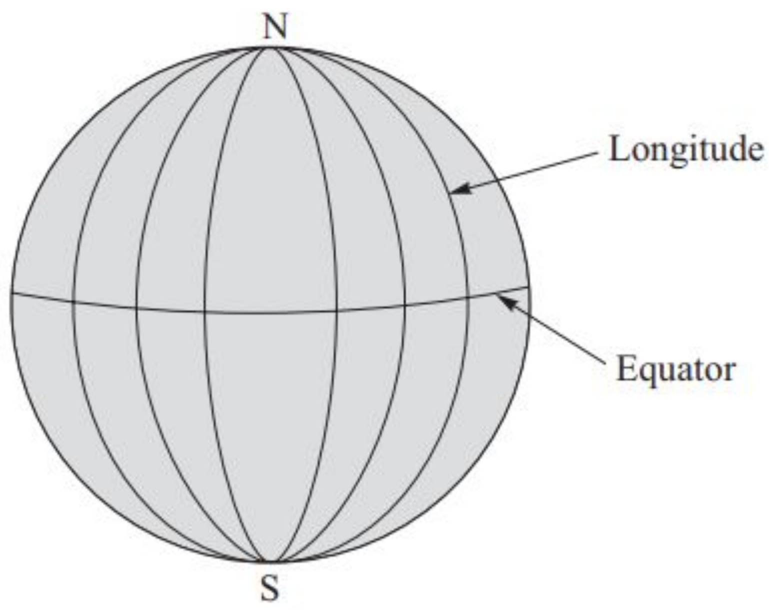
$$td = \frac{2\omega}{15} = \frac{2}{15} cos^{-1} - \{tan\phi\ tan\delta\}$$

Latitude and longitude:

- **Latitude:** On a globe of the earth, line of latitude is circle of different sizes. The largest one is at the circle of equator (circle at equator with centre at earth's centre) whose latitude is taken as zero.
- The circles at the poles have latitude of 90° North and 90° South (or -90°) where these circles shrink to a point, there are 180 circles of which 90 in each hemisphere specify the latitude of various points on earth's surface as shown in Figure 2.15 (a).
- Each degree of latitude is about 111 km apart. Latitude lines run horizontally and these lines are parallel.



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



- **Longitude:** On the globe, vertical lines of constant longitude (meridians) extend from pole to pole similar to the segment boundaries on a peeled orange.
- Every meridian has to cross the equator and equator is a circle, like any circle, it has 360° of divisions.
- Hence, the longitude of a point is marked a value of that division where its meridian meets the equator circle.
- The meridian passing through the Royal Astronomical observatory at Greenwich, UK has been chosen as zero latitude. The meridian passing through this location is called prime meridian.

- This prime meridian or longitude is considered zero longitude and there are 180 longitude lines or degree as east (+180°) and 180° at west (-180°) of Greenwich.
- The longitude lines meet at poles and these have wide separation at equator about (111 km).
- The longitudinal lines are shown in Figure Solar noon is the time when the sun is at the longitude of place.

Apparent motion of the sun:

- To an observer on the earth, on any given day, the sun rises in the east, moves in a tilted plane in the angle of [90° - ∅] with the horizontal, and finally sets in the west. Thus, the apparent plane in which the sun moves intersects the horizontal plane in a line positioning east-west.

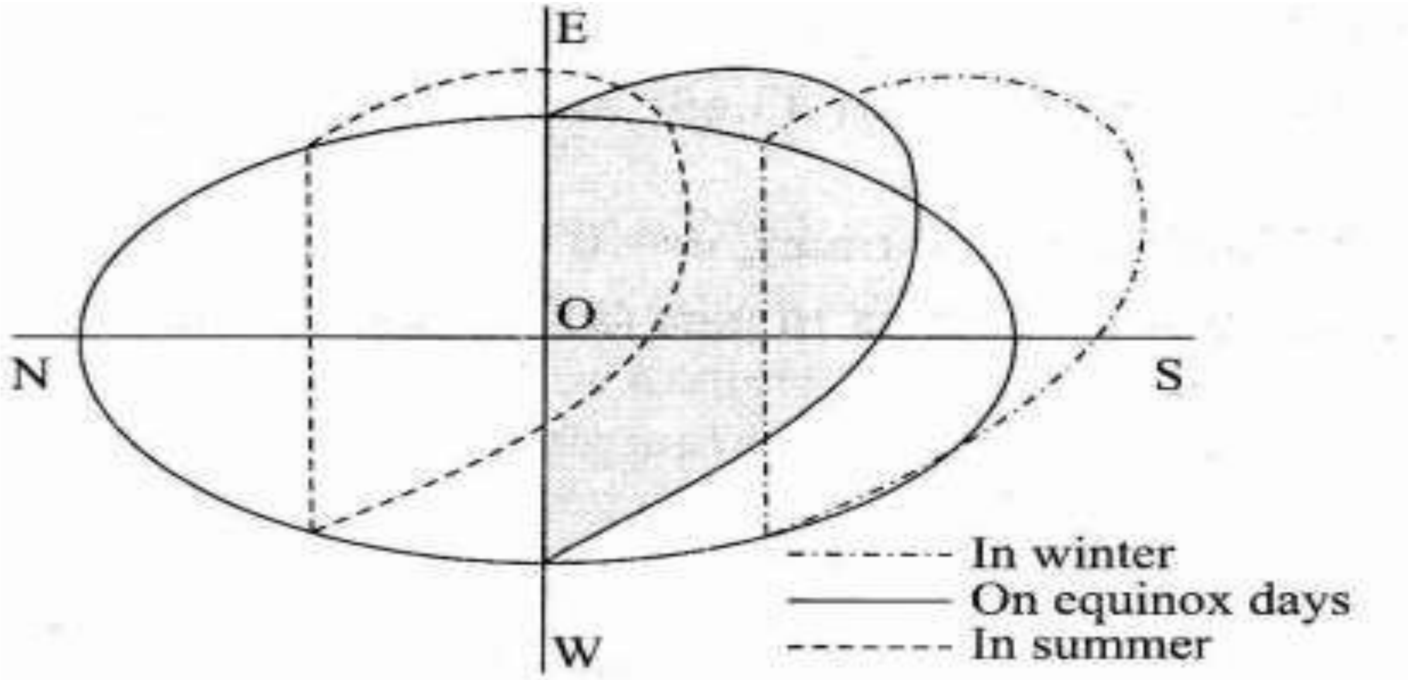
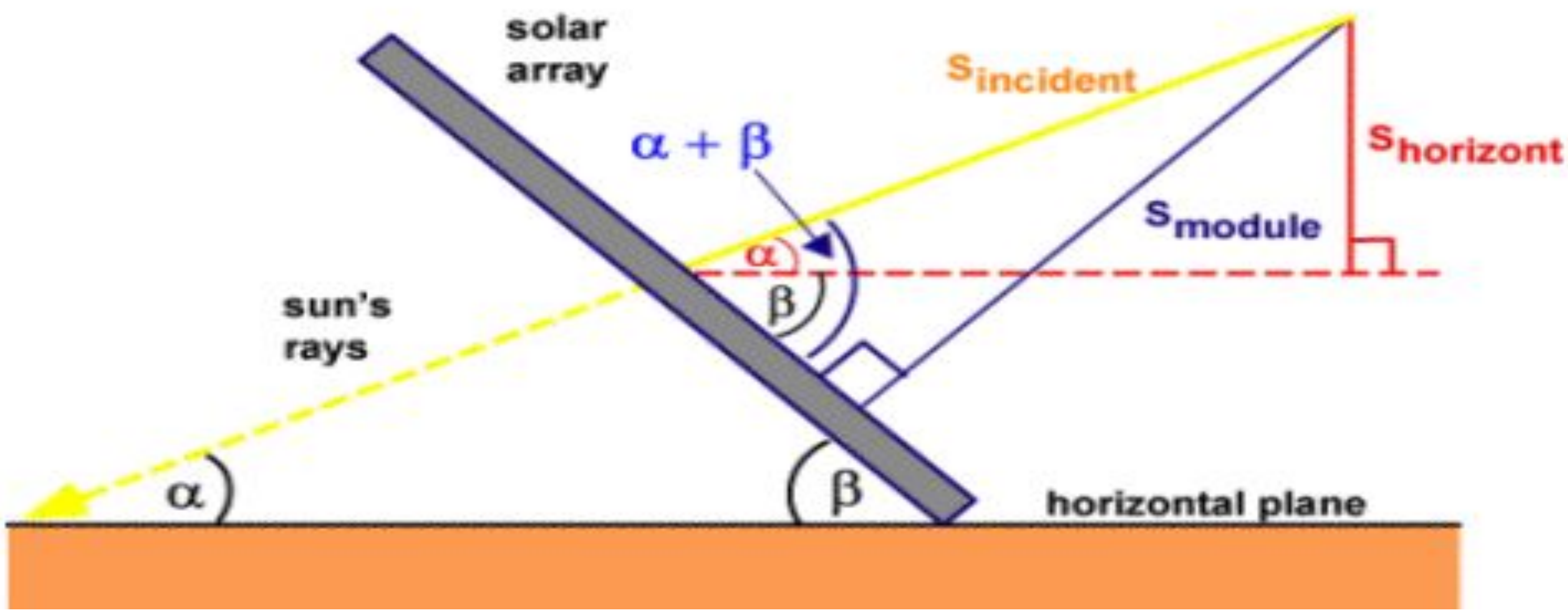


Figure 2 .15 Apparent motion of the sun

- However because of the declination angle this E- W line of intersection does not coincide with E-W passing through the observer O, for a location in the northern hemisphere, this line is to the south in winter (declination negative, 21st December with an angle of -23.45°) to the north in summer (declination positive, 21st June with an angle of 23.45°) and coincides with the E–W line passing through the observer on two equinox days i.e. 21st March & 21 September (declination is zero).

Local Solar Time (Local Apparent Time (LAT)):

- Local Solar Time can be calculated from standard time by applying two corrections.
- The first correction arises due to the difference in longitude of the location and meridian on which standard time is based.
- The correction has a magnitude of 4minutes for every degree difference in longitude.
- Second correction called the equation of time correction is due to the fact that earth's orbit and the rate of rotation are subject to small disturbance of motions. This is based on the experimental observations.
- Local Solar Time = Standard time ± 4(Standard time Longitude - Longitude of the location)+(Equation of time correction).



Relation between θ and other angles is as follows,

$\cos\theta = \sin\phi_l(\sin\delta \cos\beta + \cos\delta \cos\gamma \cos\omega \sin\beta) + \cos\phi_l (\cos\delta \cos\omega \cos\beta - \sin\delta \cos\gamma \sin\beta) + \cos\delta \sin\gamma \sin\omega \sin\beta$.

ϕ_l=Latitude (north positive).

δ=declination (north positive).

ω=solar hour angle (Positive between midnight and solar noon).

Day Length:

- At the time of sunset or sunrise the zenith angle $\theta_z = 90^o$, we obtain sunrise hour angle as,

$$Cos\ \omega s = -\frac{Sin\phi Sin\delta}{cos\phi\ Cos\delta} = -tan\phi\ tan\delta$$

$$\omega s = Cos^{-1}\{-\tan\phi\ tan\delta\}$$

Since 15^0 of the hour angle are equivalent to 1 hour

The day length(hrs) is given by

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Numericals

- **Example 1:** Determine the local solar time and declination at a location latitude $23^0 15'N$, longitude $77^0 30'E$ at 12.30 IST on June 19. Equation of Time correction is = - (1'01").

Solution:

The Local solar time= IST- (Standard time longitude - Longitude of location)+ Equation of time correction.

$=12^h 30' - 4\,(82^0\,30' - 77^0\,30') - 1'01''.$

Indian standard time (IST) is the local civil time corresponding to 82.5^0E longitude.

$=12^h\,30' - 4\,(82^0\,30' - 77^0\,30') - 1'01''.$

$=12^h\,30' - 4*5 - 1'01''.$

$=12^h\,8'\,59''.$

- Declination δ can be calculated Cooper's Equation i.e,

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

- = 23.45 sin {360/365 (284 + 170) }. ('n' is the day on here = 170 on June 19).
- = 23.45 sin (447)
- = 23.45 sin (360+87)
- δ = 23.45 sin 87°
- δ = 23.41°.

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

As collector is pointing due south,

$$\gamma = 0$$

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

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

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

$$= -22.11°$$

w = [Solar time - 12] * 15°

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

$= -45°$

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

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

$\times \cos 45 \times \cos(28.58 - 36)$

$= 0.6982$

$\theta = 45.7°$

- Calculate an angle made by beam radiation with normal to a flat plate collector on December 1 at 9.00 A.M, Solar time for a location at $28^0 58'$N. The collector is tilted at an angle of latitude plus 10^0, with the horizontal and is pointing due south.

- ***Solution:*** Here $\gamma=0$ since collector is pointing due south. For this case we have equation.

Solution:

$\gamma = 0$, since collector is pointing due south.
For this case we have the equation.

$$\cos \phi_T = \cos(\phi - s) \cos \delta \cos \omega + \sin(\phi - s) \sin \delta$$

Declination 'δ' can be obtained with the help of cooper equation on December 1,

$n = 335$.

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

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

$$= 23.45 \sin(610.52)$$

$\sin(610.52) = -0.9427$

$\sin(360 + 250.52)$

$\sin(250.52)$

$= -0.9427$

$$= 23.45(-0.9427)$$

$$= -22.10 \simeq -22.4^\circ$$

Hour angle ω corresponding to 9.00 hour = 45°

$$\cos\theta_T = \cos(28.58° - 38.58°) \cdot \cos(-22.11°) \cdot \cos(45°) + \sin(-22.11°) \cdot \sin(28.58° - 38°58°)$$

$$= \cos(-10°) \cdot \cos(-22.4°) \cos(45°) + \sin(-22.11) \sin(-10°)$$

$$= \cos 10° \times \cos 22.11° \times \cos 45° + \sin(22.11°) \cdot \sin(10°)$$

$$= 0.9848 * 0.9264 \times 0.7071 + 0.376 \times 0.1736$$

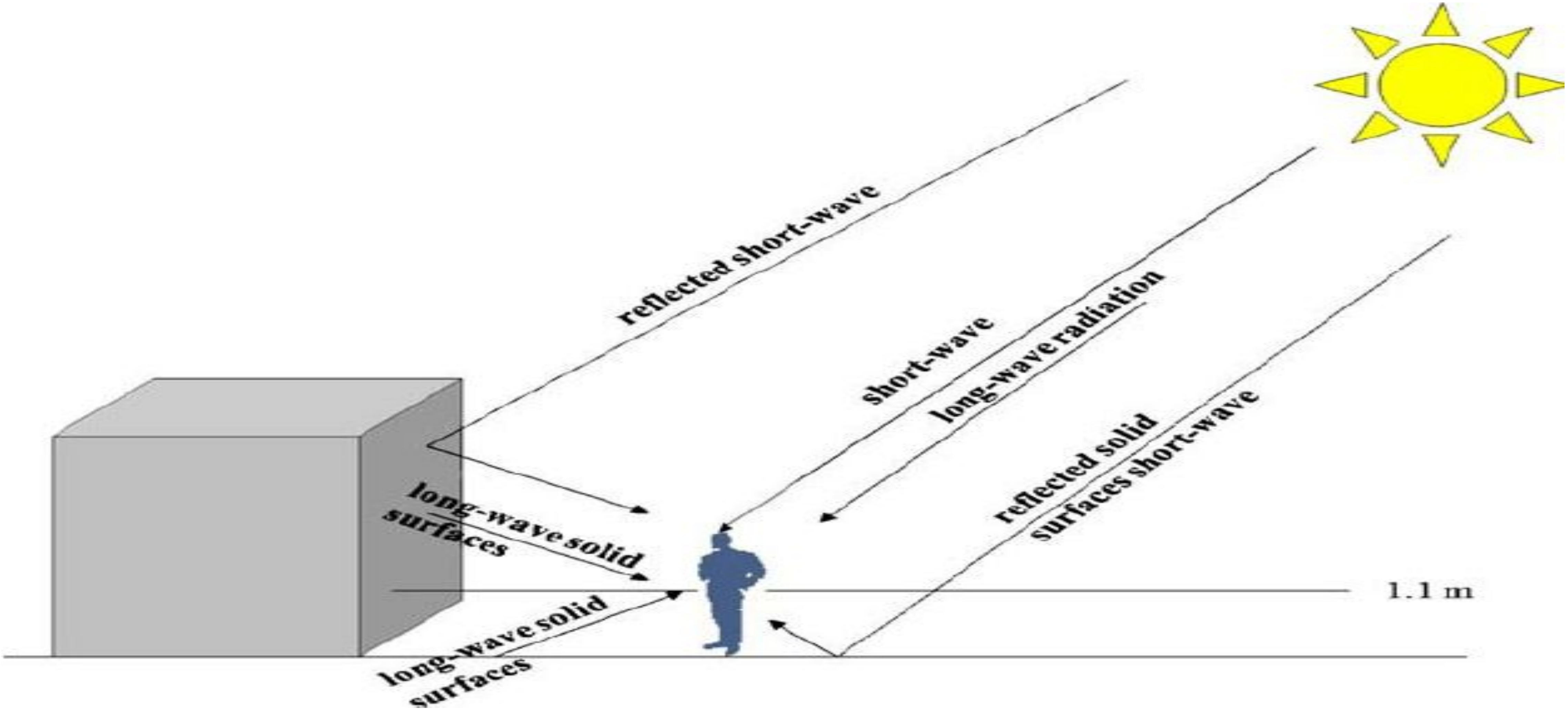
$$\cos\theta_T = 0.7103$$

$$\theta_T = \cos^{-1}(0.7103)$$

$$\underline{\underline{\theta_T = 44.74°}}$$

Beam Radiation:

- ***TILT FACTOR (r_b):*** The ratio of beam radiation flux falling on the tilted surface to that of horizontal surface is called the *TILT FACTOR* for beam radiation.



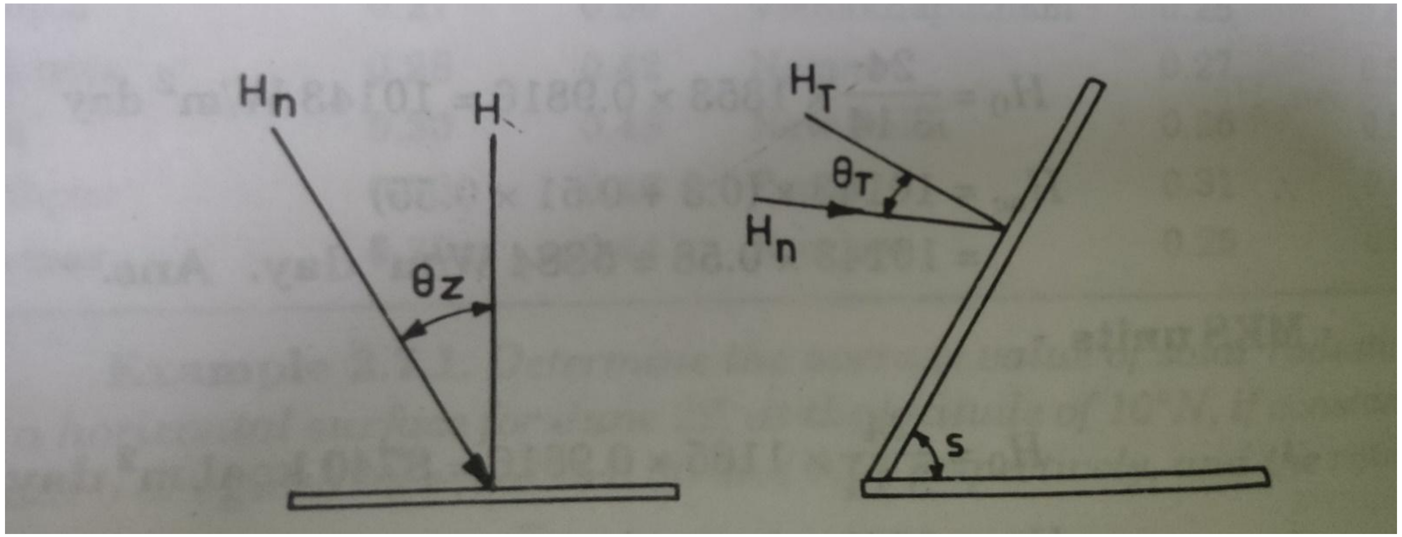
- **For case of tilted surface facing due south γ=0**

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

while for a horizontal surface

$$\cos\theta_z = \sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega$$

Hence $$r_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\sin\delta \sin(\phi - \beta) + \cos\delta \cos\omega \cos(\phi - \beta)}{\sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega}$$



Diffuse Radiation:

- ***TILT FACTOR (r_d):*** The ratio of diffuse radiation flux falling on the tilted surface to that of horizontal surface is called the *TILT FACTOR* for diffuse radiation.
- Its value depends on the distribution of diffuse radiation over the sky and the portion of the sky dome seen by the tilted surface.
- Assuming that the sky is an isotropic source of diffuse radiation, for a tilted surface with slope β, we have,

$$r_d = \frac{1 + \cos\beta}{2}$$

- (1+ cosβ)/2 is the shape factor for a tilted surface w.r.t. sky
- For Total radiation, let H_b=Hourly beam radiation and H_d=Hourly diffuse radiation.

- Thus the total beam radiation incident on a tilted surface is given as,

$$H_T = H_b R_b + \frac{Hd(1+cosS)}{2} + \frac{(Hb+Hd)\,(1-cosS)}{2}\rho$$

ρ = diffuse reflectance which is used to account for the reradiated.

Solar collector

Solar collector is a device for collecting solar radiation and then transferring the absorbed energy to a fluid passing through it.
A solar collector absorbs solar energy in the form of heat and simultaneously transfers this heat to a fluid so that the heat can be transported by the fluid.
The transport fluid takes this transferred heat from the collector and delivers it to a thermal storage tank, boiler or heat exchanger so that it can be utilized in a solar thermal system.

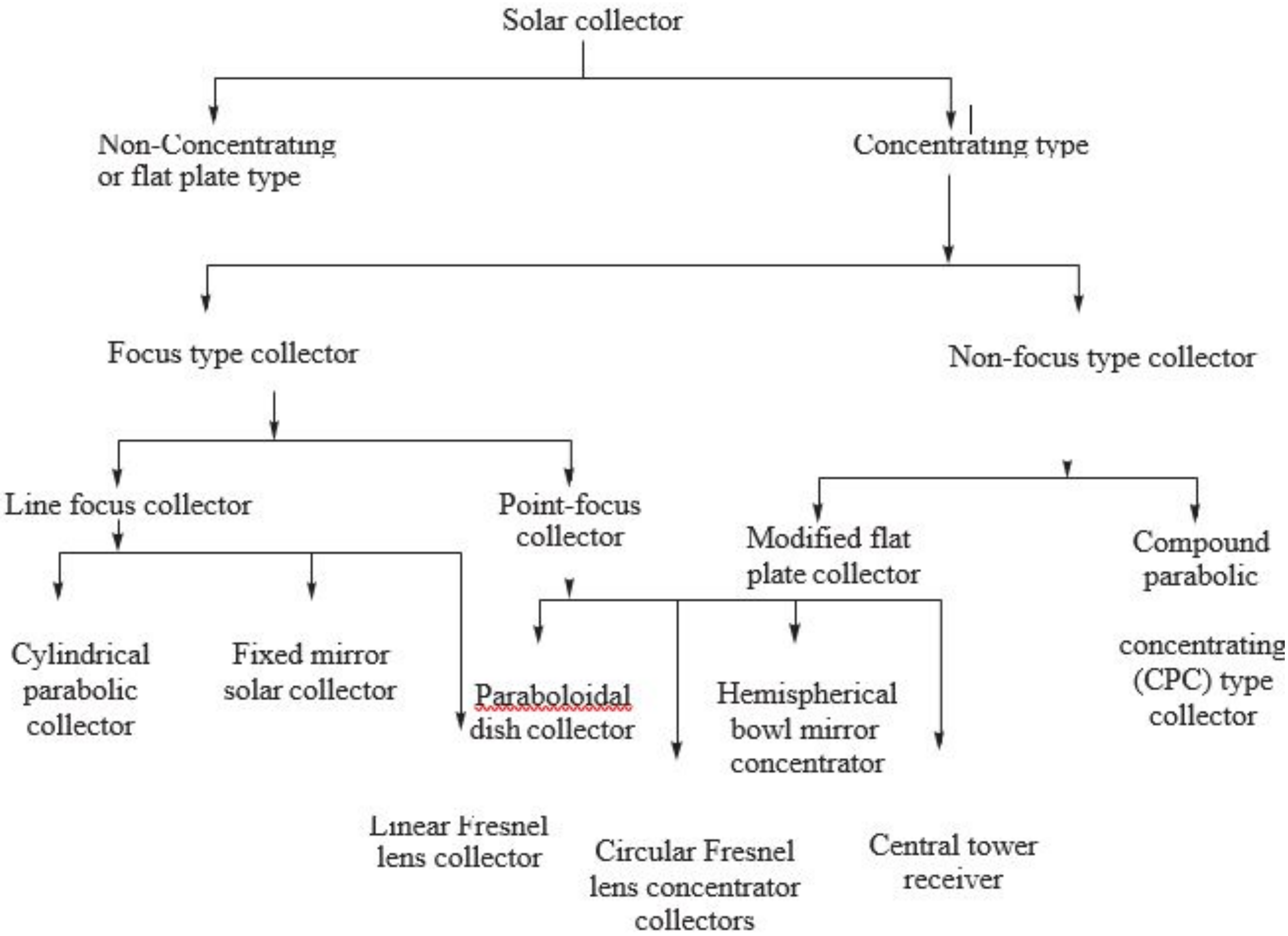
solar collector for the conversion of solar radiation energy into more usable form of energy such as heat or electricity.

Solar collectors:

- Solar collectors are the devices used to collect solar radiation.
- Generally there are two types of solar collectors. They are,
- 1) Non-concentrating type or Flat plate collector and 2) Concentrating or Focusing collector.
- In a non-concentrating type, the area of the absorber is equals the area of the collector and since the radiation is not focused, the maximum temp achieved in this type is about 100° C.
- In a concentrating type, the area of the absorber is very small (50-100 times) as compared to the collector area. This results in less loss of heat and also since the radiation is focused to a point or a line the maximum temp achieved is about 350° C.

Principle of solar energy conversion to heat:

- The principle on which the solar energy is converted into heat is the — "greenhouse effect".
- The name is derived from the first application of green houses in which it is possible to grow vegetation in cold climate through the better utilization of the available sunlight.
- The solar radiation incident on the earth's surface at a particular wavelength increases the surface temp of the earth.
- As a result of difference in temp between the earth's surface and the surroundings, the absorbed radiation is reradiated back to the atmosphere with its wavelength increased.


