

CHAPTER

3

SOLAR THERMAL ENERGY COLLECTORS

3.1 Solar thermal energy – General aspects – Collectors in various ranges and applications – Principles (physical) of conversion of solar energy into heat – Green-house effect – Collector systems – Characteristic features of a collector system – Factors adversely affecting collector system's efficiency; **3.2 Types of collectors;** **3.3. Flat-plate collector (FPC)** – Description – Selective absorber coatings/surfaces – Advantages, disadvantages and applications of flat-plate collectors – Evacuated collectors – Performance analysis of a flat-plate collector; **3.4 Concentrating (or focusing) collectors** – Need of orientation in concentrating collectors – Types of concentrating collectors – Advantages and disadvantages of concentrating collectors – Parabolic trough collector – Mirror-strip collector – Fresnel lens collector – Flat-plate collector with adjustable mirrors – Compound parabolic concentrator (CPC) – Paraboloidal disk collector – Comparison between flat-plate and concentrating collectors – Performance analysis of a concentrating collector; **3.5 Solar-thermodynamic conversion.** *Highlights – Theoretical Questions – Unsolved Examples.*

3.1 SOLAR THERMAL ENERGY

3.1.1. General Aspects

The solar thermal energy is a *clean, cheap and abundantly available renewable energy* which has been used since ancient times. The sun is a sustainable source of providing solar energy in the form of radiations, *visible light* and *infrared radiation*. This solar energy is captured naturally by different surfaces to produce thermal effect or to produce electricity by means of photovoltaic or day lighting of the buildings. Solar energy can be converted into '*thermal energy*' by using solar collector. It can be converted into '*electricity*' by using photovoltaic cell.

'Solar collector' surface is designed for *high absorption and low emission*.

Advantages:

1. Solar energy is *easily and abundantly* available.
2. It is *re-usable* source of energy.
3. It is *eco-friendly* (i.e. pollution free).
4. It reduces Green-house gas emissions.

Disadvantages:

1. Availability is *limited* to sun hours.

2. *Need of storage.*
3. Large area entails *high capital cost.*
4. Owing to change in the position of sun, *tracking is required.*

Applications:

1. Solar energy is used in solar water heating.
 2. It is used for solar pumping.
 3. It is employed in solar distillation.
 4. It finds use in solar cooking.
 5. It is used in the generation of electric power.
- In the solar energy utilisation, the first step is the *collection* of this energy. This is done through “collectors” whose surfaces are designed for *high absorptivity and low emissivity*.

Solar energy conversion can be achieved by the following two completely different routes:

- (i) *Solar thermodynamic;*
- (ii) *Solar-photovoltaic.*

When an object receives radiant energy, a proportion, depending upon the angle of incidence and nature of surface, is *reflected*, a part is *absorbed* and some of it *transmitted* through the object. With a few important exceptions (e.g., photovoltaic cells), energy of the absorbed radiation is *rapidly degraded to heat*.

The temperature attained is determined by a *balance between the input of absorbed energy, the rate of heat removal and the heat loss to the environment*. The heat loss increases with temperature and *limits the ultimate temperature attained by a ‘collector system’*. It also *reduces the proportion of useful heat extractable from the system*. The *highest temperature and maximum output of useful power* are therefore obtained when a *highly absorbent, well-insulated body* is exposed to a *high intensity of solar radiation*.

- Solar collectors, based on their geometry, can be divided into a number of generic types. These *vary in efficiency* and, consequently, *useful heat output, depending on demand temperature*, as shown in Fig. 3.1.

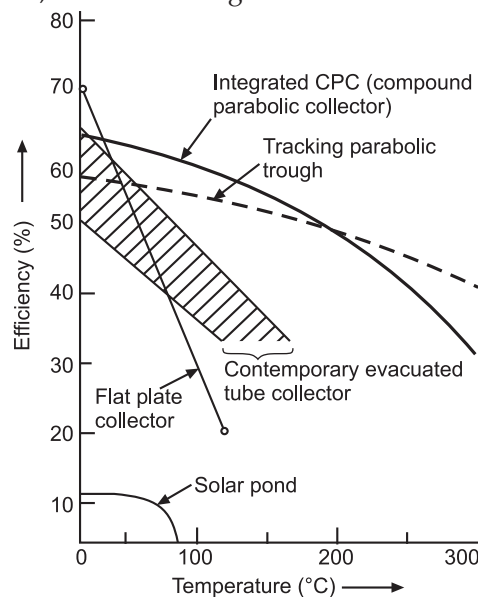


Fig. 3.1. Efficiency for solar collectors (Halcrow/ITP, 1983b).

3.1.2. Collectors in Various Ranges and Applications

The following list gives the *thermal applications of solar energy and possible temperature ranges*:

1. **Low temperature:**

($t = 100^\circ\text{C}$)

- (i) Water heating
- (ii) Space heating
- (iii) Space cooling
- (iv) Drying.

}...Flat plate

2. **Medium temperature:**

(t : 100 to 200°C)

- (i) Vapour engines and turbines
- (ii) Process heating
- (iii) Refrigeration
- (iv) Cooking.