Solar collector
Non-Concentrating or flat plate type
Concentrating type
Focus type collector
Non-focus type collector
Line focus collector
Point-focus collector
Modified flat plate collector
Compound parabolic concentrating (CPC) type collector
Cylindrical parabolic collector
Fixed mirror solar collector
Paraboloidal dish collector
Hemispherical bowl mirror concentrator
Linear Fresnel lens collector
Circular Fresnel lens concentrator collectors
Central tower receiver

- In the non-concentrating solar collectors, the collector²s or radiation interceptor²s area is the same as that of absorber²s area.
- Concentrating collectors can be used to generate steam of medium temperature and pressure.
- The concentrating collectors use different arrangements of mirrors and lenses to concentrate solar radiation for effective generation of steam in the boilers and other devices.
- The concentrating type solar collectors have better efficiency than that of flat plate type collectors. To improve their efficiency, the collectors should be movable by the tracking system so as to make the collectors always facing the sun when the sun moves through the sky. T
- he line focus type collectors require one axis tracking while the point focus type collectors require two axes tracking.
- The line focus, point-focus and non-focus type collectors are as enumerated in the classification as shown in Figure

- While non-focus type collectors utilize both beam and diffuse radiation, the focus type collectors utilize only beam radiation as diffuse radiation cannot be focused.
- Concentrating collectors can increase the power flux of sunlight by hundreds of times. This class of collectors is used for high temperature applications, such as steam generation.
- Concentrating collectors are best suited to such climates that have a high percentage of clear sky days as cloudy days have diffuse radiation which cannot be concentrated. The main type of concentrating collectors are (i) parabolic dish collectors, (ii) parabolic trough collectors, (iii) power tower and stationary concentrating collectors.

The important features of a solar collector are as follow:

Collector efficiency

Concentrating ratio (CR)

Temperature range

Collector efficiency

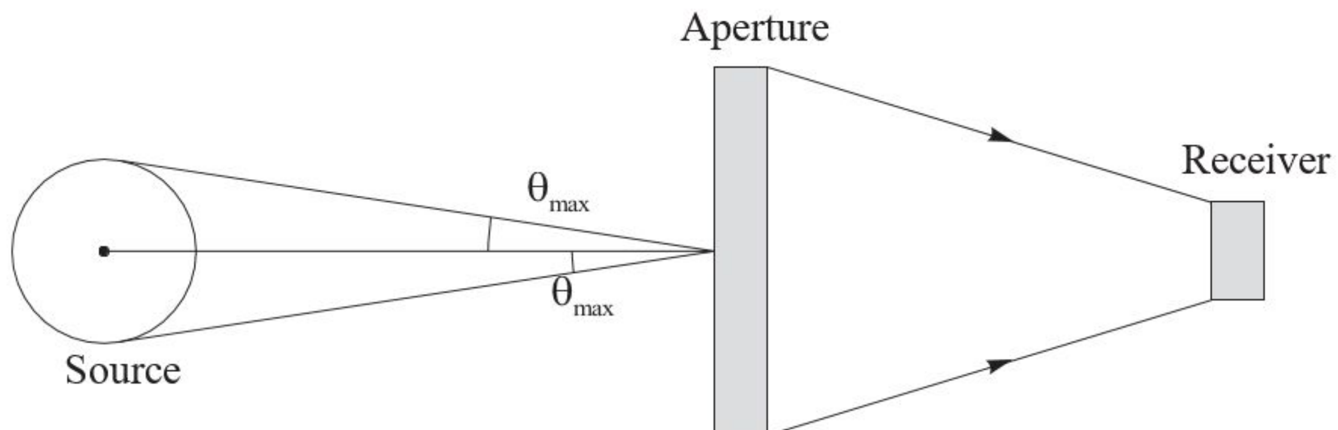
It is defined as the ratio of energy actually absorbed by the collector to the energy incident on the collector. The absorbed energy by a collector is the solar energy which is transferred to the transport fluid as heat energy.

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

Concentrating ratio

It is defined as the ratio of the area of aperture of the collector system to the area of the receiver.

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



Temperature range

- It is the range of temperature to which the heat transporting fluid is heated up by the collector. The temperature range depends upon the concentration ratio.
- The flat plate collectors have concentration ratio of unity as no focusing or optical concentration system is utilized in them to concentrate the solar radiation. This is the reason why the temperature range of flat collectors is less than l00°C.
- Line focus collectors have concentration ratio up to l00 and these collectors can have temperature range on the order of l50–S00°C.
- Point focus collectors have very high concentration ratio (CR > l000) and these collectors have temperature range in the order of 500–l000°C.

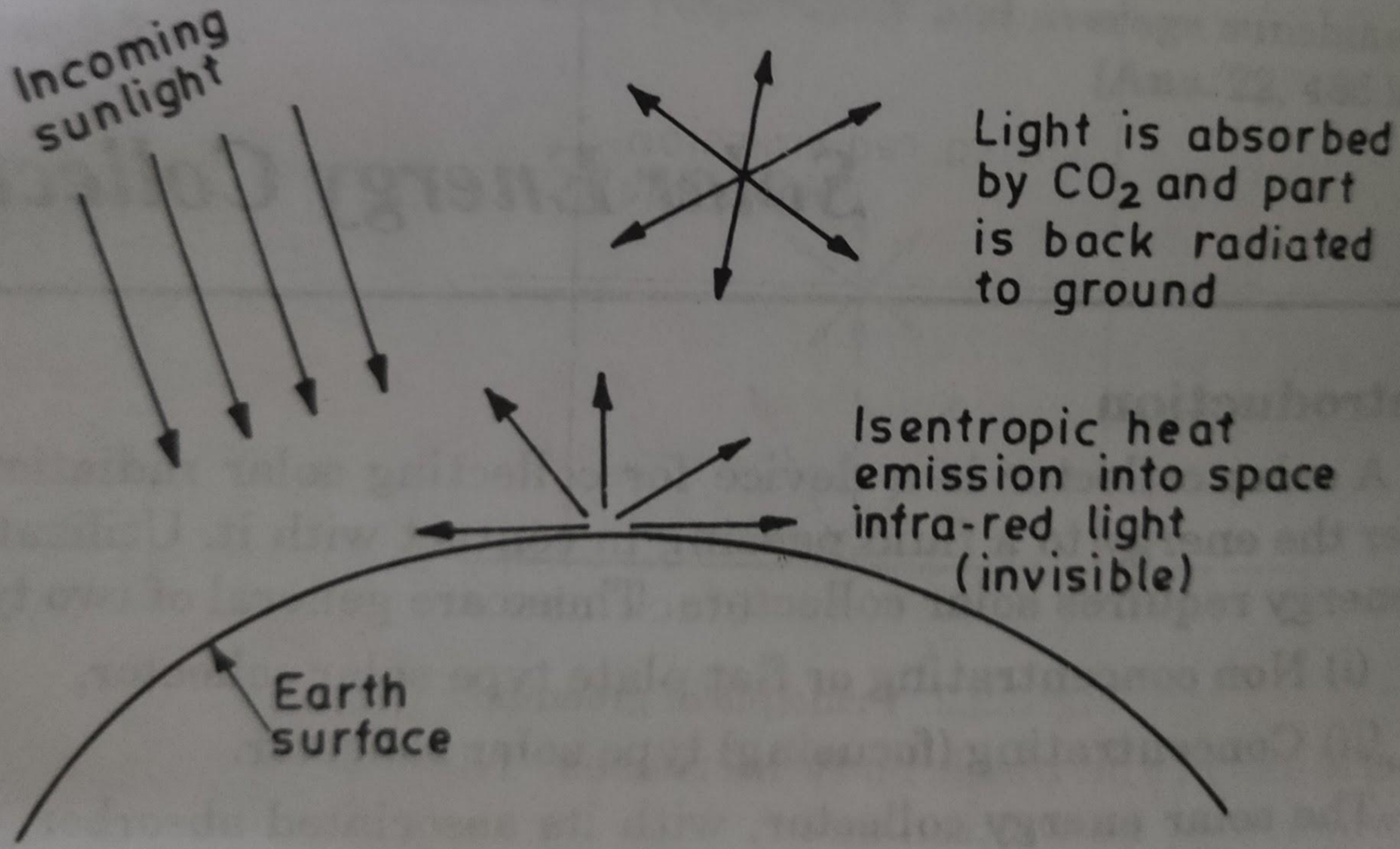


Fig. 3.2.1. The green house effect radiated to the CO_2 content of the atmosphere.

- The CO_2 gas in the atmosphere is transparent to the incoming shorter wavelength solar radiation, while it is opaque to the long wavelength reradiated radiation.
- As a result of this the long wavelength radiation gets reflected repeatedly between the earth‘s atmosphere and the earth‘s surface resulting in the increase in temp of the earth‘s surface. This is known as the —Green House Effect.

Flat plate collector (FPC):

- In a flat plate collector the absorber plate which is a black metal plate absorbs the radiation incident through the glass covers. The temp of the absorber plate increases and it begins to emit radiation of longer wavelength.
- The repeated reflection of radiation between the covers and the absorber plate results in the rise of the temp of the absorber plate.

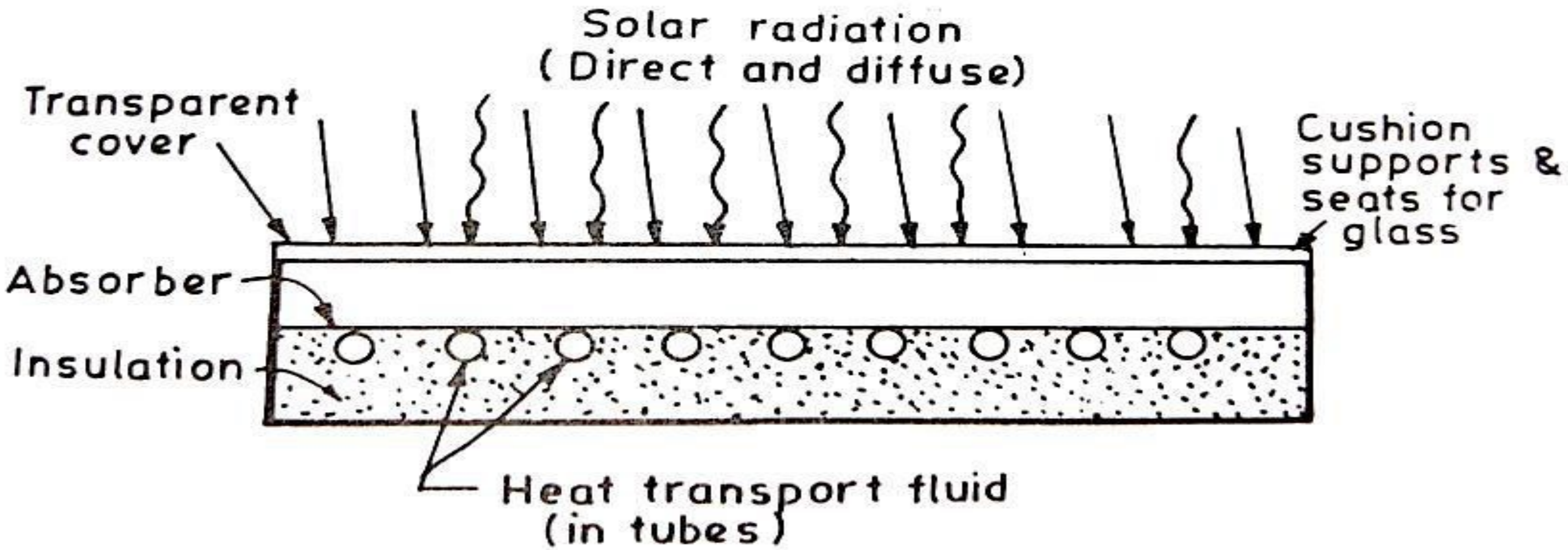


Fig. 3.3.1. Selection through typical flat-plate collector.

- The schematic diagram of a FPC is as shown in fig. it consists of a casing either made up of wood or plastic having an area of about 2m*1m*15cm. In the casing insulator is provided at the bottom to check conductive heat transfer.
- Mineral wool, glass wool, fibre glass, asbestos thermocol etc. are used as insulator. Above the insulator the absorber plate is fixed.
- The absorber plate is made of good conducting material like aluminium or copper. It is coated black to increase its absorption property.
- The underside of the plate consists of absorber tubes which run along the length of the plate. These plates are also made of the same material as that of the absorber plate.

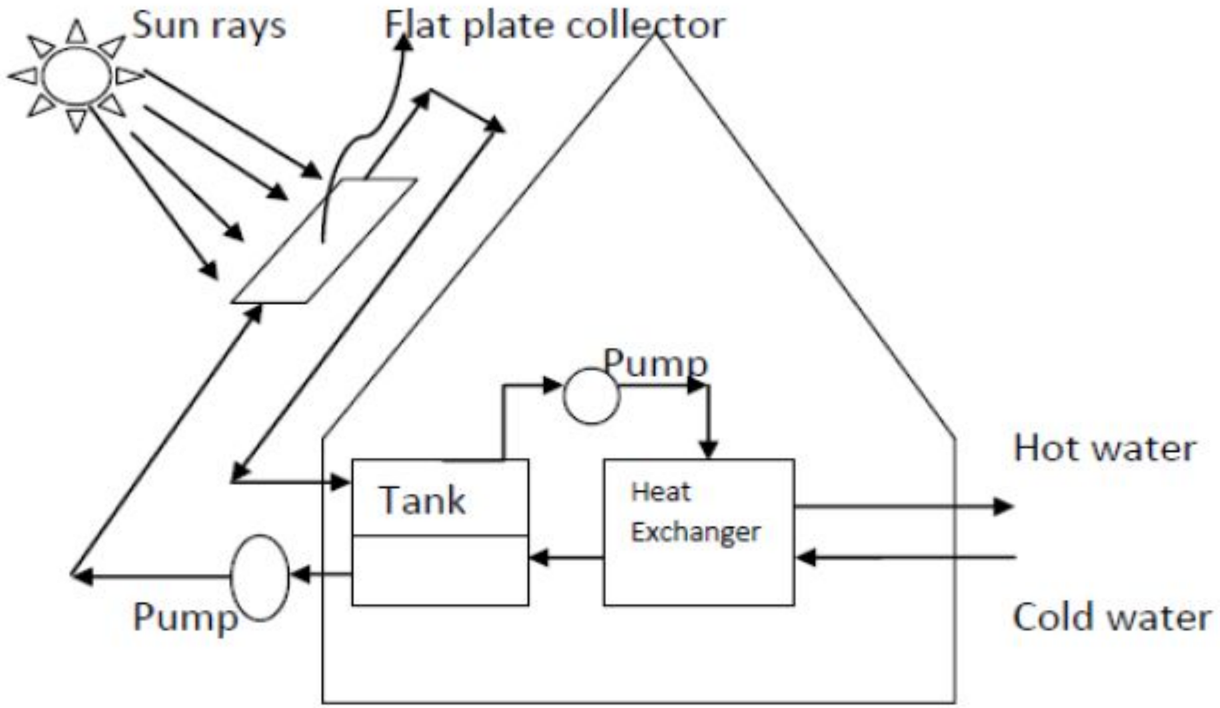
- Sometimes the plate itself is bent into the form of tubes. Through these tubes the heat absorbing medium (water) is circulated. This medium will absorb the heat from the plates and the tubes and its temp increases.
- This medium will absorb the heat from the plates and the tubes and its temperature increases. This way solar energy is collected as heat energy.
- Above the absorber plate glass covers are provided.
- These glass covers help to bring out the greenhouse effect, thus increasing the η of the collector.
- More than one cover is used to prevent the loss of radiation by refraction.

- The Sun is most prominent source of energy in our system.
- The source of solar energy is process of thermonuclear fusion in the sun's core. This energy is radiated from sun in all directions and reaches to the earth.
- Solar thermal energy is used for water heating, space heating, electric power generation, solar cooker for cooking of food etc.
- Solar collector absorbs the incident solar radiation and converts it to the useful heat which is use for heating a collector fluid such as water, oil or air.
- Flat plate collector are used where temperature below 100°C are required.

- Solar collectors are heat exchangers that use solar radiation to heat a working fluid, usually liquid or air.
- They can be classified in three groups:

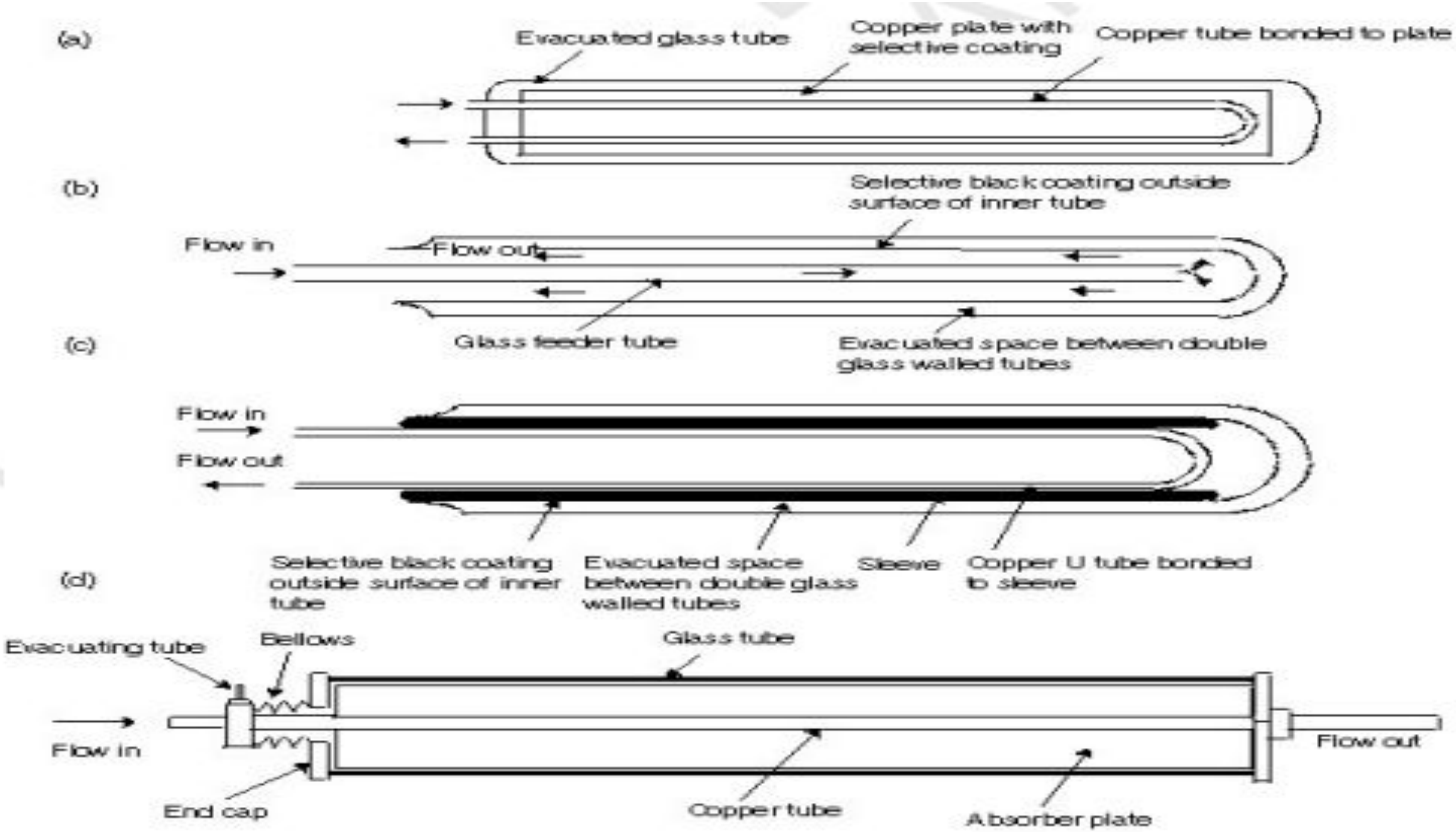
  - Flat- plate collectors.
  - Evacuated-tube collectors.
  - Focusing collectors.
  - Solar air collector.

- **Solar flat plate collector type space heating system**



- Water is heated by incident solar radiation on flat plate collector. This heated water is collected in a tank.
- The energy is transferred to the air circulating in the house by water to air heat exchanger .

Evacuated Tube

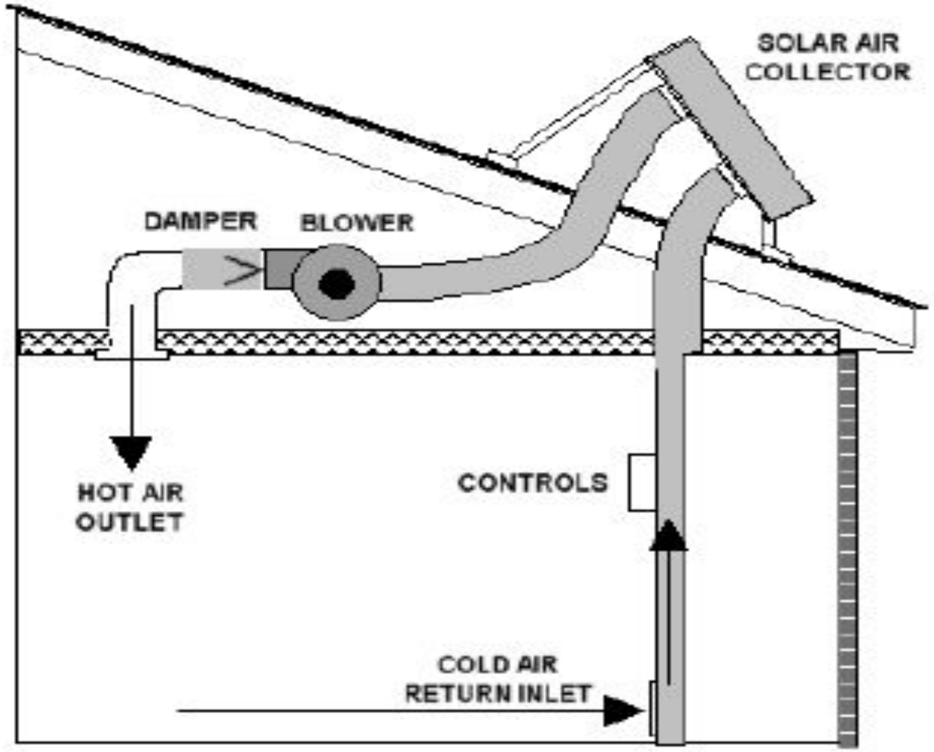


- The performance of evacuated tube collectors may be improved by introducing a small level of concentration -1.5 to 2.0 - by forming a mirror from part of the internal concave surface of a glass tube.
- This reflector can focus radiation on an absorber plate inside the tube.
- External concentrators of radiation may also be coupled to an evacuated collector for improvement of performance over the simple evacuated tube.

Solar Air Collectors

Also known as air heaters

- Modular, off the shelf design
  - Rreal
  - Show SRCC
- Fresh air
  - Used to preheat incoming air for fresh air exchange
- Site-Built Solar Air Collectors



A SOLAR AIR COLLECTOR SYSTEM

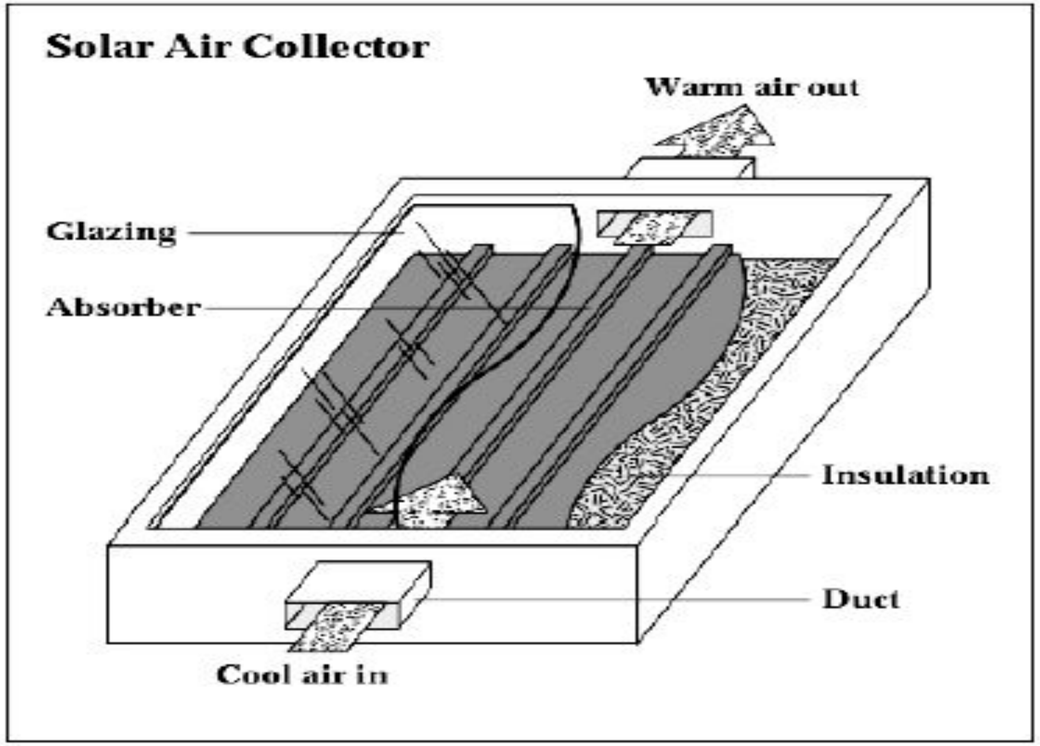
Advantages and Disadvantages of Solar Air Collectors

- Air is a Lower Technical Risk!!!
  - Leaking
  - Freezing
  - Boiling
- Easier to build
- Build into architectural design
- Not as efficient heat transfer
  - Lower Temperatures
  - More collector area needed

Air Collector Components

- Glazing/Cover: A transparent material to create a separation between ambient air and the air being heated
- Absorber: The material inside the collector that absorbs solar radiation
  - Air passing over the absorber then removes its energy through forced convection
- Backplane: Backside of the collector providing insulation so energy is not lost to surrounding
- Framing: Material used to hold the components together

Air Collector Components Cont.



An air collector is a simple flat-plate collector used mainly for space heating. Air flows through the collector by natural convection or when forced by a fan.

SOLAR CONCENTRATORS:

- Solar concentrator is a device that allows the collection of sunlight from a large area and focusing it on a smaller receiver or exit.
- A conceptual representation of a solar concentrator used in harnessing the power from the sun to generate electricity is shown in Figure1.
- The material used to fabricate the concentrator varies depending on the usage. For solar thermal, most of the concentrators are made from mirrors.

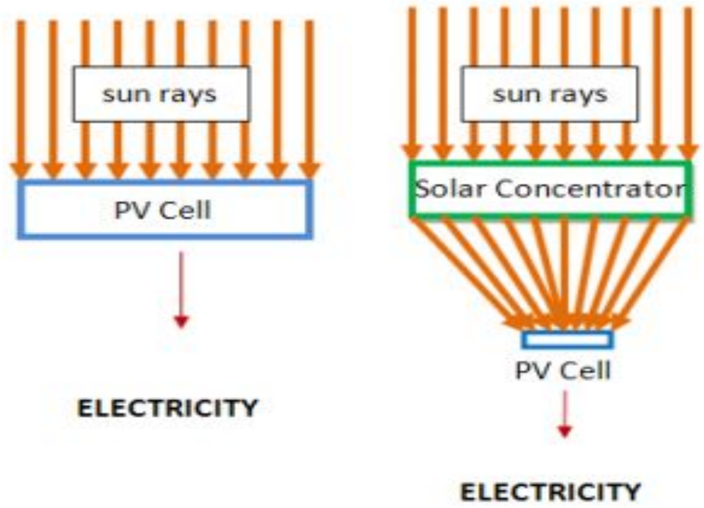
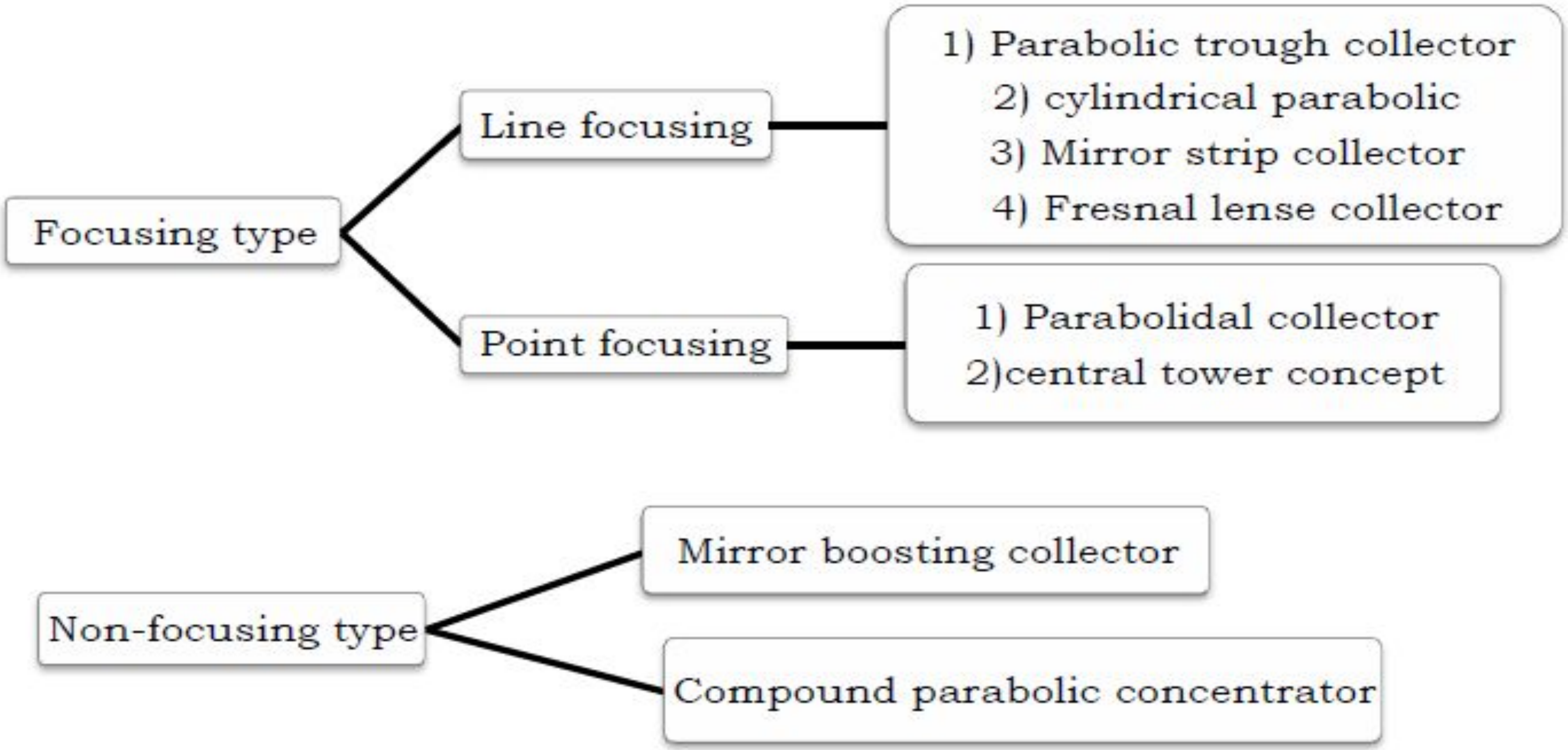


FIGURE 1: Generating electricity from the sun, with and without a solar concentrator.

- The concentrator is either made of glass or transparent plastic. These materials are far cheaper than the PV material.
- The cost per unit area of a solar concentrator is therefore much cheaper than the cost per unit area of a PV material.
- By introducing this concentrator, not only the same amount of energy could be collected from the sun, the total cost of the solar cell could also be reduced.
- Arizona Public Service has concluded that the most cost-effective PV for commercial application in the future will be dominated by high concentration collector incorporated by high-efficiency cell.

- **Concentrating collectors:** These are the solar collectors where the radiation is focused either to a point (focal point of the collector) or along a line (focal axis of the collector). Since the radiation is focused, the η of concentrating collector is always greater than that of non-focusing or FPC.
- This is because of the following reasons,
- In case of focusing collector the area of the absorber is many times smaller than that of the area of the collector. Where as in a non-concentrating type the area of the absorber equals area of the collector.
- In a concentrating collector since the radiation is focused, its intensity is always greater than that in the non-focusing type.

- **Classification of concentrating collectors:**



Compound Parabolic Concentrator (CPC):

- Compound Parabolic Concentrator 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.
- The concentration ratio achieved from this collector is in the range of 3 -7.

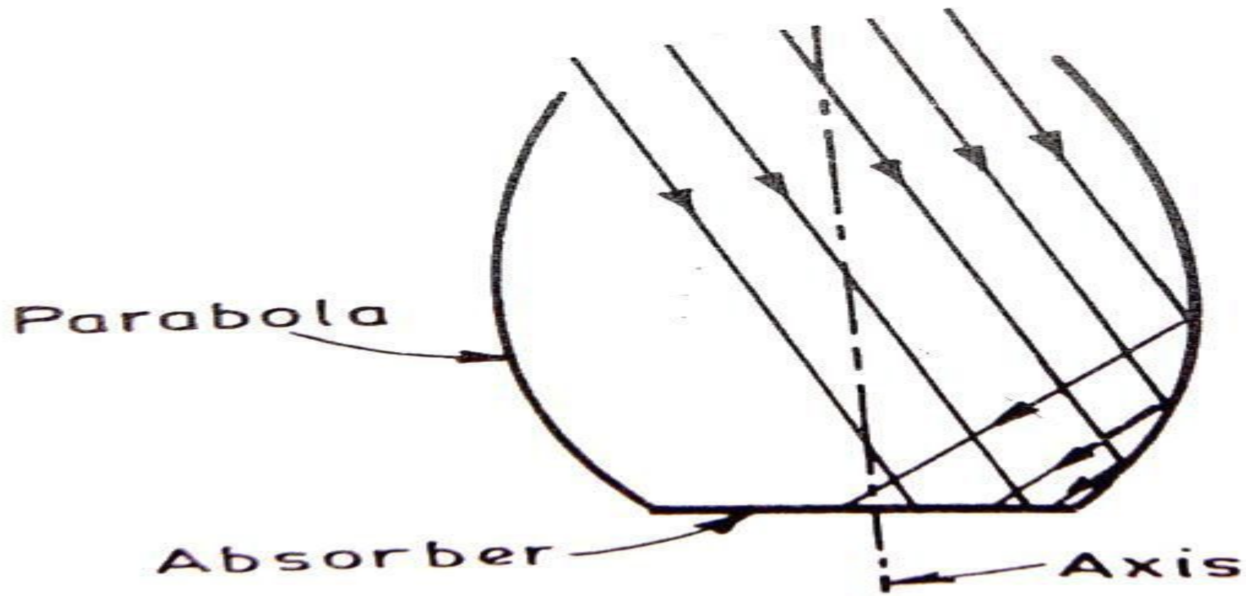


Fig. 3.7.10. Compound parabolic concentrator.

Cylindrical Parabolic Concentrator:

- It consists of a cylindrical parabolic through reflector and a metal tube receiver at its focal line as shown in figure above.
- 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.

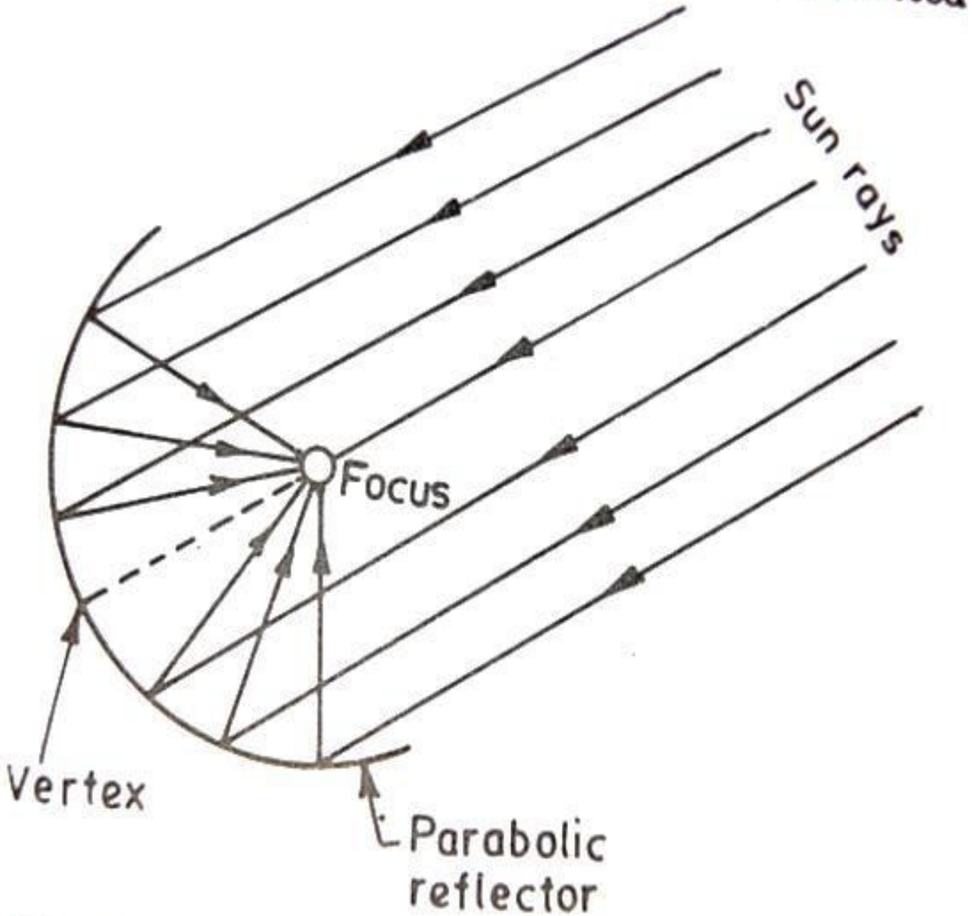
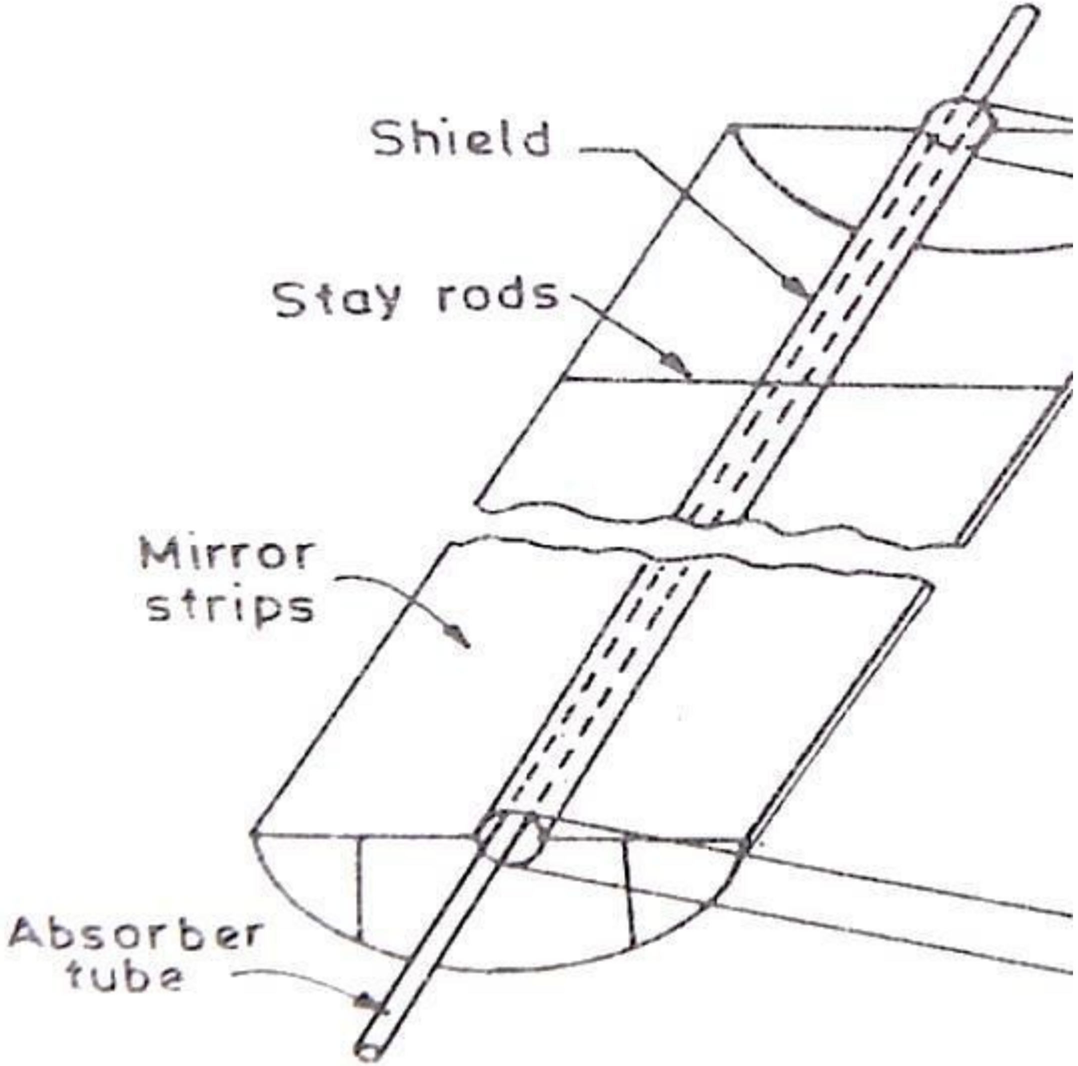


Fig. 3.7.1. Cross-section of parabolic-trough collecto:



- **Fixed Mirror Solar Concentrator:**
- Due to practical difficulty in manufacturing a large mirror in a single piece in 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 Figure.
- The receiver tube is made to rotate about the center of curvature of reflector module to track the sun.

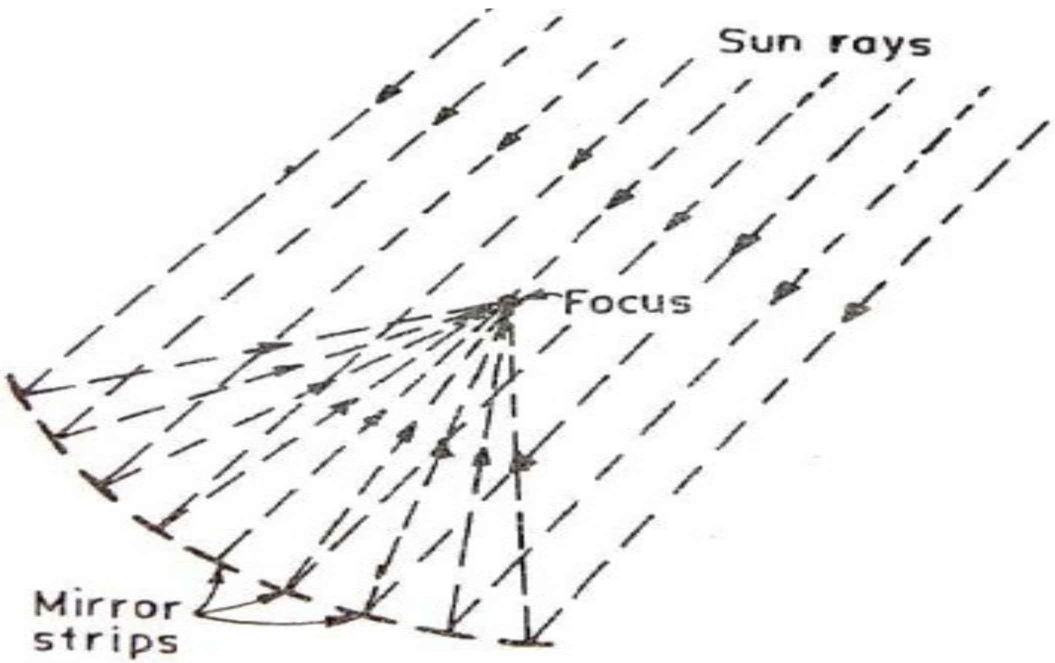
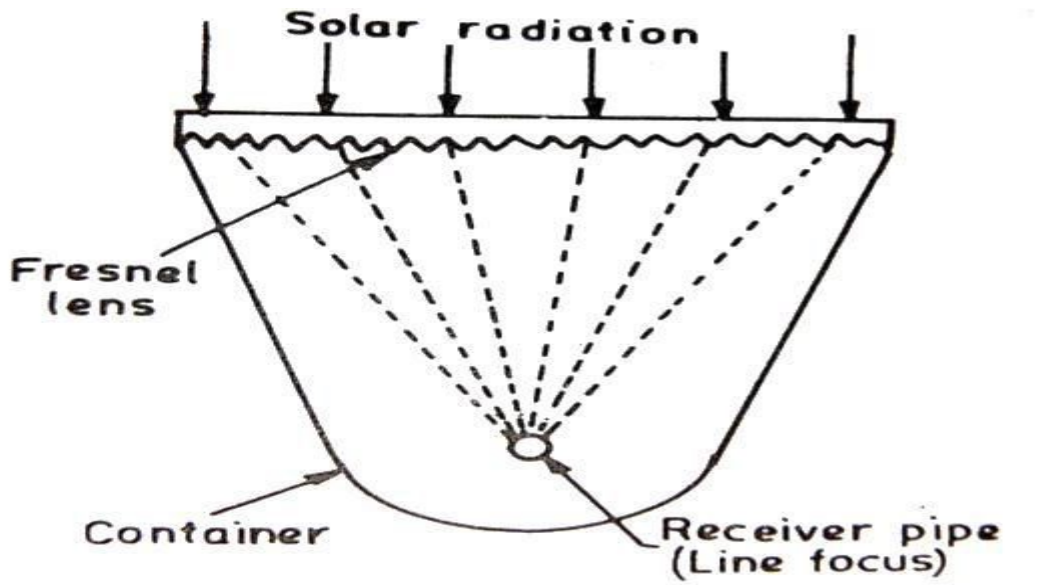


Fig. 3.7.3. Mirror-strip solar collector.

Linear Fresnel Lens Collector:

- In this collector a Fresnel lens, which consists of fine, linear grooves on the surface of 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 behaviour similar to a spherical lens. The beam radiation, which is incident normally, converges on focal line, where a receiver tube is provided to absorb the radiation.



3.7.4. Cross-section of Fresnel lens through collector.

Paraboloidal Dish Collector:

- When a parabola is rotated about its optical axis a paraboloidal surface is produced. Above figure 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 concentration ratio ranging from 10 to few thousands and can yield temperature up to 3000oC.
- Paraboloidal dish collectors of 6- 7m in diameter are commercially manufactured.

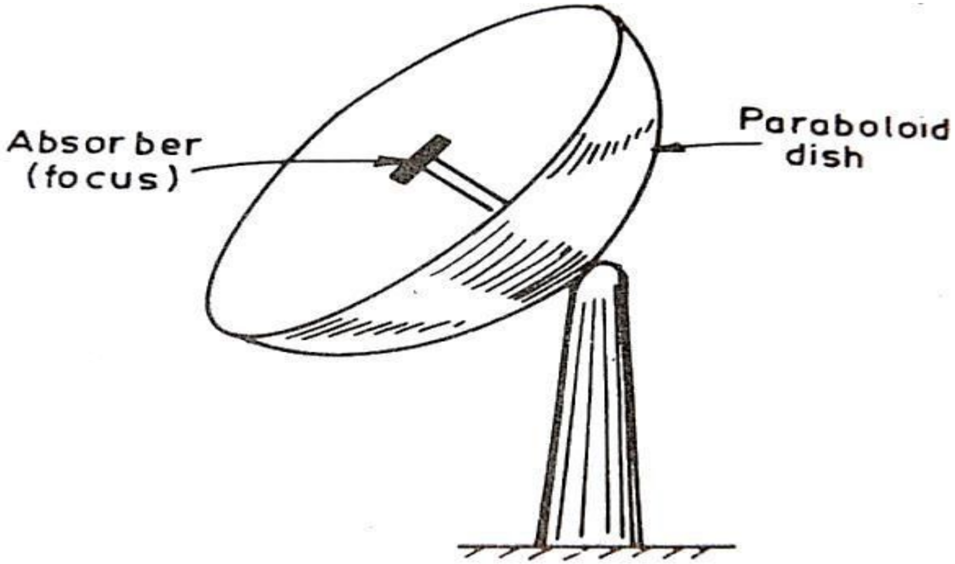


Fig. 3.7.7. Point focus solar collector (Paraboloid).

Hemispherical Bowl Mirror Concentrator:

- It consists of hemispherical fixed mirror, a tracking absorber and supporting structure, as shown in Figure.

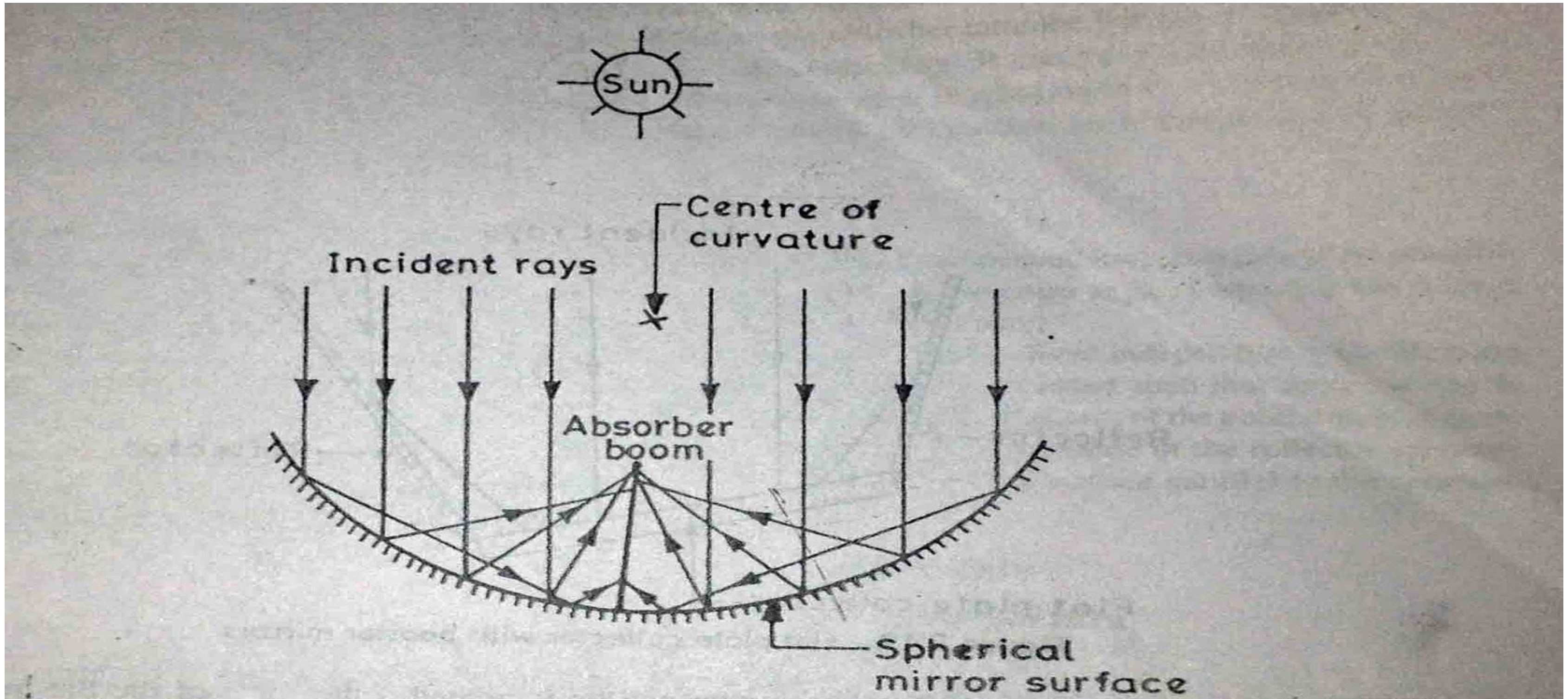


Figure . Cross-sectional view of hemispherical mirror concentrator.

- 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 center 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 center of the sphere.

Central Tower Receiver:

- In 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.