}...Cylindrical Parabola

3. **High temperature:**

($t > 200^\circ\text{C}$)

- (i) Steam engines and turbines
- (ii) Stirling engine
- (iii) Thermo-electric generators.

}...Paraboloid Mirror arrays

The above classification of low, medium and high temperature ranges is *somewhat arbitrary*.

- Heating water for domestic applications, space heating and cooling and drying of agricultural products (and industrial products) is generally at temperature below 100°C , achieved using “flat plate collectors” with one or two glass plate covers.
- Refrigeration for preservation of food products, heating for certain industrial processes, and operation of engines and turbines using low boiling organic vapours is possible at somewhat higher temperature of 100 to 200°C and may be achieved using “focusing collectors” with cylindrical-parabola reflectors requiring only one directional diurnal tracking. Conventional steam engines and turbines, stirling hot air engines, and thermoelectric generators require the solar collectors to operate at high temperatures.
- Solar collectors operating at temperature above 200°C generally consist of paraboloid reflector as an array of mirrors reflecting to a central target, and requiring two directional diurnal tracking.
- ☞ ● The “concentrators or focusing type collectors” can give high temperatures than flat plate collectors, but they entail the following shortcomings/limitations.
 1. Non-availability and high cost of materials required. These materials must be easily shapeable, yet have a long life; they must be lightweight and capable of retaining their brightness in tropical weather. Anodised aluminium and stainless steel are two such materials but they are expensive and not readily available in sufficient quantities.
 2. They require direct light and are not operative when the sun is even partly covered with clouds.

3. They *need tracking systems* and reflecting surfaces undergo deterioration with the passage of time.
4. These devices are also subject to *similar vibration and movement problems as radar antenna dishes*.

3.1.3. Principles (physical) of Conversion of Solar Energy into Heat—Green-house Effect

When solar radiation from the sun, in the form of light (a *shortwave radiation*), reaches earth, visible sunlight is absorbed on the ground and converted into heat energy but *non-visible light* is re-radiated by earth (a *longwave radiation*). CO_2 in atmosphere *absorbs this light and radiates back a part of it to the earth*, which results in the *increase in temperature*. This whole process is called **Green-house effect**. Hence, the Greenhouse effect brings about an accumulation of energy of the ground.

- The name '*Green-house effect*' related to its first use in green houses, in which it is possible to *grow exotic plants in cold climes through better utilisation of the available light*.

3.1.4. Collection Systems

- **Solar thermal collection system:**

A solar thermal collection system works in the following manner:

- (i) It gathers the heat from the solar radiation and gives it to *the heat transport fluid* (also called *primary coolant*).
- (ii) The fluid delivers the heat to the *thermal storage tank* (*viz.* boiler steam generator, heat exchanger etc.).
- (iii) The storage system *stores heat for a few hours*. The heat is released during cloudy hours and at night.

- **Thermal-electric conversion system:**

This system receives thermal energy and drives steam turbine generator or gas turbine generator. The electrical energy is supplied to the electrical load or to the grid.

- **Co-generation plants:**

In *co-generation plants heat in the form of hot water or steam may also be supplied to the consumer in addition to the electrical energy*. In this case, hot water/steam from the reservoir may be pumped through outlet pipes to the load side.

3.1.5. Characteristic Features of a Collector System

The characteristic features of a collector system include the following:

1. The type of collector – *Focussing or non-focussing*.
 2. The temperature working fluid attained – *Low temperature, medium temperature, high temperature*.
 3. *Non-tracking type or tracking in one plane or tracking in two planes*.
 4. *Distributed receiver collectors or central receiver collectors*.
 5. *Layout and configuration of collectors in the solar field*.
 6. *Simple and low cost or complex and costly*.
- '*Solar collector cost*' is a significant component of installation cost. Hence it is important to keep *unit cost of collectors low and total surface area of collectors as small as possible*.

- 'Flat plate collectors' are used for *low temperature applications only*. They are *not* economical for high temperature applications. They are *not* suitable for high temperature applications and solar electric power plants.

3.1.6. Factors Adversely Affecting Collector System's Efficiency

The following *factors which adversely affect the efficiency of a collector system* are: *Shadow, Cosine loss, Dust etc.*

1. Shadow factor:

When the angle of elevation of the sun is *less than 15°* (i.e. around sunrise and sunset), the *shadows* of some of the neighbouring collector panels fall on the collector's surface. The shadow effect is reduced with the increase of sun's elevation angle.

The shadow factor is given as:

$$\text{Shadow factor} = \frac{\text{Collector's surface receiving light}}{\text{Total collector's surface}}$$

Its value is less than 0.1 when the angle of elevation of sun is less than 15° and 1 during noon when angle of sun's elevation angle is nearly 90°.

2. Cosine loss factor:

When the collector's surface receives the sun rays *perpendicularly*, *maximum power collection* is realised. If the angle between the perpendicular to collector's surface and the direction of sun ray is θ , the area of sun beam intercepted by the collector's surface is *proportional to* $\cos \theta$. Hence solar power collected is *proportional to* $\cos \theta$ (Fig. 3.2).