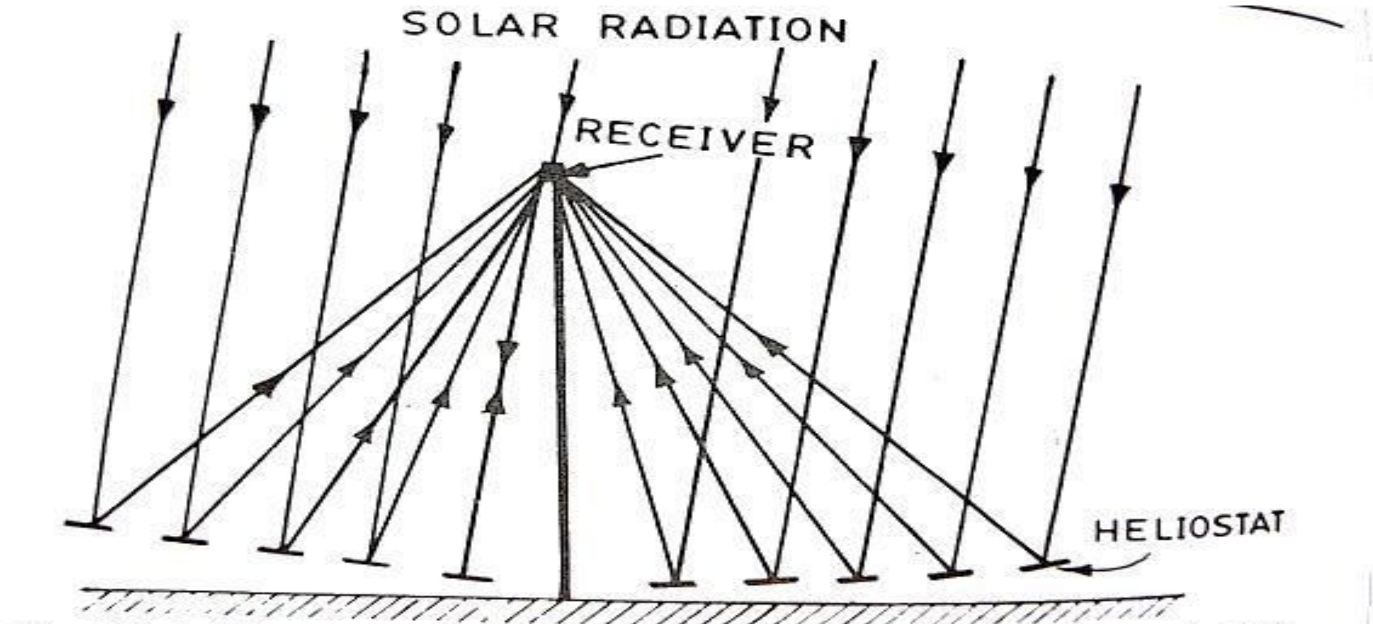
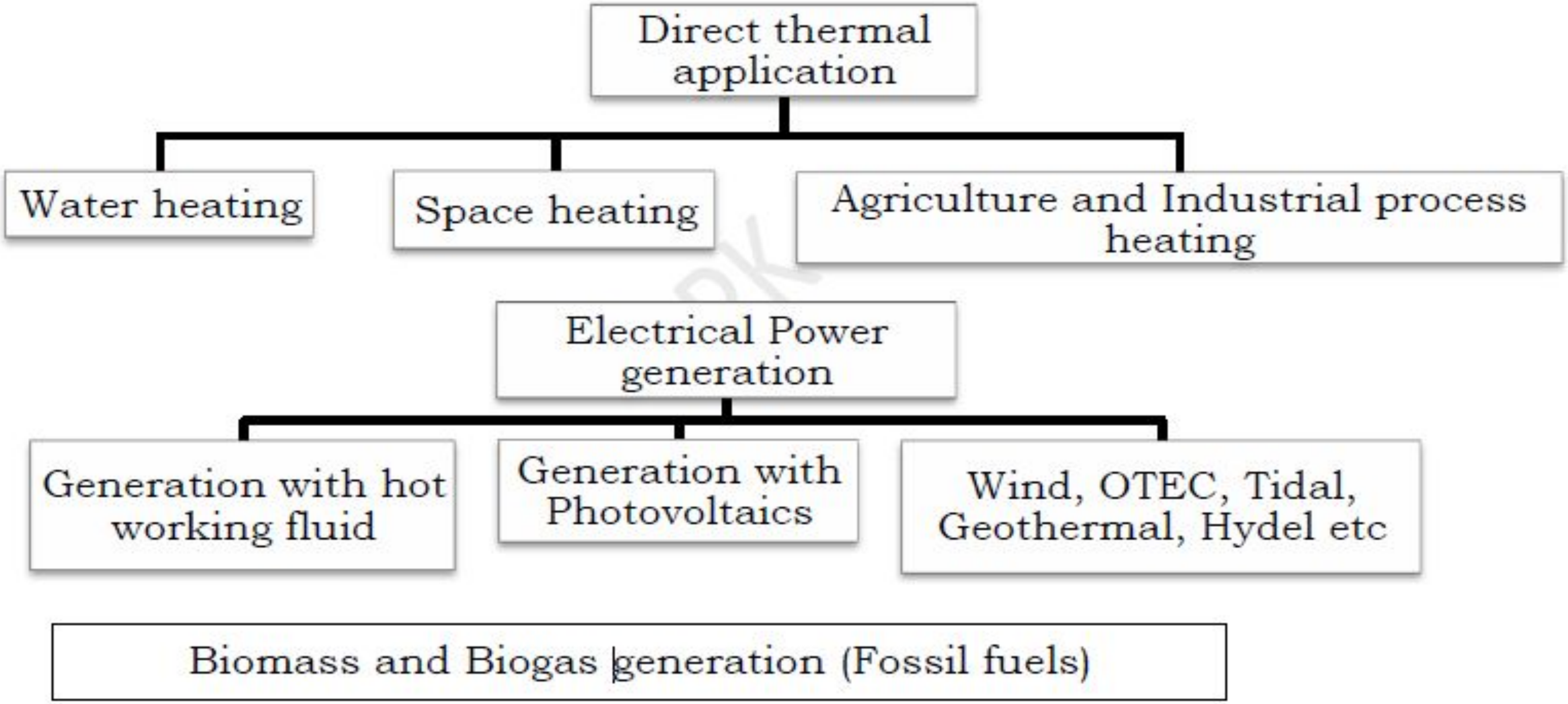


Fig. 5.5.4. Schematic arrangement of central receiver heliostat array.

- The heliostats, together act like a dilute paraboloid of very big size. Concentration ratio of as high value as 3,000 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.

- **Applications of Solar Energy:**



Thermal applications:

- Water heating
- Space heating or cooling
- Process heating
- Refrigeration
- Distillation
- Furnace heating
- Electric power generation
- Cooking
- Pumping

WATER HEATING SOLAR SYSTEM

NATURAL CIRCULATION SOLAR WATER HEATER (PRESSURIZED):

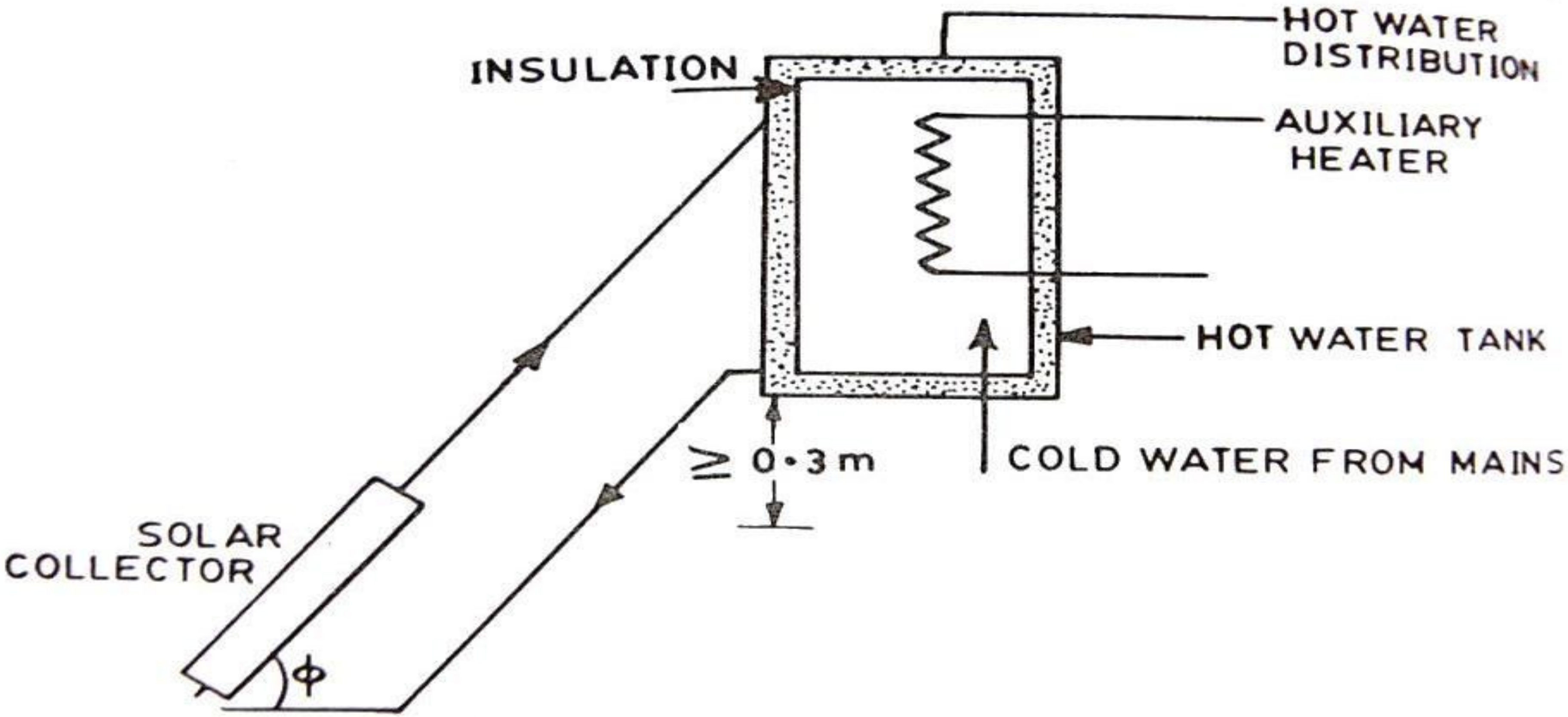


Fig. 5.2.1. Schematic of a neutral circulation solar water heater (pressurized).

- A natural circulation system is shown in Fig. 5.2.1.
- It consists of a titled collector with transparent cover glasses, a separate highly insulated water storage tank, and well insulated pipes connecting the two.
- The bottom of the tank is at least 1ft the top of the collector, and no auxiliary energy is required to circulate water through it.
- The density difference between the hot and cold water thus provides the driving force for the circulation of water through the collector and the storage tank.
- Hot water is drawn off from the top of the tank as required and is replaced by cold water from the service system.
- Thermosiphon solar water heaters are passive systems and used extensively in rural areas, where electricity is expensive.

- **NATURAL CIRCULATION SOLAR WATER HEATER (NON-PRESSURIZED):**

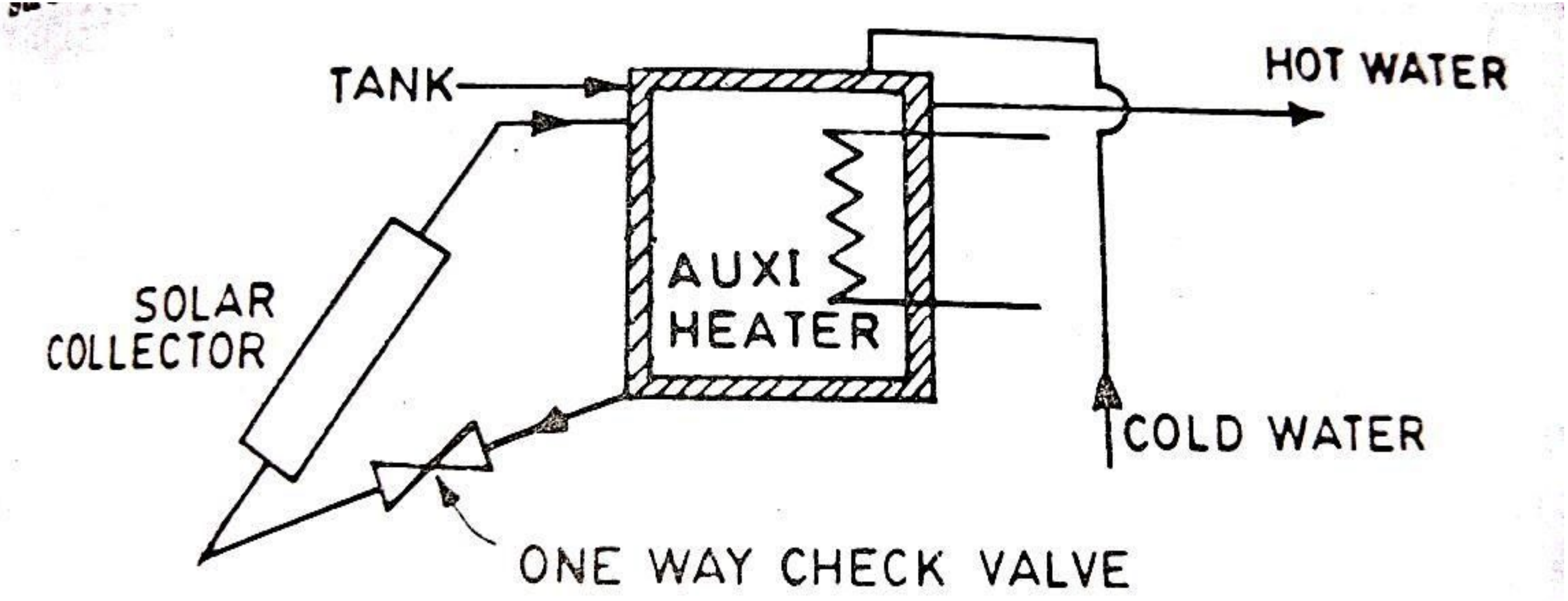


Fig. 5.2.2. Non-pressurized solar water heater.

- The pressurized system is able to supply hot water at locations of the storage tank.
- This creates considerable stress on the water channels in the collector which must be designed accordingly.
- The non-pressurized systems supply hot water by gravity flow only to users lower than tank.
- If pressurized hot water is required (for showers, or appliances) the difference in height will have to be large enough to meet the requirements.
- If the height of difference cannot be accommodated, the only solution is to install a separate pump and pressure tank.

- A typical system for domestic water heating is shown in Fig.5.2.3.

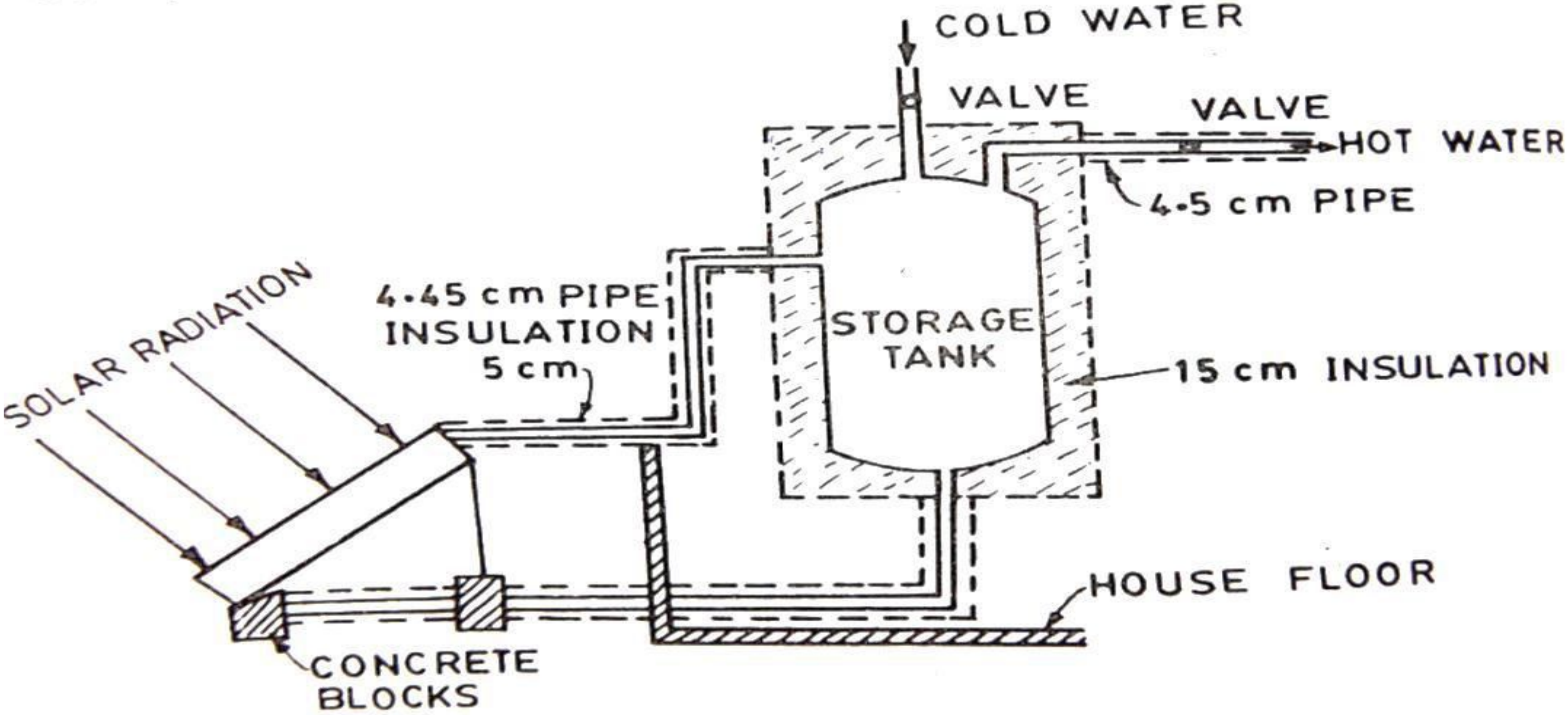


Fig. 5.2.3. A typical solar water heater.

FORCED CIRCULATION SOLAR WATER HEATER (WITHOUT ANTIFREEZE):

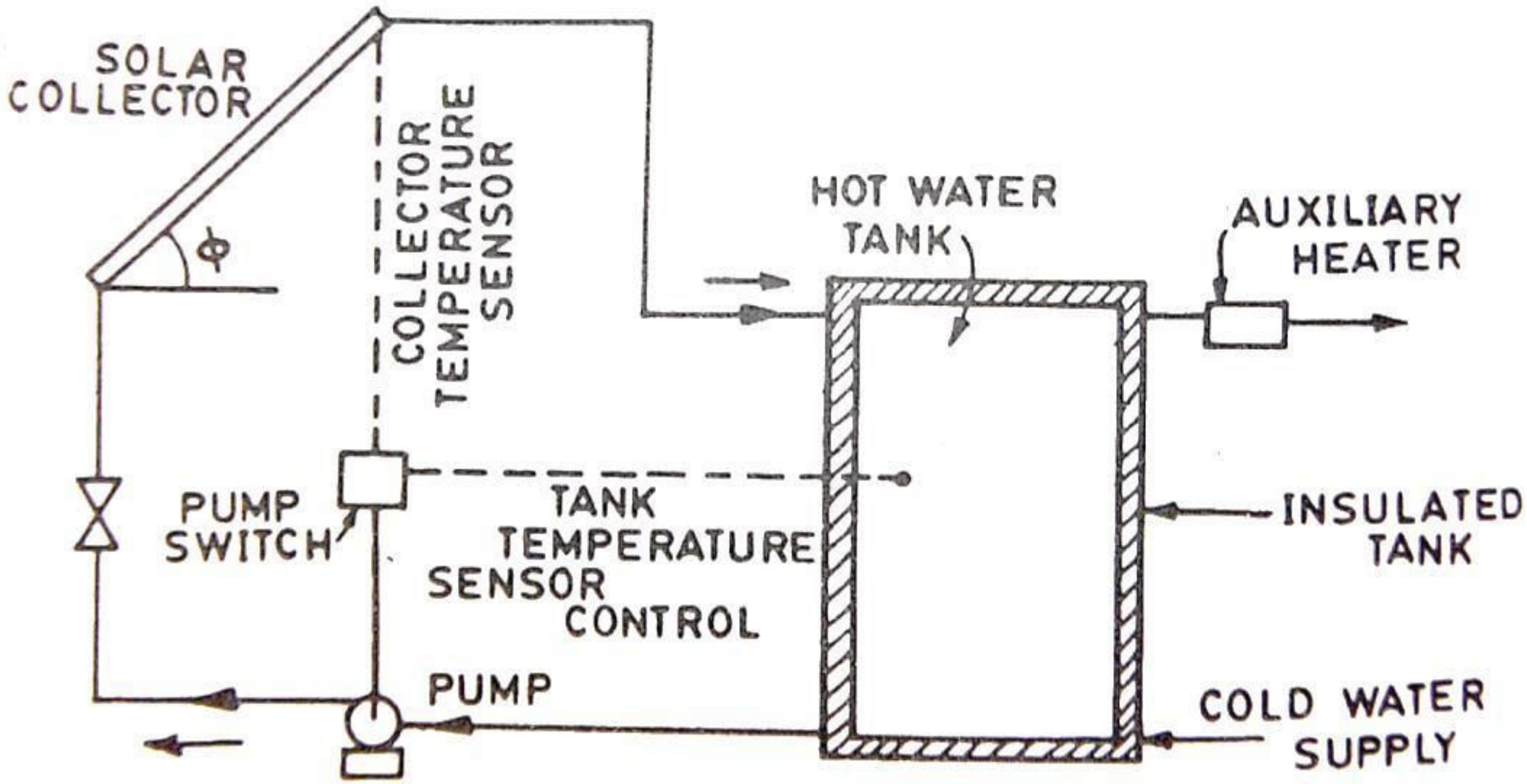


Fig. 5.2.4. Schematic of a forced circulation solar water heater.

- Fig.5.2.4 shows schematically an example of forced circulation system.
- By including an electric pump in the return circuit between the bottom of the storage tank and the lower header of the collector, the tank can be placed at a more convenient level (e.g. in the house basement).
- This is now an active system. A control unit permits the pump to operate only when the temperature of the water at the bottom of the tank is below that of the water in the upper header.
- A check valve is needed to prevent reverse circulation and resultant night time thermal losses from the collector. In this example, auxiliary heater is shown as provided to the water leaving the tank and going to the load.

- **FORCED CIRCULATION SOLAR WATER HEATER (WITH ANTIFREEZE):**

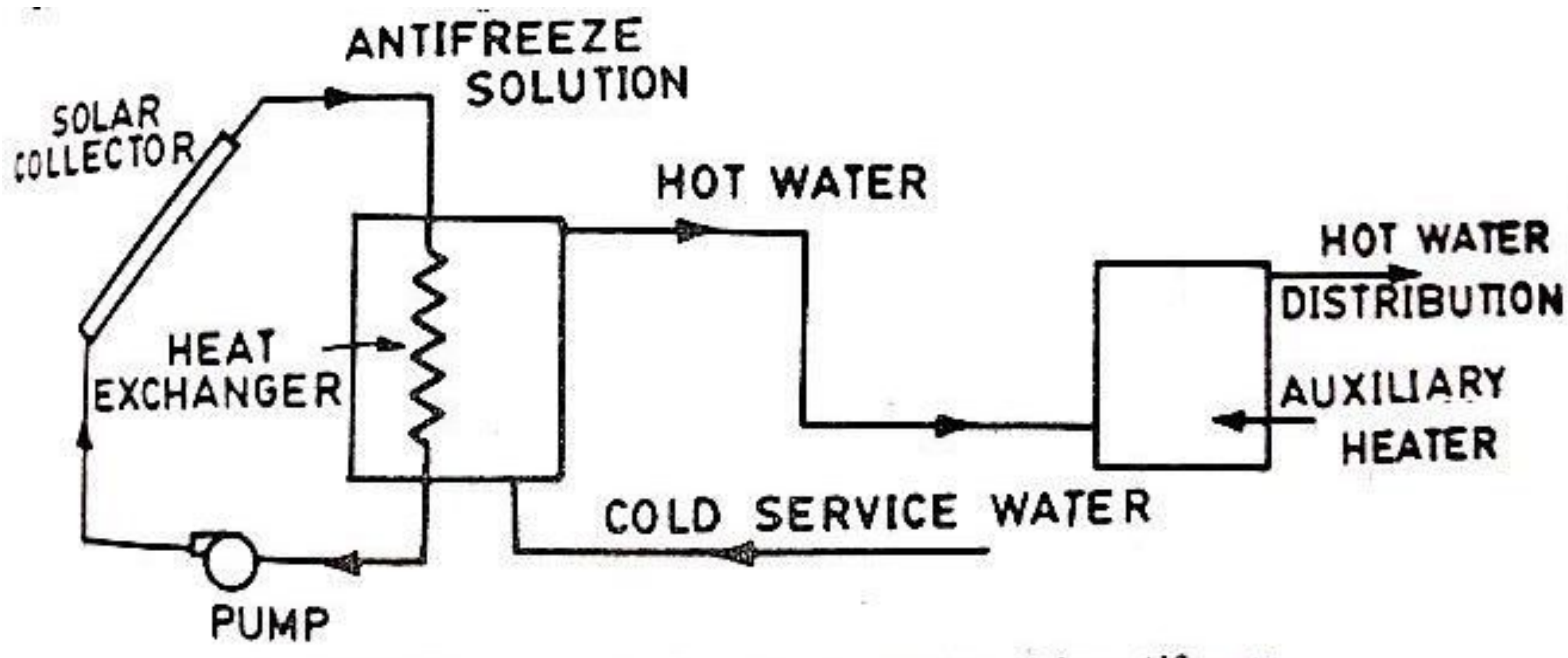


Fig. 5.2.5. Solar water heating system with antifreeze.

SPACE-HEATING:

SOLAR HEATING OF BUILDING:

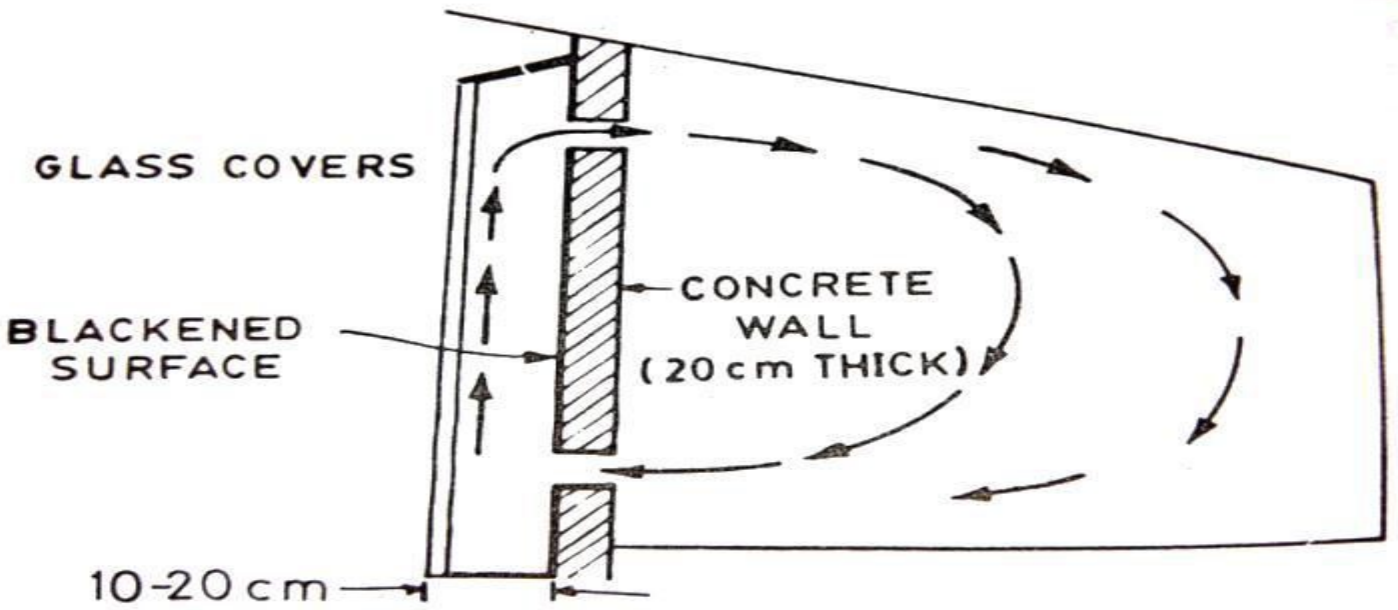


Fig. 5.3.1. A passive solar heating system.

- A sunspace is any enclosed space, such as a green house or sun porch, with a glass wall on the south side.
- A sunspace may be attached (or built on) to a thick south wall of the building to be heated by the sun.
- Vents near the top and bottom of the wall, as in Fig. 5.3.1, permit circulation through the main building of the heated in the sunspace.
- Heat storage is provided by the thick wall, a concrete or masonry floor, water containers, and other materials in the sunspace.
- Thus, an attached sunspace system combines features of direct gain and storage wall concepts.

- **ROOF STORAGE OF SOLAR HEAT:**

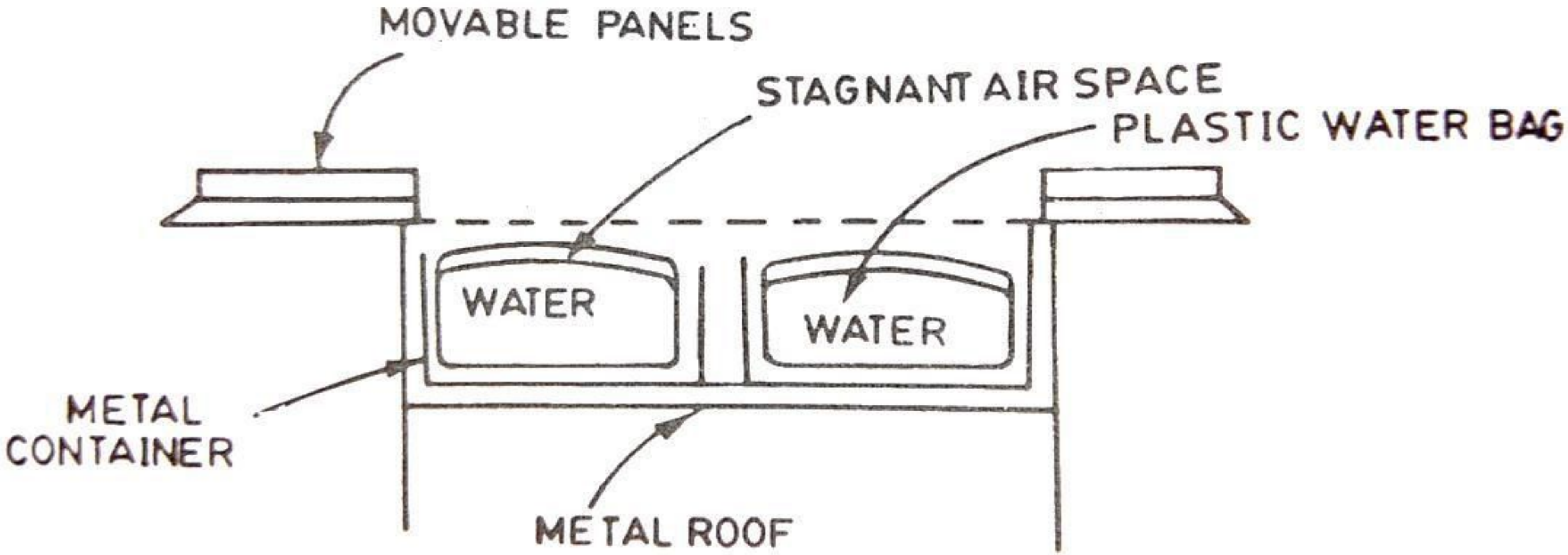


Fig. 5.3.2. Roof storage of Solar heat.

- A passive solar system, trade named Sky Therm, was designed for house having a flat roof located in a mild climate.
- The heat is absorbed and stored in water about 0.25 m deep contained in plastic bags held in blackened steel boxes on the house roof.
- In a later design, a layer of clear plastic sealed to the top of the bag provides a stagnant airspace to reduce heat losses to the atmosphere.
- Heat is transferred from the heated water to the rooms below by conduction through a metal ceiling.

- **CONVECTIVE LOOP PASSIVE SOLAR HEATING:**

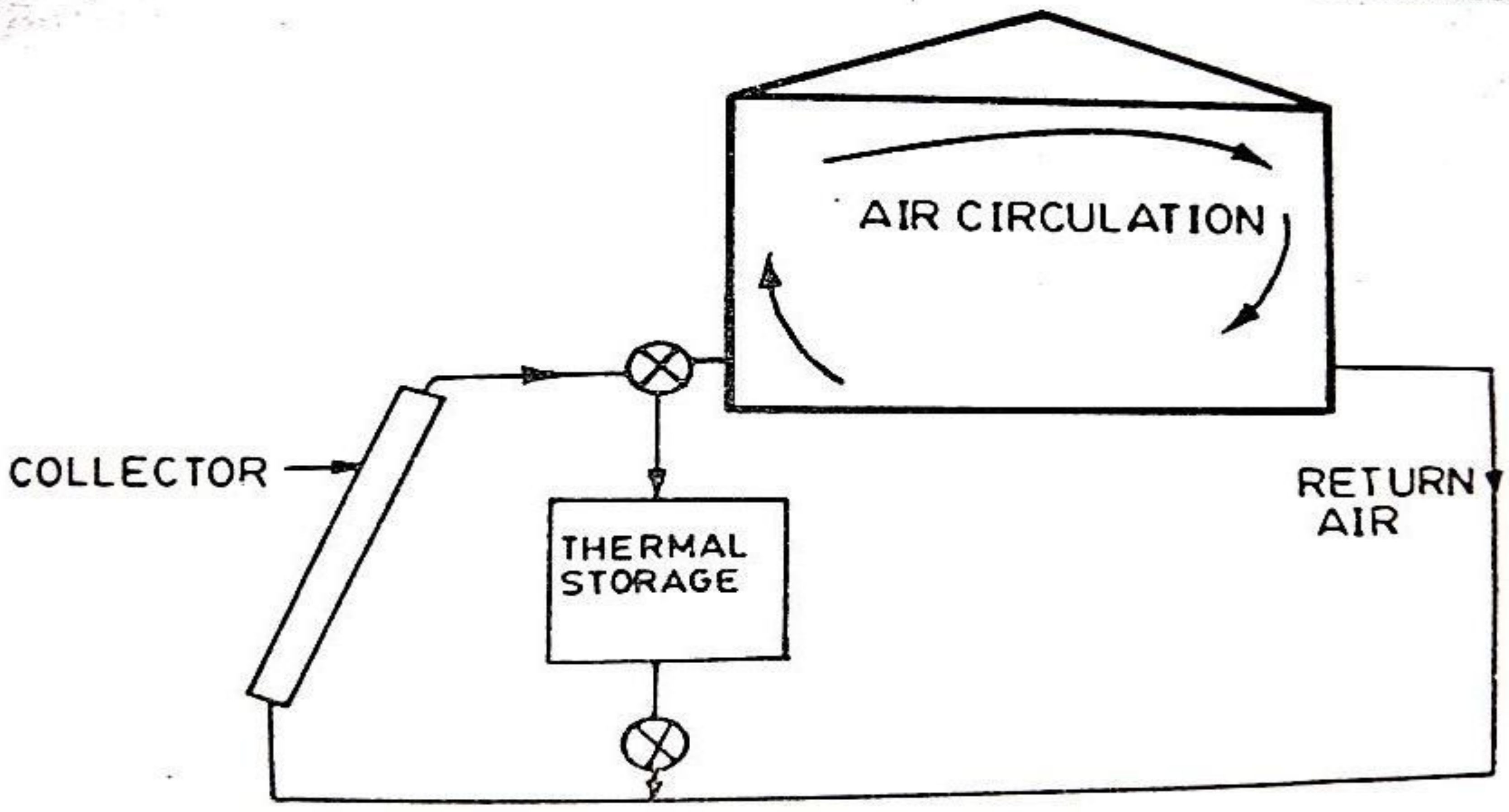


Fig. 5.3.3. Convective loop passive Solar heating.

- In most passive solar space heating systems, the heated air is circulated by convection, but the term convective loop is applied to systems that resemble the Thermosiphon hot-water scheme described earlier.
- Such a convective loop heating system is outlined in Fig.5.3.3.
- It includes a convectional flat plate collector at a level below that of the main structure.
- A bed of rock, which may be located beneath a sunspace, provides thermal storage.
- In normal operation, air passing upward through the collector is heated and enters the building through floor vents.
- The cool, denser air leaving the building returns to the bottom of the collector and is reheated.

- **BASIC HOT WATER ACTIVE SYSTEM:**

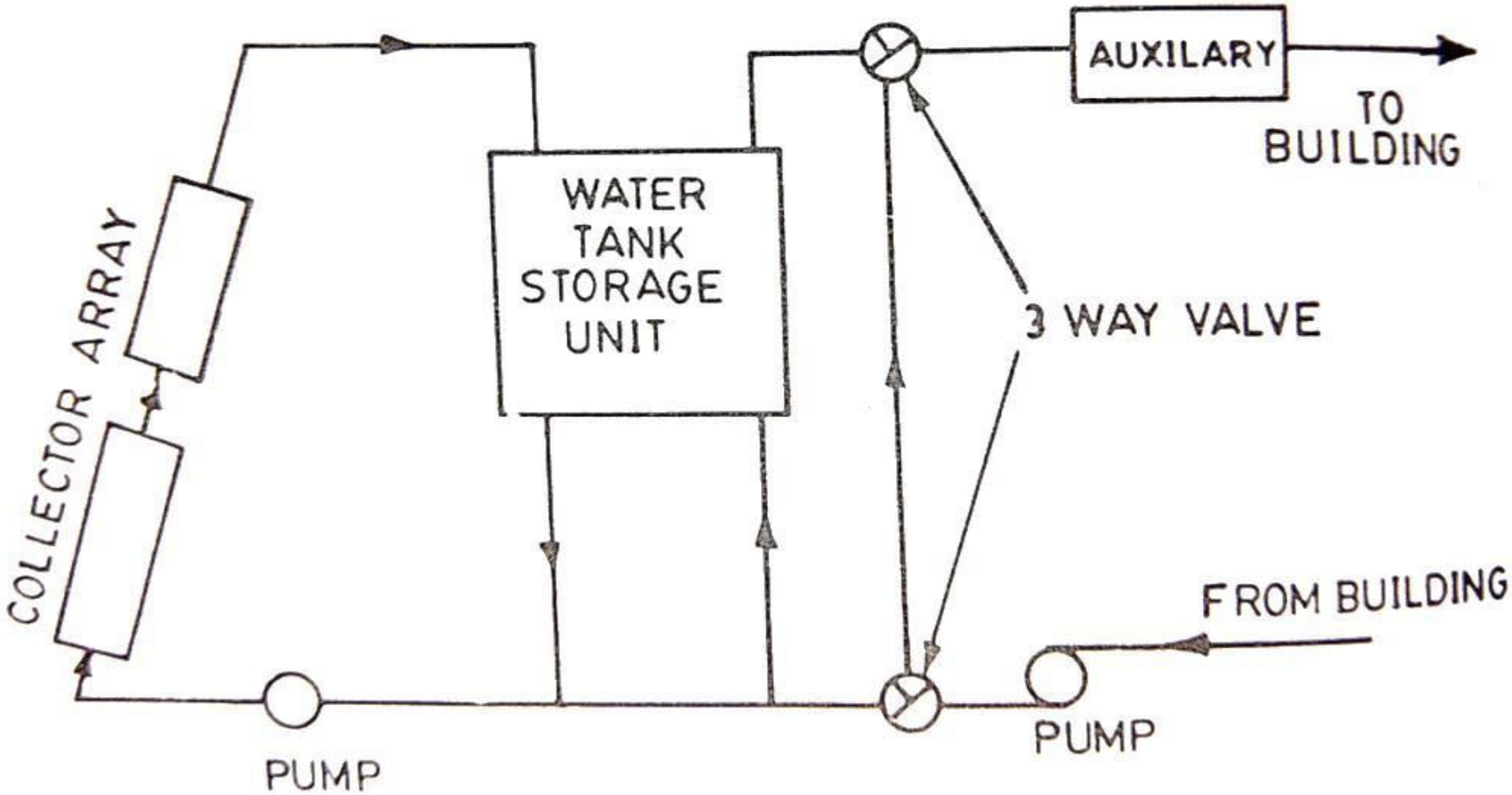


Fig. 5.3.4. Schematic of a basic hot water active system.

- An outline of an active heating system with a sloping flat plate collected located on the roof of the building is given in Fig.5.3.4.
- This is a basic hot water heating system, with water tank storage and auxiliary energy source.
- Heat is transferred to the water in the storage tank, commonly located in the basement of the building.
- The solar heated water from the tank passes through an auxiliary heater, which comes on automatically when the water temperature falls below a prescribed level.
- For space heating, the water may be pumped through radiators or it may be used to heat air in a water to air heat exchanger.

Contd…,

- During normal operation, the three way valves are set to permit solar heated water to flow from the storage tank and auxiliary heater to the distribution system and back to the tank.
- If after several cloudy days, the heat in storage is depleted, the valves will adjust automatically to bypass the storage tank.

- **BASIC HOT WATER ACTIVE SYSTEM (WITH ANTIFREEZE):**

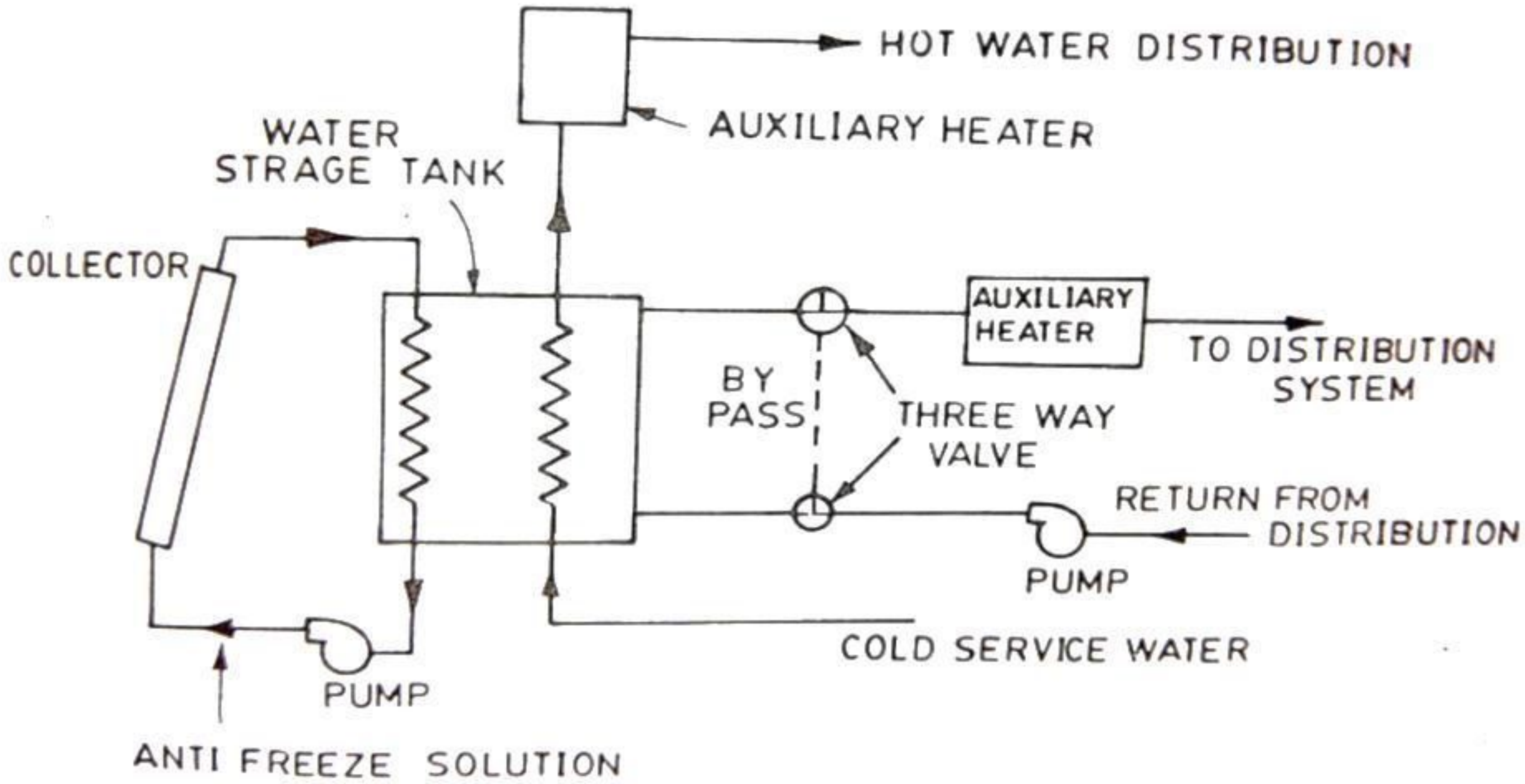


Fig. 5.3.5. Solar space heating and hot water system.

- If in this system, the heat transport medium is an antifreeze solution, then there is a closed circuit of it, with the heat exchanger coil in the storage tank.
- This type of solar space heating system with hot water system is shown in Fig.5.3.5.

Advantages and disadvantages of basic hot water system are listed below:

- **Advantages:**
- In case of water heating, a common heat transfer and storage medium, water is used, this avoids temperature drop during transfer of energy into and out of the storage.
- It requires relatively smaller storage volume.
- It can be easily adopted to supply of energy to absorption air conditioners, and
- Relatively low energy requirements for pumping of the heat transfer fluid.

Disadvantages:

- Solar water heating system will probably operate at lower water temperature than conventional water systems and thus require additional heat transfer area or equivalent means to transfer heat into building.
- Water heaters may also operate at excessively high temperature (particularly in spring and fall) and means must be provided to remove energy and avoid boiling and pressure build up.
- Collector storage has to be designed for overheating during the period of no energy level.
- Care has to be taken to avoid corrosion problems.

- **BASIC HOT AIR SYSTEM:**

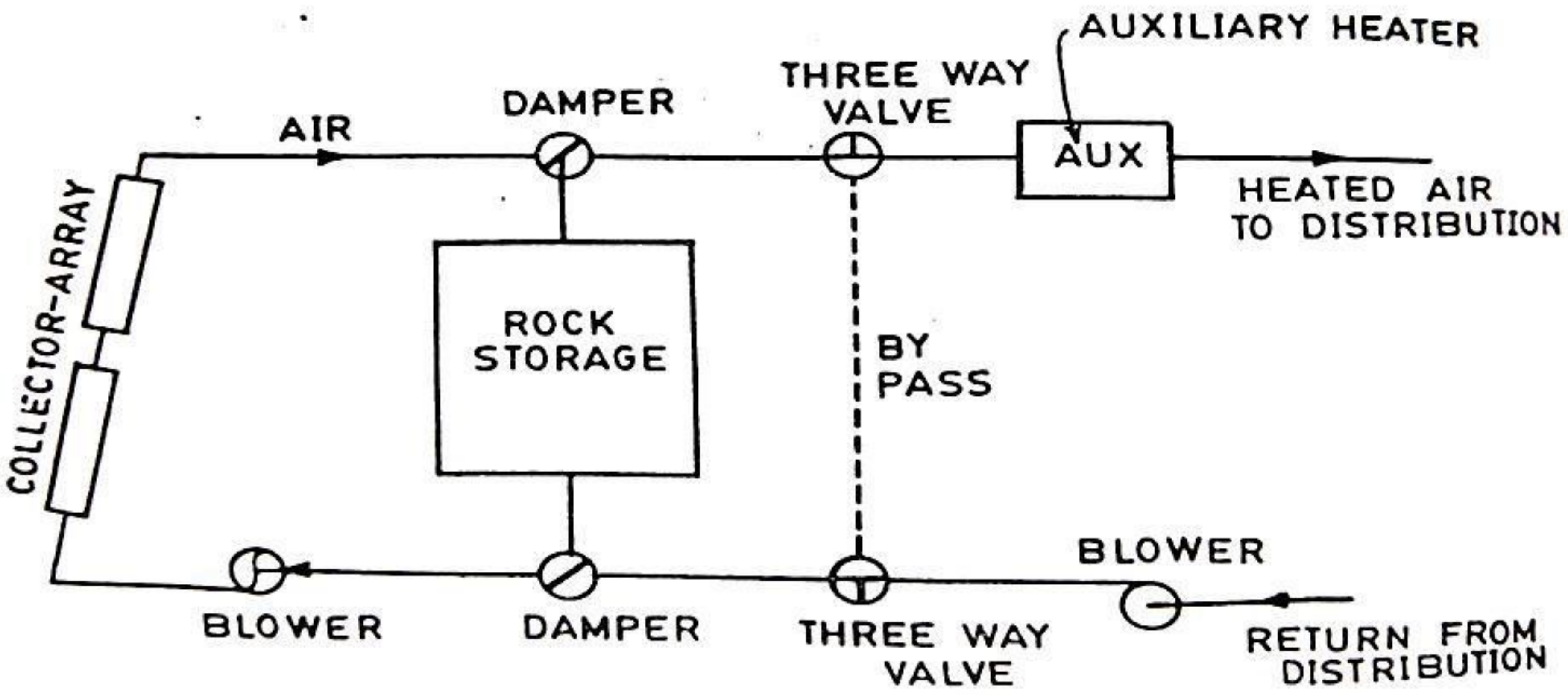


Fig. 5.3.6. Schematic diagram of a basic hot air heating system.

Schematic diagram of a basic hot air heating system is shown in Fig.5.3.6.

- In this system the storage medium is held in the storage unit, while air is the fluid used to transport energy from collector to the storage and to the building.
- By adjusting the dampers, the heated air from the collector can be divided between rock storage and the distribution system, as might be required by the conditions.
- For example, when the sun shines after several cloudy days it would be desirable to utilize the available heat directly in the distribution system rather than placing it in storage.
- Two - three way valves can be used to bypass the storage tank, as explained above. An auxiliary source of heating is also provided.
- Auxiliary heating can be used to augment the energy supply to the building from the collector or storage if the supply of heat from it is inadequate.

SOLAR SPACE COOLING OF BUILDINGS:

- **VAPOUR ABSORPTION AIR COOLING (LiBr-H_2O SYSTEM85 to 95°C with FPC /NH_3-H_2O COOLER 120 to 130°C with concentrating collectors):**

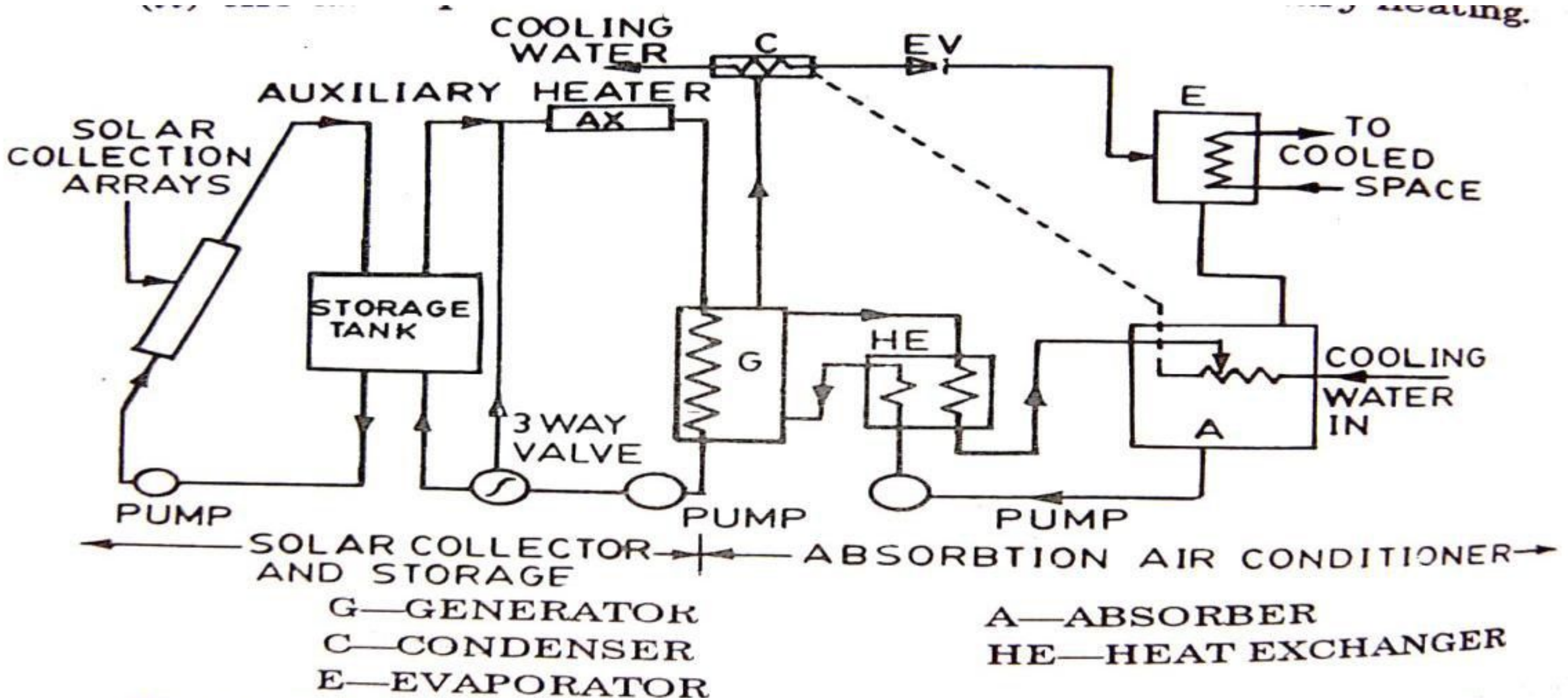


Fig. 5.4.1. Schamatic of Solar Operated Absorption Air Conditioner.

The absorption air conditioning system is shown schematically in Fig.5.4.1.

The system consists of two parts

- (i) The solar collector and storage, and
- (ii) The absorption air conditioner and the auxiliary heating.

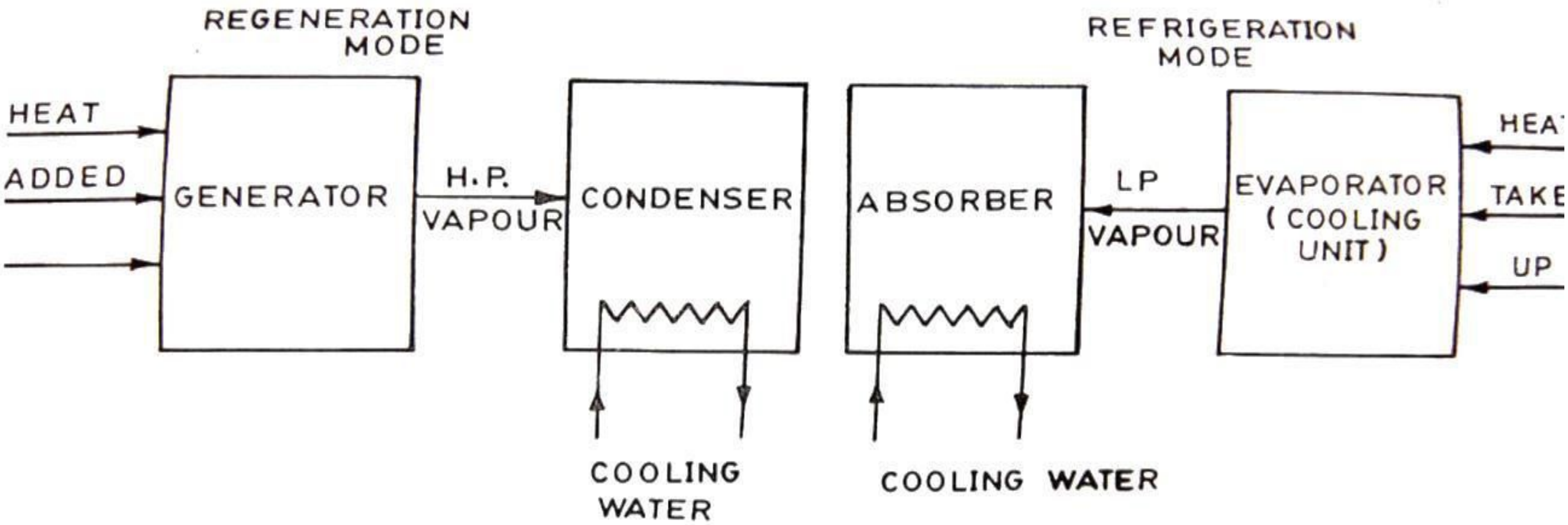
The essential components of the cooler are (i) generator (G), (ii) condenser

- (C), (iii) evaporator (E), (iv) absorber (A), (v) heat-exchanger (HE).
- The operation of air conditioners with energy from flat-plate collector and storage systems is the most common approach to the solar cooling today.
- In essence cooling is accomplished as the generator of the absorption cooler is supplied with heat by a fluid pumped from the collector storage system or from auxiliary.

- Heat is supplied to a solution of refrigerant in absorbent in the generator, where refrigerant is distilled out of the absorbent fluid.
- The refrigerant is condensed and goes through a pressure reducing valve to the evaporator where it operates and cools air or water for the cooling space.
- The refrigerant vapour goes to the absorber where it comes in contact with the solution which is weak in refrigerant and which flows from the generator. The vapour is absorbed in the solution, which is then returned to the generator. A heat exchanger is used for sensible heat recovery and greatly improves cooler C.O.P.
- The pressure in the condenser and generator is fixed largely by temperature drops across heat transfer surfaces in the generator and condenser.

- The pressure in the evaporator and absorber is fixed by the temperature of the cooling fluid to the absorber and by the temperature drop across the heat transfer surfaces in the evaporator and the absorber.
- Thus, to keep the generator temperatures within the limits imposed by the characteristics of flat-plate collector, the critical design factors and operational parameters include effectiveness of the heat exchangers and coolant temperature.

- **INTERMITTENT ABSORPTION COOLING:**



A modified method for absorption cooling which operates intermittently rather than continuously is based on the following principle.

- In this system, it consists of two vessels which function in two alternative modes.
- In one (regeneration) mode, one of the vessels is the generator and the other is the condenser of an absorption system.
- During this phase, heat is supplied to the generator by oil, gas, steam or solar energy.
- In the alternative mode (refrigeration), the first vessel becomes the absorber and the other the evaporator.
- During this phase refrigeration occurs. The system operates in the regeneration mode for a few hours and is then changed to the refrigeration mode, and so on.
- This technique can also be used for food preservation in rural areas, where electric power is not readily available.

- In the refrigeration mode, heat is supplied to a dilute solution of lithium bromide in water contained in the generator unit. Water vapour at a moderately high pressure passes to the condenser unit and is condensed by cooling water.
- The other refrigerant absorbent combinations used in this system are ammonia water (NH_3-H_2O) and ammonia-sodium thiocynanate (NH_3- NasCN).

SOLAR THERMAL ELECTRIC CONVERSION: SOLAR POND:

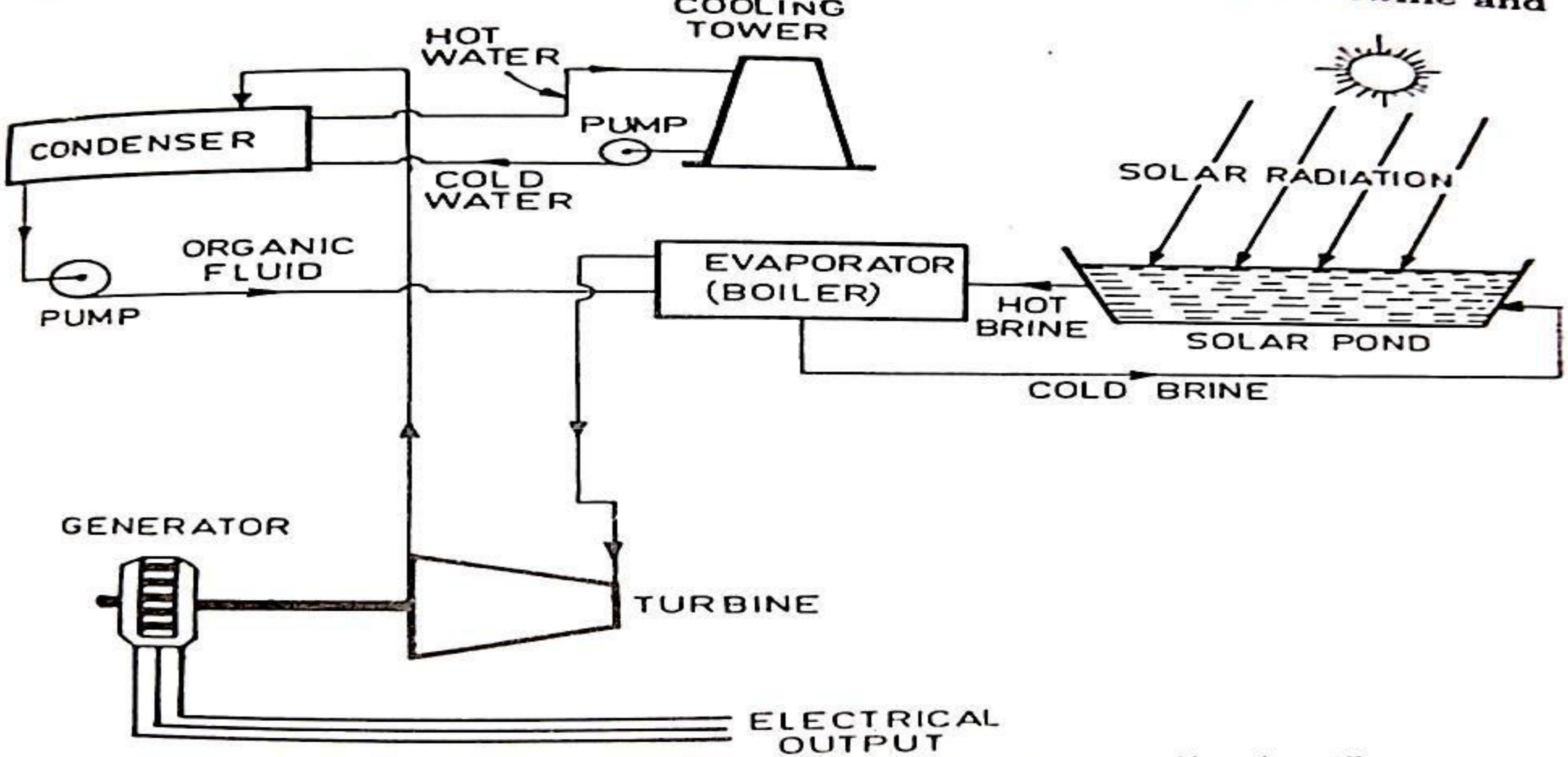


Fig. 4.3.3. Solar pond electric power plant with cooling tower.

- A solar pond is a mass of shallow water about 1 or 2 metres deep with a large collection area, which acts as a heat trap. It contains dissolved salts to generate a stable density gradient.
- Part of the incident solar radiation entering the pond surface is absorbed throughout the depth and the remainder which penetrates the pond is absorbed at the black bottom.
- If the pond were initially filled with fresh water, the lower layers would heat up, expand and rise to the surface. Because of the convective mixing and heat loss at the surface, only a small temperature rise in the pond could be realized.
- On the other hand, convection can be eliminated by initially creating a sufficiently strong salt concentration gradient.

- Materials used for the liner include butyl rubber, black polyethylene and hypalon reinforced with nylon mesh.
- Salts like magnesium chloride, sodium chloride or sodium nitrate are dissolved in the water, the concentration varying from 20 to 30 percent at the bottom to almost zero at the top.

- **Solar Chimney Power Plant:**

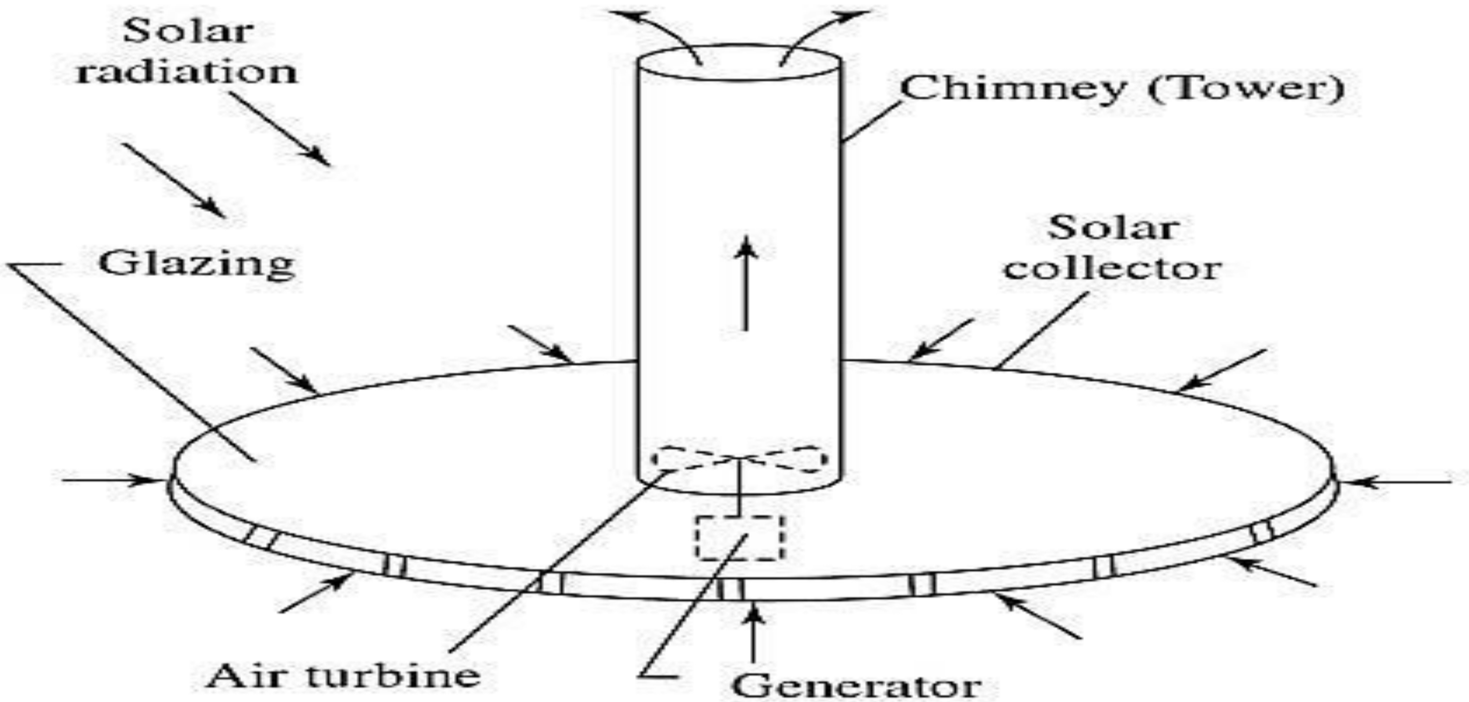


Fig. 2.20 *Solar chimney power plant*

Solar chimney is much simpler but works with much lower efficiency as compared to central tower receiver power plant. The circular field of heliostats is replaced by a circular area of land covered with glazing.

- The central receiver tower is replaced by a tall chimney that houses a wind turbine.
- The air under the glazing is heated by solar energy and drawn up through the chimney driving the turbine coupled with a generator.

- **LOW-TEMPERATURE SOLAR POWER PLANT (Max 100°C by FPC and solar pond)):**

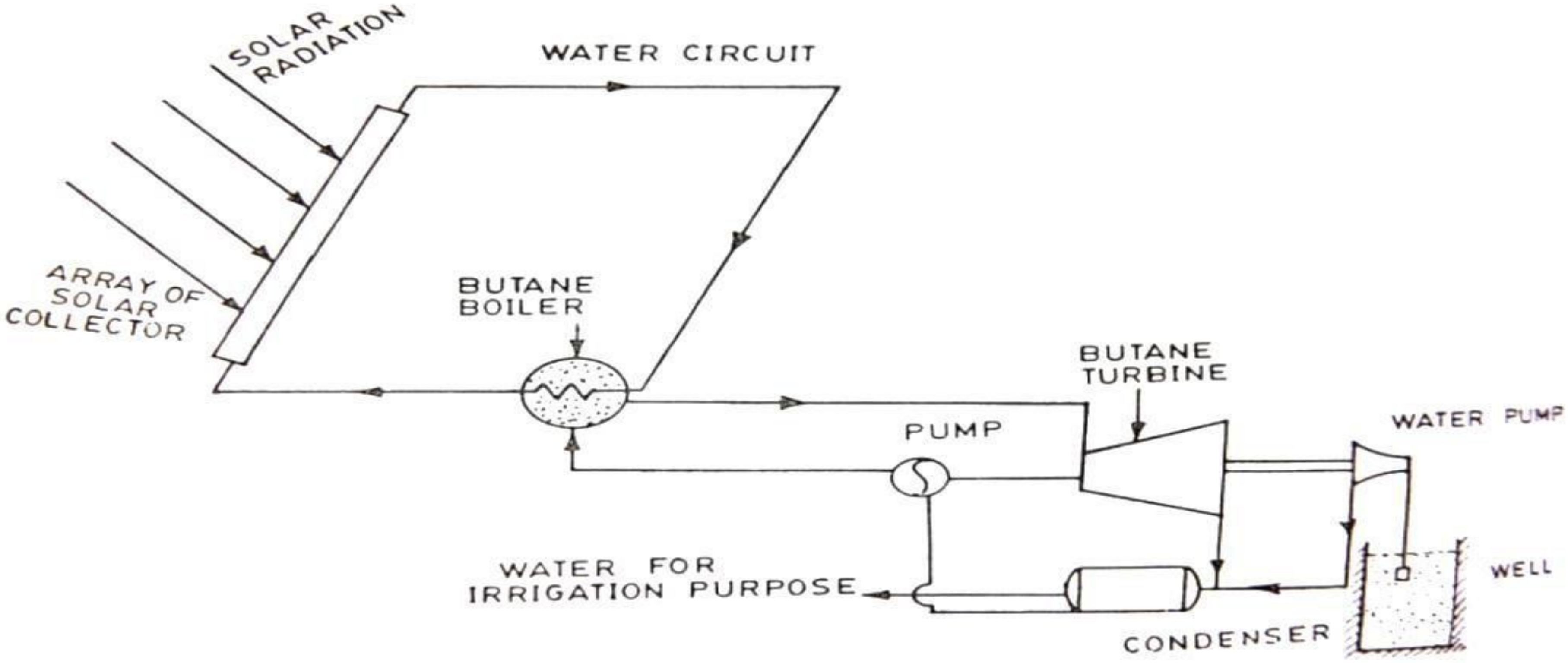


Fig. 5.5.2. Schematic of a low temperature solar power plant.

- The system has a array of flat-plate collectors to heat water upto nearly $70^{o}C$ and in the heat exchanger, the heat of water is used for boiling butane.
- The high pressure butane vapour runs a butane turbine which operates a hydraulic pump which pumps the water from well and used for irrigation.
- The exhaust butane vapour from butane turbine is condensed with the help of water which is pumped by the pump. This condensate is fed to the heat exchanger or butane boiler.

- **MEDIUM TEMPERATURE SYSTEMS WITH CONCENTRATING COLLECTORS (100 - 300°C by Concentrating collectors):**

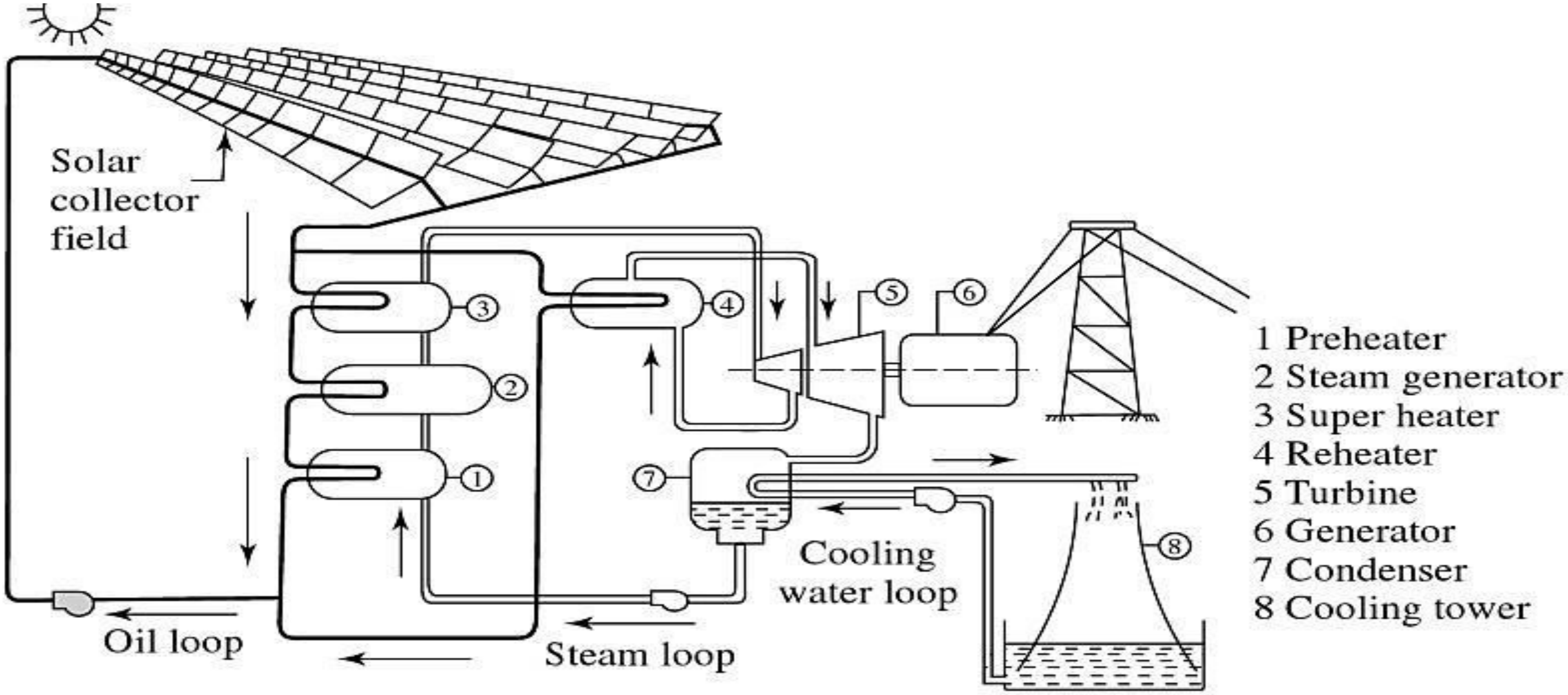


Fig. 2.21 *Medium temperature power generation cycle using cylindrical parabolic concentrating collectors*

- These systems generally employ an array of parabolic trough concentrating collectors, which give temperature above 100^0C.
- General range of temperature is of the order of 250 to 500^0C. As described earlier, a simple parabolic cylindrical concentrator for medium temperature system is shown in Figure.
- It consists of a parabolic cylindrical reflector to concentrate sunlight on to a collecting pipe within a Pyrex or glass envelope.
- A selective coating of suitable material is applied to pipe to minimize infrared emission.
- Proper sun tracking arrangement is made so that maximum sunlight is focused on the absorber.

- **HIGH TEMPERATURE SYSTEMS (above 300°C) [CENTRAL RECIEVER SYSTEM TOWER POWER PLANT]:**

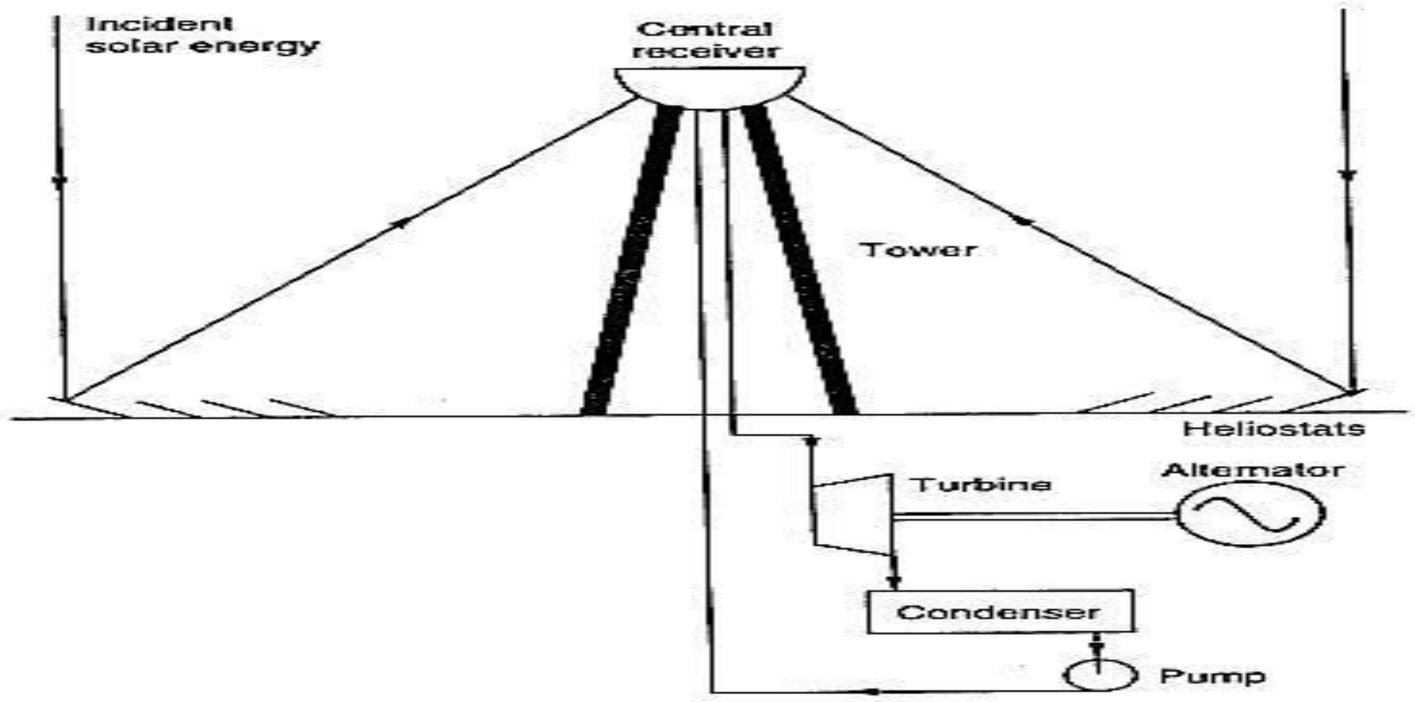


Fig. 2.16 Central Receiver Power Plant

- This power plant uses central tower receiver to collect solar radiation from a large area on the ground.
- The receiver mounted at the top of the tower, converts water into high-pressure steam at around 500ºC.
- This high pressure steam is expanded in a turbine coupled with an alternator.
- The electric power produced is fed to a grid.
- Thermal buffer storage is provided to continue operating the plant for some time during cloud cover and a bypass is used for starting and shutdown operations.

SOLAR ELECTRIC POWER GENERATION BY SOLAR PHOTOVOLTAIC CELLS:

- A PVC is one which converts photons into voltage or light energy to electricity.
- The materials used for this is silicon which has 4 free valence electrons in its outermost cell.
- When the silicon is doped with phosphorous or arsenic having 5 valence electrons in the outer most cell it forms an 'n-junction' 4 electrons of phosphorous with 4 electrons of silicon and one negative charged electron is left out in the 'n-junction'.
- Similarly the 'p-junction' is formed by doping silicon with boron having 3 valence electrons in its outermost cell to create positively charged hole which attracts negatively charged electron from n to p junction through external load of cell.

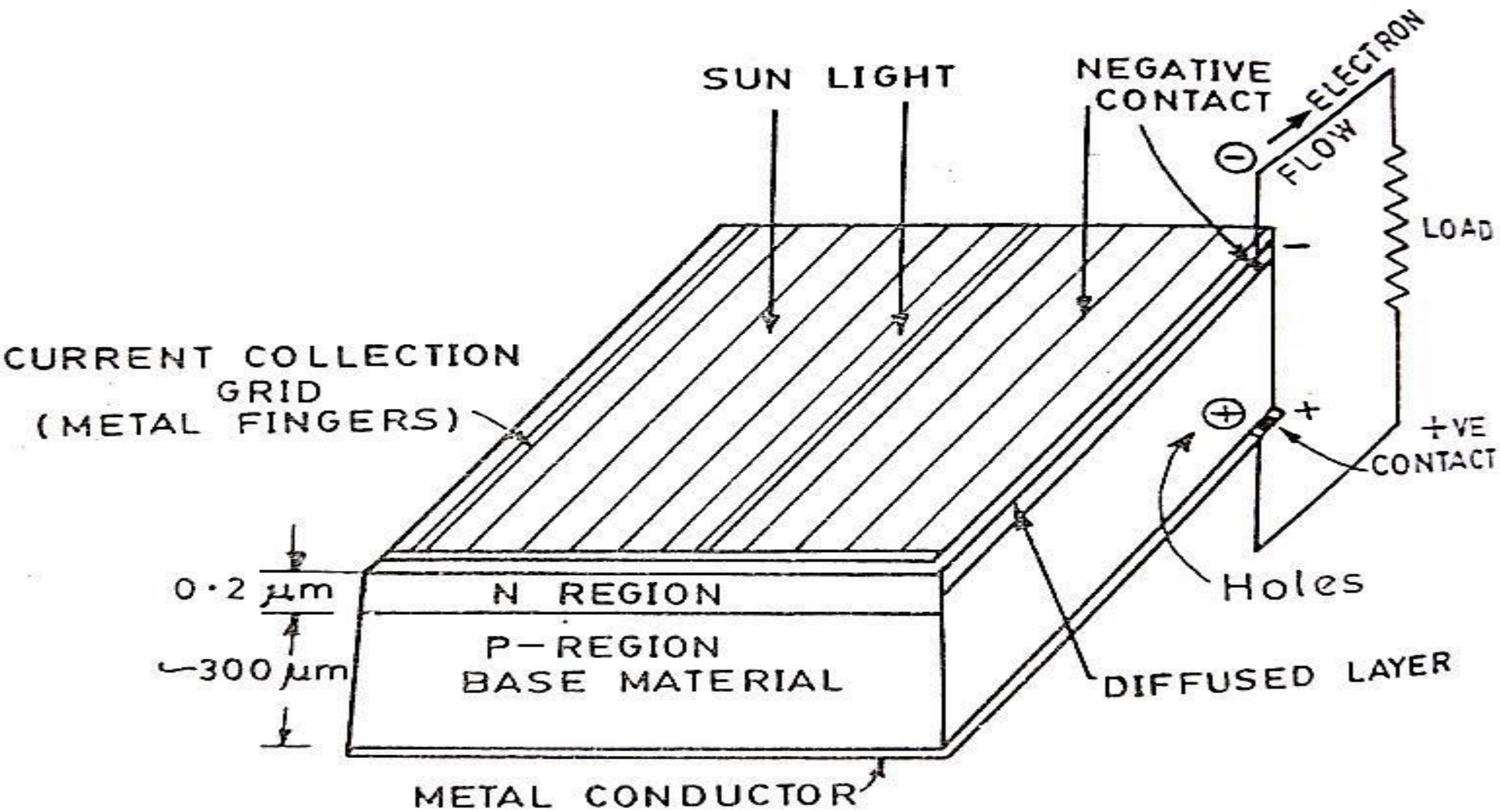


Fig. 5.6.1. Schematic view of a typical solar cell.

A Basic Photovoltaic system for power generation

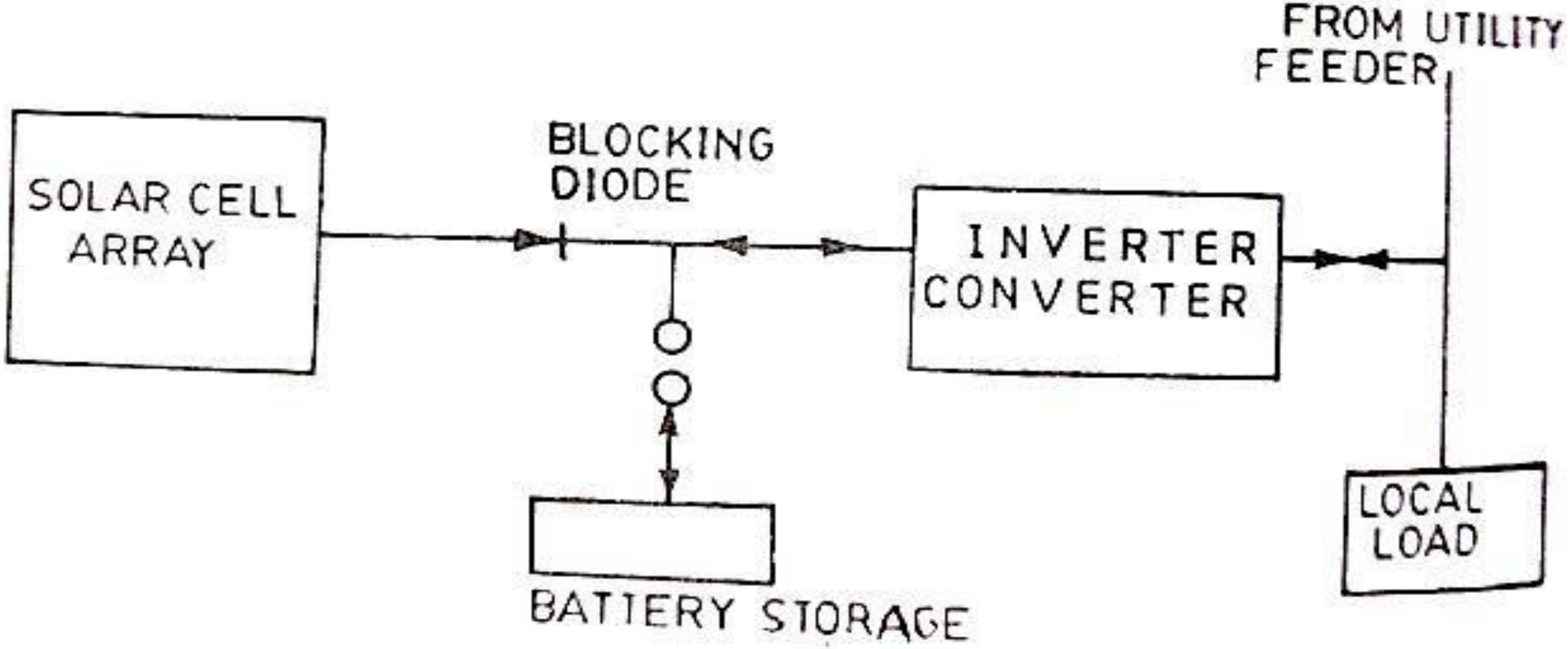


Fig. 5.6.5. Basic photovoltaic system integrated with power grid.

AGRICULTURAL AND INDUSTRIAL APPLICATIONS:

- In this application there are 3 categories namely
- 1) Low Temp (below 100°C)
- 2) Intermediate Temp (100-175°C)
- 3) High Temp (above 175°C)
- In low temp applications FPC's are used and the working fluid used is either water or air. The applications are heating and cooling of commercial green houses, space heating, dairy facilities and poultry houses, curing of bricks, drying of grains and distillation of water.
- Intermediate temp applications are food processing, laundry, pickling etc.

- In high temp applications solar energy is used for thermal electric conversion their by generating electric power.

- **SOLAR DISTILLATION:**

..., generally known as

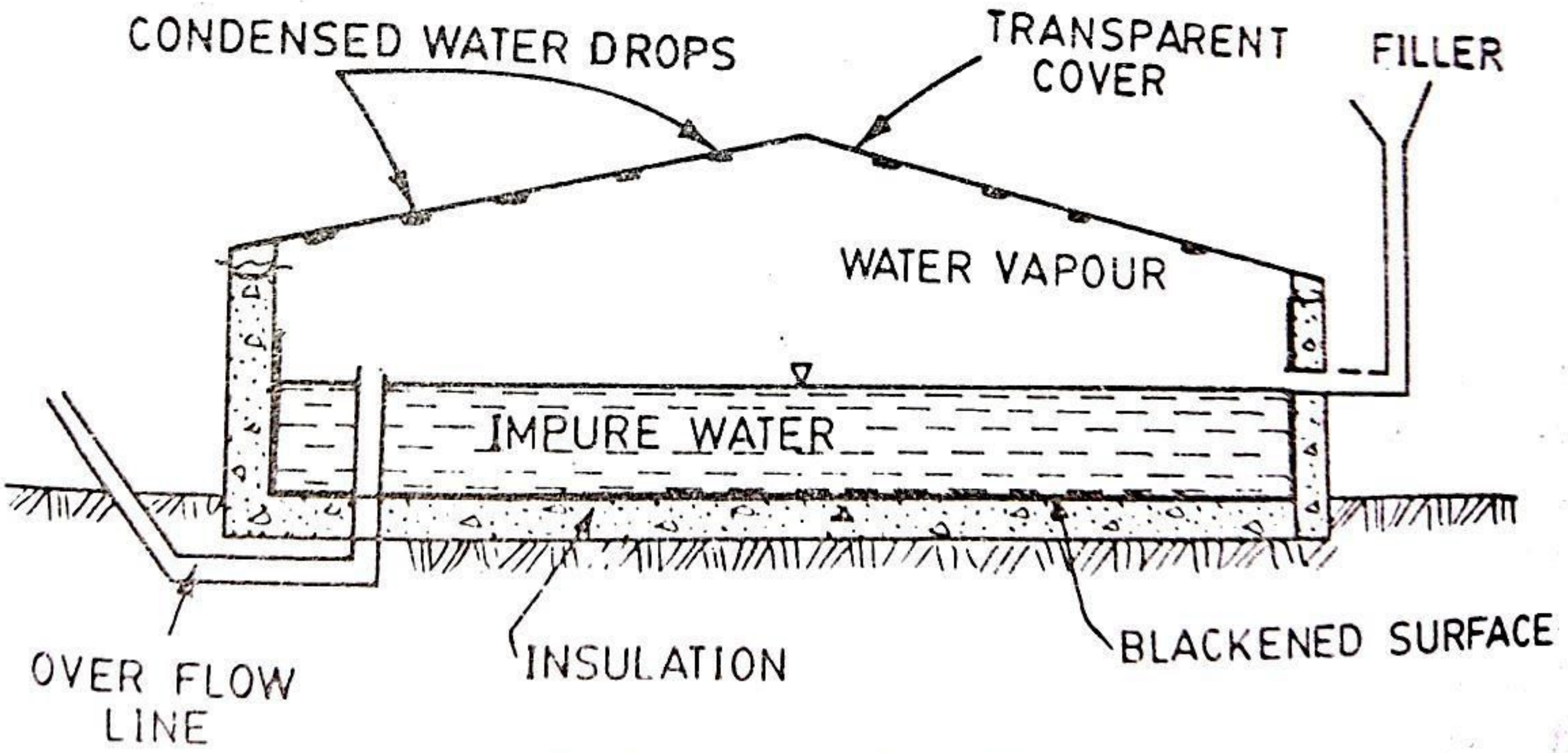


Fig. 5.8.1. Solar Water Still.

- The use of solar energy for desalting seawater and brackish well water has been demonstrated in several moderate sized pilot plants in the Unites States, Greece, Australia and several other countries. The idea was first applied in 1982.
- A simple basin type solar still consists of a shallow blackened basin filled with saline or brackish water to be distilled. The depth of water is kept about 5-10 cm. It is covered with sloppy transparent roof.
- Solar radiation, after passing through the roof is absorbed by the blackened surface of the basin and thus increases the temperature of the water.

- The evaporated water increases the moisture content, which gets condensed on the cooler underside of the glass. The condensed water slips down the slope and is collected through the condensate channel attached to the glass.

- **SOLAR PUMPING:** working non-freezing organic fluids- Toulene, Monochlorobenzene, Trifluoro ethanol, Hexafluoro benzene, Pyridine, Freon- 11,113, Thiopene etc.

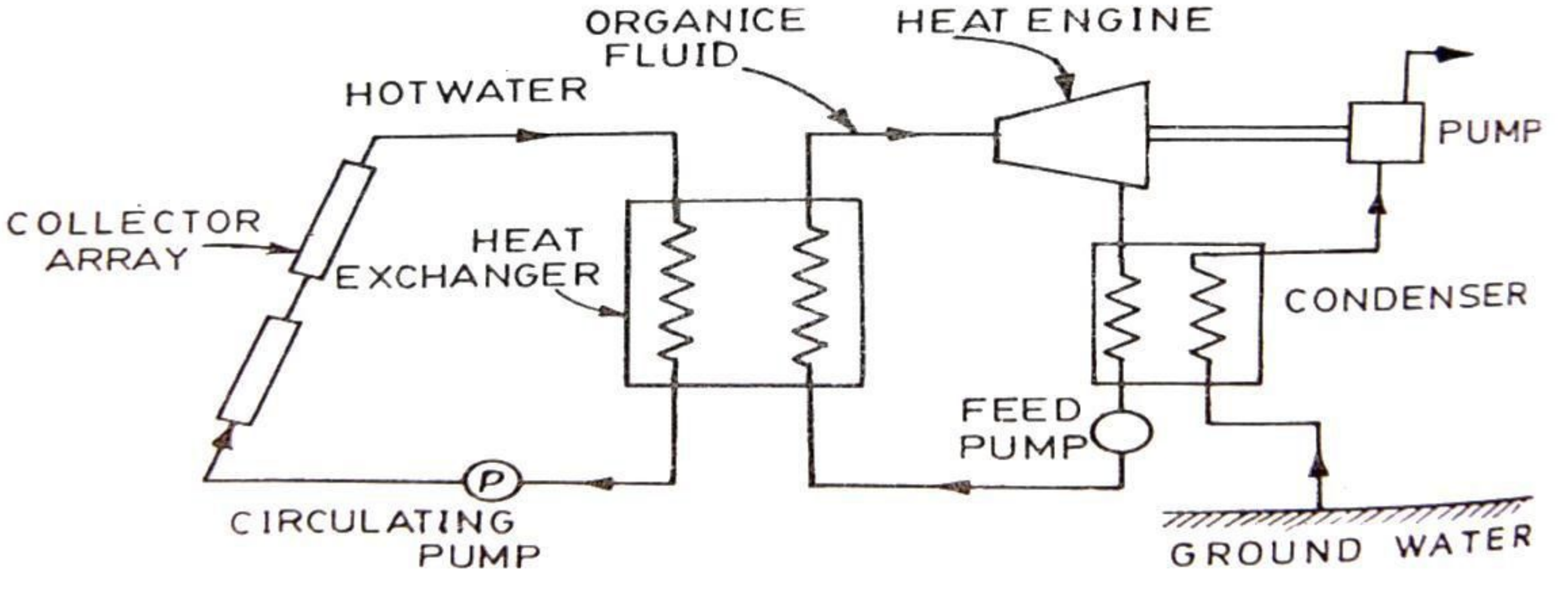


Fig. 5.9.1. Schematic of a solar pump.

- The solar pump is not much different from a solar heat engine working in a low temperature cycle.
- The sources of heat is the solar collector, and sink is the water to be pumped.
- A typical solar powered water pumping system is shown in above Fig.5.9.1.
- The primary components of the system are an array of flat-plate collectors and an Rankine engine with an organic fluid as the working substance.
- During operation a heat transfer fluid flows through the collector arrays.

- Depending upon the collector configuration, solar flux and the operating conditions of the engine, the fluid will be heated in the collector to a higher temperature, the solar energy which is thus converted to the thermal energy.
- The fluid flows into a heat exchanger, due to temperature gradient, and comes back to the collector. This water yields its heat to an intermediate fluid in the boiler.
- This fluid evaporates and expands in the engine before reaching the condenser, where it condenses at low pressure.
- The expansion engine or Rankine engine is coupled to the pump and it could of course be coupled to an electric generation.

TURBINE-DRIVEN PUMP USING SOLAR ENERGY:

- A simplified outline of a turbine –driven pump system utilizing solar energy is shown in Figure below.

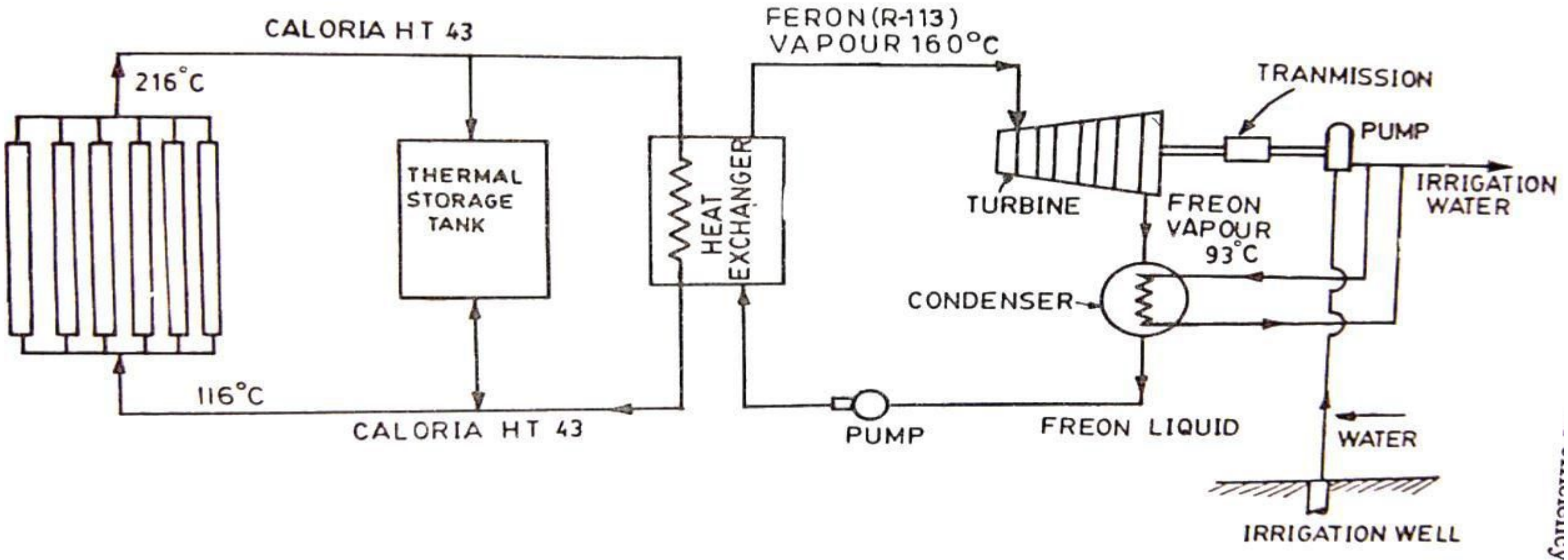


Fig. 5.9.2. A schematic of a turbine-driven pump using solar energy.

- In a particular system in New Mexico, the heat transport fluid (HT - 43) is heated to 216^{o}C in parabolic through collectors with a total operature area of 624 m^2.
- Part of the heated liquid is stored for use when the sun is not shining.
- The turbine working fluid (Freon type R- 113) leaves the boiler and enters the turbine as vapour at a temperature of 160^{0}C and 15 atm pressure.
- After expansion in the turbine, the vapour leaves at 93^{0}C and 0.7 atm; it is converted back to liquid in the condenser and returns to the boiler.
- The irrigation pump operates at a rated power of 19 kw and delivers water at 500 to 600 gal/min (32 to 38 litres/sec) from a well roughly 30m deep.

- **SOLAR FURNACE (3800°C):**

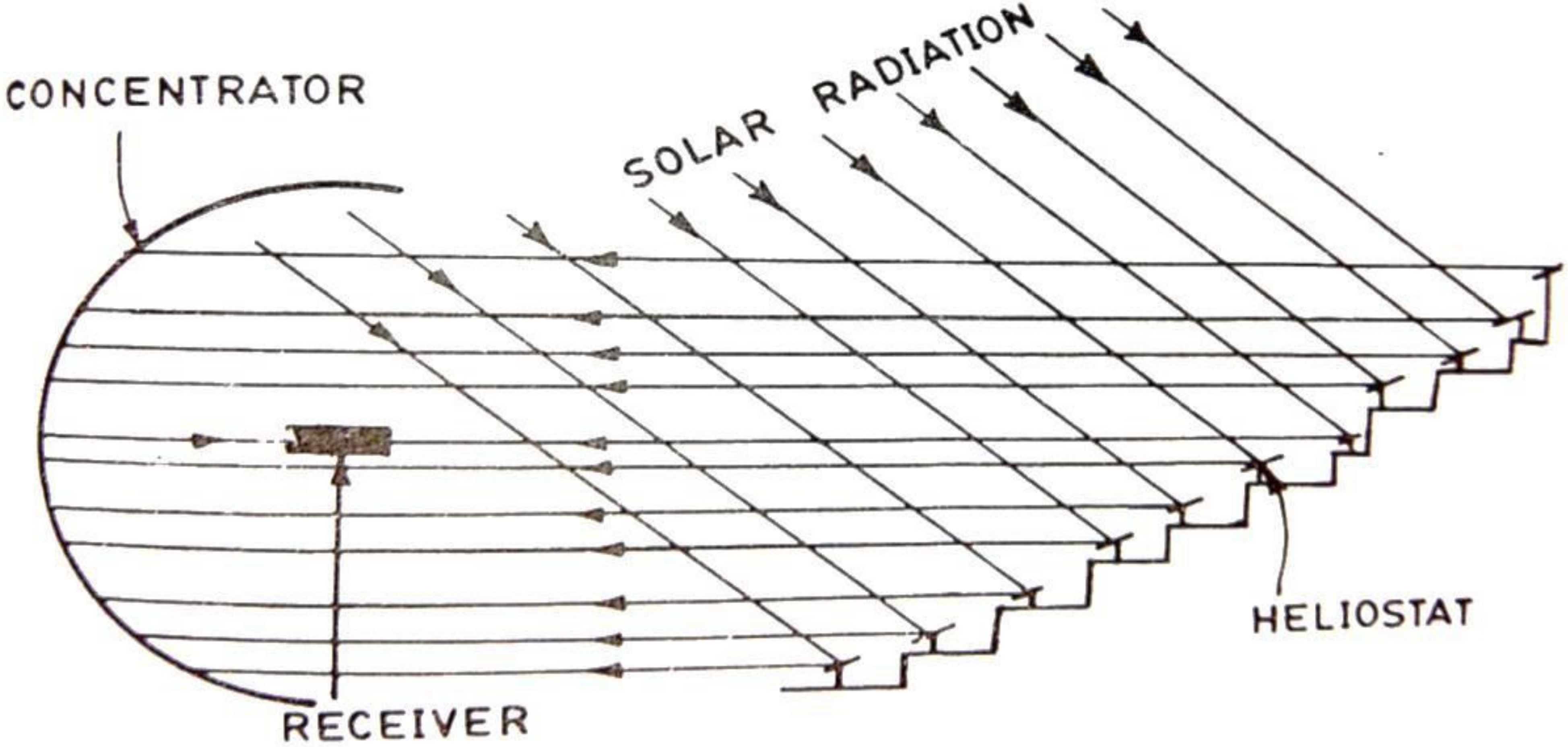


Fig. 5.10.1. Principle of Solar Furnace.

- The principle of the solar furnace is outlined in Fig.5.10.1.
- A number of heliostates are arranged in terraces on a slopping surface so that, regardless of the sun‘s position, they always reflect solar radiation in the same direction onto a large paraboloid reflecting collector made up of many fixed mirrors attached to the face of a structure.
- The collector then brings the radiation to a focus within a small volume.
- In figure a heliostat type furnace with horizontal optical axis is shown which is comparatively convenient and widely used in large furnaces.
- The most desirable mirror is that obtained by grinding and polishing a glass plate into an optical flat, aluminizing or silvering by vacuum evaporation, and cooling with a suitable film.

SOLAR COOKING:

- Thermal energy requirements for cooking purpose forms a major share of the total energy consumed, especially in rural areas.
- Variety of fuels like coal, kerosene, cooking gas, firewood, dung cakes and agricultural wastes are being used to meet the requirement.
- Fossil fuel is a fast depleting resource and need to be conserved, firewood for cooking causes deforestation and cow dung, agricultural waste etc. may be better used as a good fertilizer.
- Harnessing solar energy for cooking purpose is an attractive and relevant option.

Solar cooker : Solar energy is used for cooking using solar cookers.

- They are generally used for cooking, drying, and pasteurization. It is used for outdoor cooking where sunlight is available.
- The solar cooker is able to perform three basic functions i.e.
- (i) to concentrate sunlight,
- (ii) to convert light to heat, and
- (iii) to trap heat.
- It is low-cost, green device because it uses sunlight for heating instead of using firewood or other heating sources.
- The solar cookers are available commercially for domestic cooking.

Solar cooker

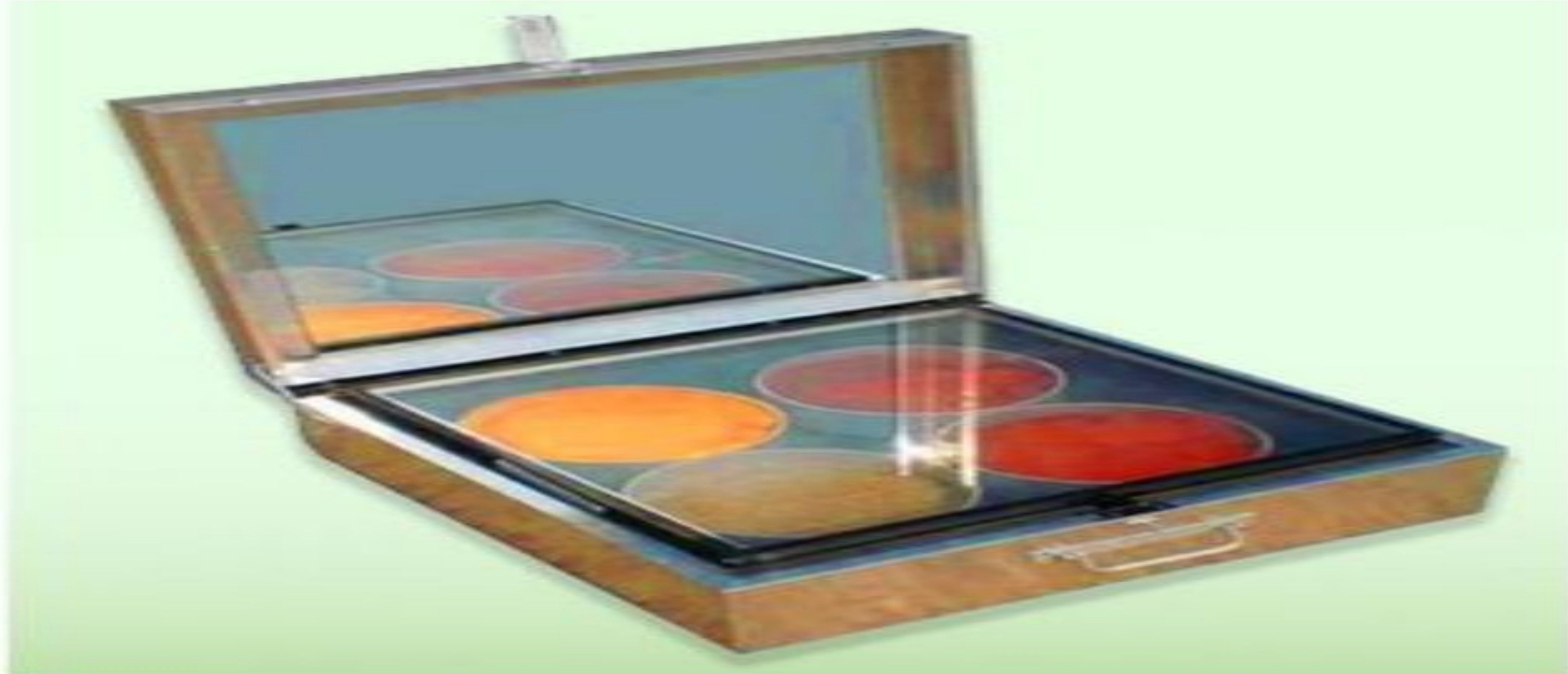
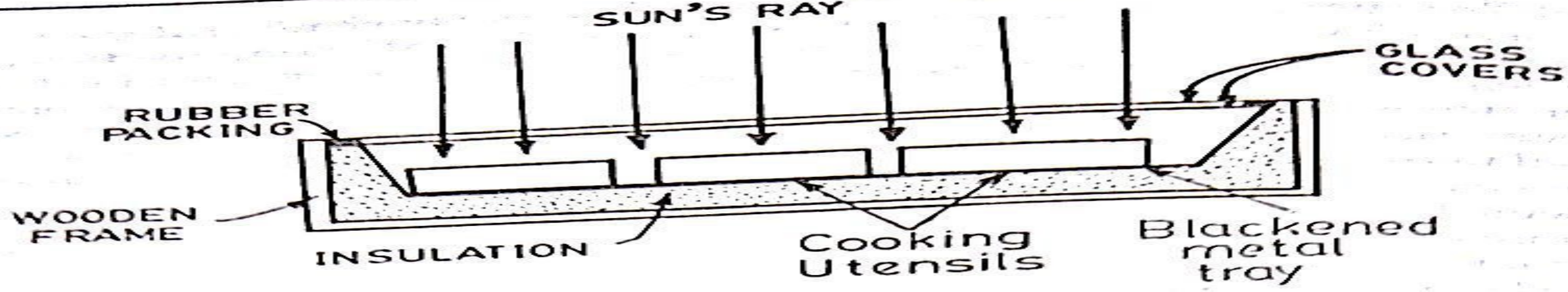
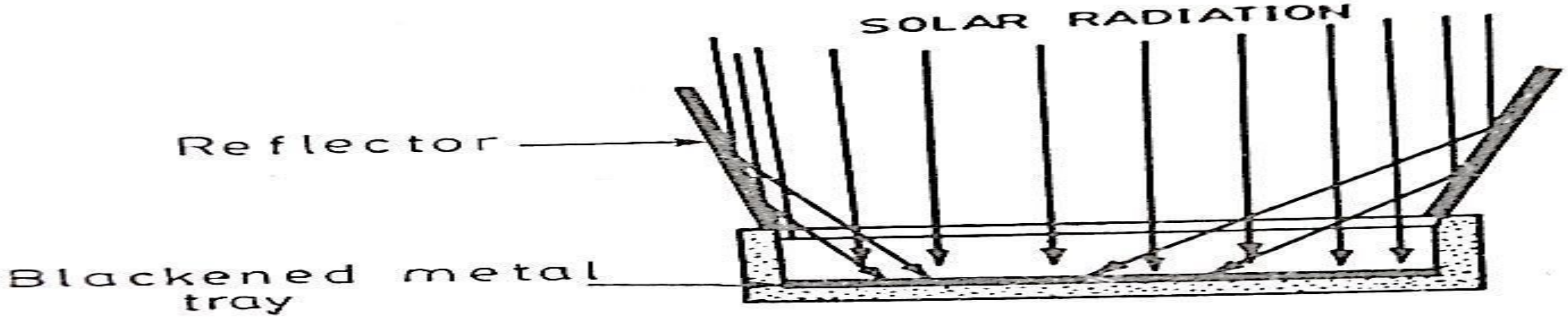


Fig. 1.11: Solar cooker



(a) Principle of box type cooker.



(b) Reflector type solar cooker.

(c) Principle of concentrating type cooker.

Fig. 5.11.1. Principle of operation of Solar cookers.

- 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) Advance solar cooker.

- **BOX TYPE SOLAR COOKER: (160°C) & Reflector type (240°C):**

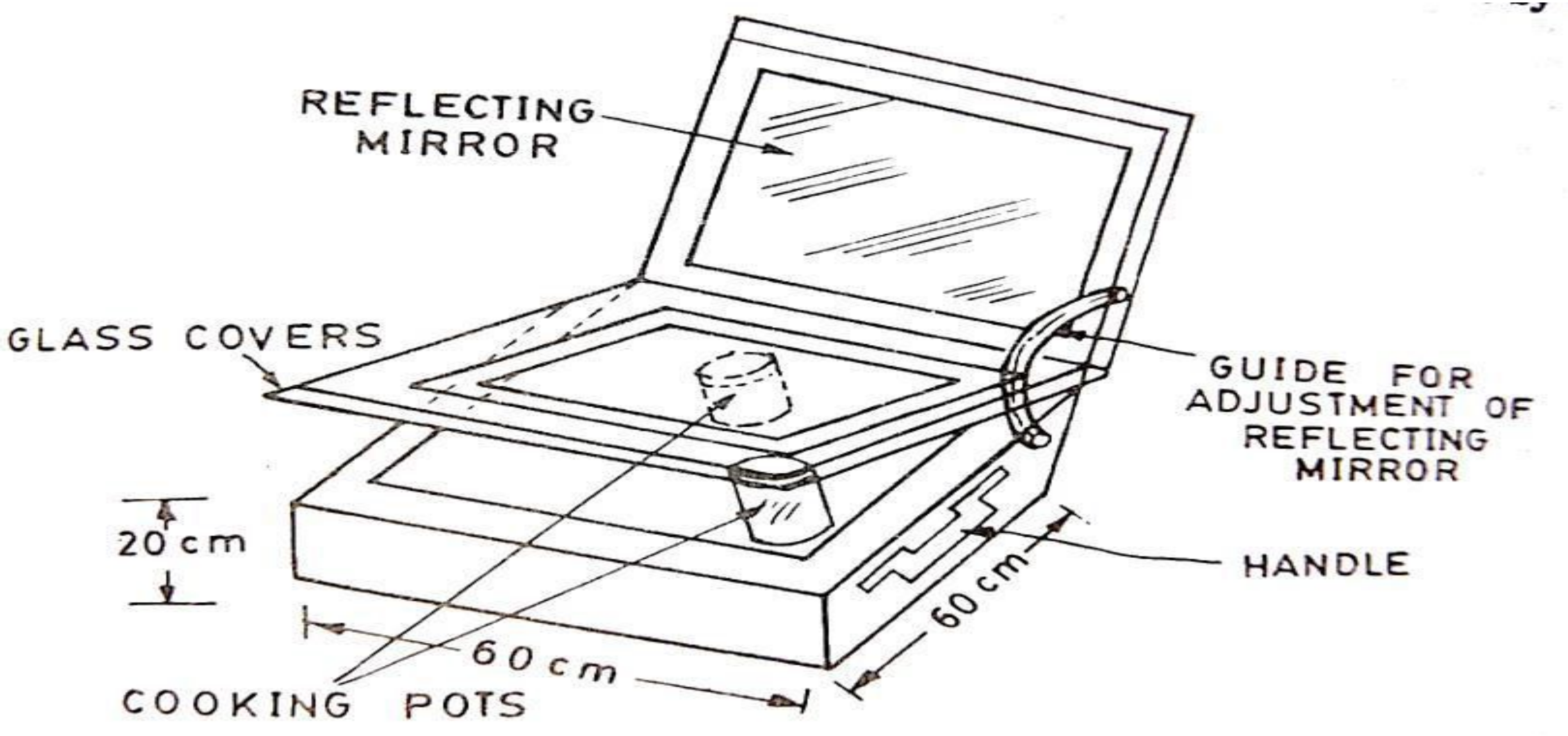


Fig. 5.11.2. Details of a box type cooker.

- The construction of a most common, box type solar cooker is schematically shown in figure above. The external dimensions of a typical family size box type cooker are 60x60x20 cm.
- An insulated box of blackened aluminium contains the utensils with food material.
- The box receives direct radiation and also reflected radiation from a reflector mirror fixed on inner side of the box cover hinged to one side of the box.
- The angle of 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 the greenhouse effect.

Advantages of solar cooker:

- No attention is needed during cooking as in other devices.
- No fuel is required.
- Negligible maintenance cost.
- No pollution.
- Vitamins of the food are not destroyed and food cooked is nutritive and delicious with natural taste.
- No problem of charring of food and no over flowing.

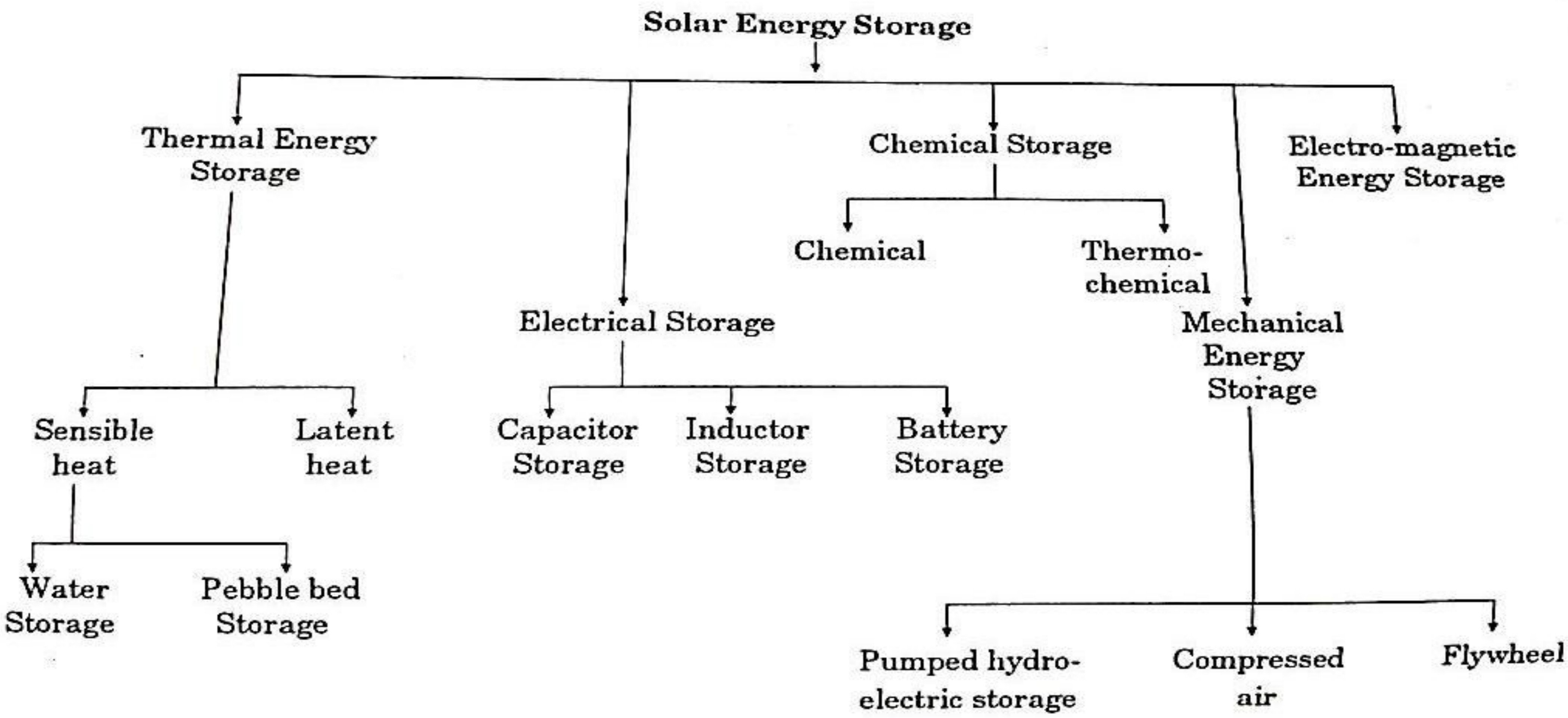
Limitations of solar cooker:

- One has to cook according to sunshine.
- One cannot cook at short notice and food cannot be cooked in the night or during cloudy days.
- It takes comparatively more time.
- Eg. Chapattis are not cooked because high temperature for baking is required.

SOLAR ENERGY STORAGE SYSTEMS:

- The thermal energy of sun can be stored in a well-insulated fluids or solids. It is either stored as,
- i) sensible heat – by virtue of the heat capacity of the storage medium, or as,
- ii) Latent heat – by virtue of the latent heat of change of phase of the medium or both.
- In the first type of storage the temp of the medium changes during charging or discharging of the storage whereas,
- In the second type the temp of the medium remains more or less constant since it undergoes a phase transformation.

- An overview of the major techniques of storage of solar energy is as shown in the fig.



The solar energy storage systems can be classified as follows:

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

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

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

Hydrogen Energy Storage: The electrical energy is used to decompose water by the electrolysis reaction into hydrogen and oxygen. These substances can be recombined to release the stored energy when required. Electromagnetic Energy Storage: The electrical energy is used to store energy in a magnetic field. The resistance of the coil wire is made almost negligible so that the stored energy in the coil is not dissipated out and stored energy in the magnetic field can be maintained indefinitely. The electromagnetic energy storage requires the use of superconducting materials. These materials develop almost zero resistance to electricity flow when cooled below a critical or transition temperature. This method of storing electromagnetic energy is also called super conducting magnetic energy storage (SMES). The electric energy can be recovered when coil is discharged.

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

Sensible Heat Storage

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

Latent Heat Storage

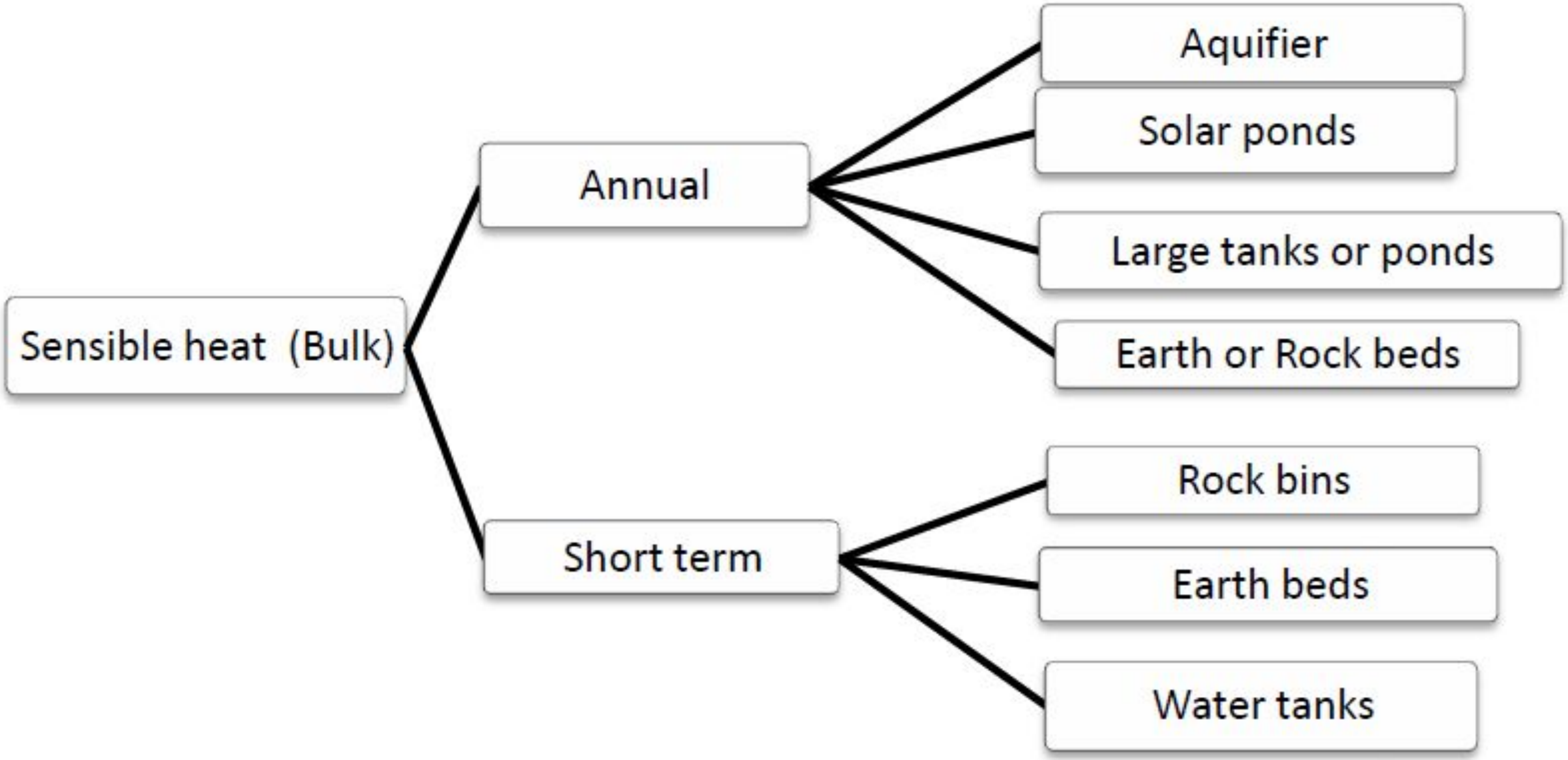
In the latent heat storage, heat energy is stored by virtue of latent heat which is required to bring about phase change of storage medium. The heat required to bring about phase change of a material is much larger compared to sensible heat change of the same material. The phase change of a material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

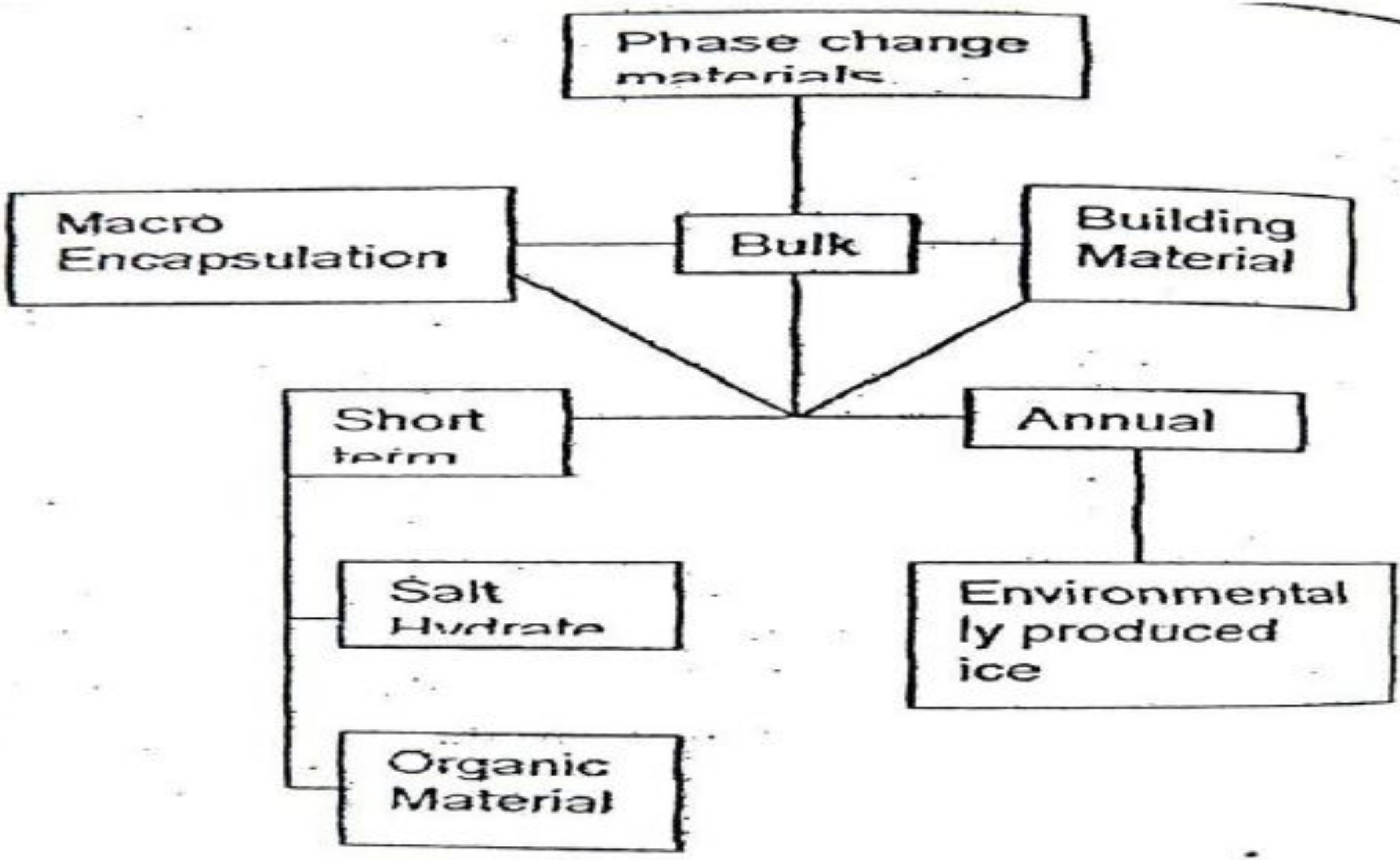
There are four main factors affecting the cost of solar thermal energy storage systems. viz,

- Thermal heat storage materials,
- Insulating material,
- Space occupied by the storage device,
- Heat exchange for charging and discharging the storage.

- The following chart shows the different storage systems used as per the required capacity. Depending on the available energy one can select the particular storage system thus optimizing the cost and the efficiency of the storage system.

Low Temperature solar thermal energy storage technology classification:




Phase change materials
Macro Encapsulation
Bulk
Building Material
Short term
Annual
Salt Hydrate
Environmentally produced ice
Organic Material

- In smaller heat storage, the surface area to volume ratio is large and hence the cost of insulating is an important factor.
- Phase change storages with higher energy densities are more attractive for small storage.
- In larger heat storage, on the other hand, the cost of storage material is more important and sensible heat storage like water is very attractive.

Desired characteristics of a thermal storage system:

- Compact, large storage capacity per unit mass and volume,
- High storage efficiency,
- Heat storage medium with suitable properties in the operating temperature range,
- Uniform temperature,
- Capacity to charge and discharge with the largest input/output rates but without temperature gradients.
- Complete reversibility.
- Ability to undergo large number of charges and discharge cycles without loss of performance and storage capacity.

Contd…,

- Small self-discharging rates,
- Quick charging and discharging,
- Long life
- Inexpensive
- Non corrosive
- No fire and toxic hazards.

Comparison of different storage techniques for solar space heating			
Property	Sensible Heating Water	Rock	Latent heat storage (solid – liquid0
Temperature Range	$0 - 100^0$ c	Large	Large, depends on the material
Specific heat	High	low	Medium
Thermal conductvity	Low	Low	Very-low (insulating)
Storage capacity /unit mass/unit vol	Low	Low	High
Stability to thermal cycling	Good	Good	Insufficient data
Availability	Good	Good	Depend on the choice of the material
Cost	Inexpensive	Inexpensive	Expensive
Heat exchanger geometry	Simple	Simple	Complex
Temp. gradient during charging/discharging	Large	Large	Small
Simultaneous charging/discharging	Possible	Not possible	Possible with appropriate H.E.
Cost of accessories	low	High	Low
Corrosion	Corrosive	Non corrosive	Insufficient data
Life	long	long	long

Fig: Comparison of different storage techniques

- Energy demands vary on daily, weekly and seasonal bases. TES is helpful for balancing between the supply and demand of energy.
- Thermal energy storage (TES) is defined as the temporary holding of thermal energy in the form of hot or cold substances for later utilization.
- TES systems deal with the storage of energy by cooling, heating, melting, solidifying or vaporizing a material and the thermal energy becomes available when the process is reversed.
- TES system for a particular application depends on storage duration, economics, supply and utilization temperature requirements, storage capacity, heat losses and available space.

Thermal energy storage for solar heating and cooling:

- Thermal energy storage is essential for both domestic water and space heating applications. Thermal energy can be stored in well insulated fluids or solids.

- There are two ways for thermal energy storage namely sensible heat storage and latent heat storage.

Sensible Heat Storage:

- In sensible heat storage the temperature of the medium changes during charging and discharging of the storage
- In this, there is no change in phase. The basic equation for energy storage is given by , $\mathbf{Q = mcp\Delta T}$.
- Where,
- Q - Total thermal capacity
- m - Mass of storage medium
- cp - Specific heat

Heat stored per unit volume (Q/Vs) is given by,

- Where Vs is the volume of the given storage container
- Water is generally used for storing thermal energy at low temperature. Heat transfer oils are used in sensible heat storage system for temperature range 100 - 300°C
- Solid materials like rocks, metals, concrete, sand and bricks etc. are also used for thermal storage.
- Water is also used as heat transfer fluid for heat flow to and from (but the temperature range is limited).

Latent heat storage:

- In latent heat storage, the temperature of the medium remains more or less constant, since it undergoes a phase transformation ie. The transition from solid to liquid or liquid to vapour.
- In a latent heat storage system, the heat is stored in a material when it melts and heat is extracted from material when it freezes example of such materials are paraffin wax, calcium chloride hexahydrate, magnesium nitrate hexahydrate, ice, sodium hydroxide etc.

- For latent heat storage- charging, phase transition solid- liquid (melting) is most suitable and for storage discharging, liquid- solid (solidification) is most suitable.
- The basic equation for energy storage is given by,
- **$Q = m\,[C_s(t_m - t_{min}) + h_m + CL(t_{max} - t_m)]$ joule**
- Where,
- m - Mass of phase change material (PCM) storage medium
- C_s - Specific heat of PCM – solid state (J/KgK)
- CL - Specific heat of PCM – liquid state (J/KgK)

- h_m – Specific melting enthalpy of PCM storage medium (J/Kg)
- t_{min}- Minimum storage temperature (°C)
- t_{max}- maximum storage temperature (°C)
- tm- Melting temperature of PCM storage medium (°C)

The latent heat storage charging process comprises three stages -

- First stage is heating of the phase change material in solid state.
- Second stage is melting of phase change material at constant temperature for pure substance or in the range of temperatures for mixed composition.
- Third stage involve heating of the molten phase change material to the maximum temperature (t_{max}).

END