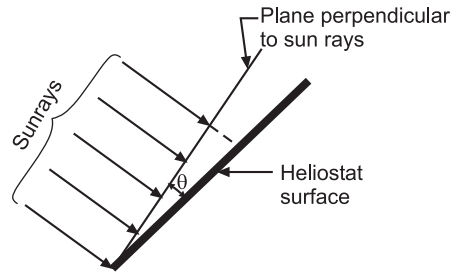


Fig. 3.2. Exhibiting $\cos \theta$ loss.

- In case of *fixed type collector panels* cosine loss *varies* due to the daily variation and seasonal variation of the direction of sun rays.

3. Reflective loss factor:

The glass surface of the *collector* and the surface of the *reflector* collect dust, dirt and moisture. As a result, the reflector surface gets rusted, deformed and loses the shine. Hence, with the passage of time, the collector's efficiency is *reduced* significantly. Thus, to prevent the loss, daily maintenance, seasonal maintenance and yearly overhaul (change of seals, cleaning after dismantling) should be undertaken.

3.2 TYPES OF COLLECTORS

A. Solar collectors are broadly *classified* into the following types:

1. "Non-concentrating" or "Flat-plate type solar collector".

In such collectors, the area of a collector to grasp the solar radiation is *equal to the absorber plate* and has *concentration ratio of 1*.

2. “Concentrating” or “Focusing type solar collector”.

In these collectors, the area of collector is kept *less than the aperture* through which the radiation passes, to concentrate the solar flux and has *high concentration ratio*.

B. Solar collectors may be *categorised* as follows:

1. Flat-plate collectors
 2. Evacuated collectors
 3. Solar ponds
 4. Stationary concentrators
 5. Linear-focus collectors
 6. Point-focus collectors
 7. Central receivers.
- One of the *disadvantages* of concentrating solar collectors is the need to align the collector's aperture with the sun's direct beam. This not only consumes power but also increases costs and the risk of failure. A single axis, tracking, time-focus, solar collector may use a number of “tracking mechanisms”.

3.3 FLAT-PLATE COLLECTORS (FPC)

3.3.1. Description

Fig. 3.3 shows a Flat Plate Collector which consists of *four essential components*:

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

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

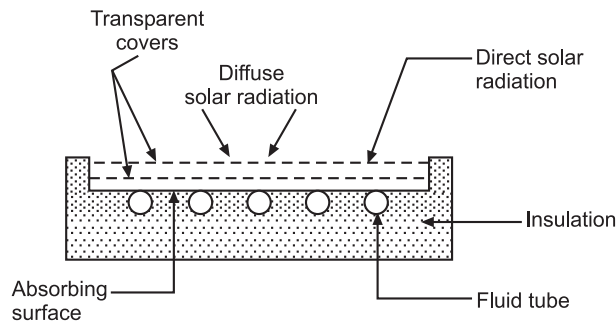


Fig. 3.3. Flat-plate solar collector.

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

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

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

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

Basically, a flat-plate collector is *effective* most of time, *reliable* for good many years and also *inexpensive*.

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

Materials for flat-plate collectors:

1. Absorber plate: Copper, Aluminium, Steel, Brass, Silver etc.
2. Insulation: Crown white wool, Glass wool, Expanded polystyrene, foam etc.
3. Cover plate: Glass, Teflon, Tedlar, Marlex etc.

3.3.2. Selective Absorber Coatings/Surfaces

In order to reduce thermal losses from the absorber plate of a solar heating panel, an efficient way is to use *selective absorber coatings*. An ideal selective coating is a *perfect absorber* of solar radiation as well as a *perfect reflector* of thermal radiation. A selective coating, thus, increases the temperature of an absorbing surface.

A “selective surface” has a *high absorptance* for shortwave radiation (less than 2.5 μm) and *low emittance* of longwave radiation (more than 2.5 μm).

A selective surface should possess the following *characteristics*:

(i) Its properties should *not change with use*; (ii) It should be of *reasonable cost*; (iii) It should be able to *withstand the temperature levels* associated with the absorber plate surface of a collector over extended period of time; (iv) It should be able to *withstand atmospheric corrosion and oxidation*.

Some selective coatings are:

(i) Black chrome; (ii) Black nickel; (iii) Black copper; (iv) Silver foil; (v) Enersorb (non-selective); (vi) Nextel (non-selective).

3.3.3. Advantages, Disadvantages and Applications of Flat-plate Collectors

Advantages:

1. Both beam and diffuse solar radiations are used.
2. Require little maintenance.
3. The orientation of the sun is *not required* (i.e. no tracking device needed)
4. Mechanically *simpler* than the focusing collectors.

Disadvantages:

1. *Low temperature* is achieved.
2. *Heavy* in weight.
3. Large heat losses by conduction due to large area.

Applications:

1. Used in *solar water heating*.
2. Used in *solar heating and cooling*.
3. Used in *low temperature power generation*.

3.3.4. Evacuated Collectors

Planar solar collectors of *evacuated type* often achieve efficiencies with an output temperature of above 80°C. In these devices a vacuum occupies the space between the absorber and the aperture cover. The absorber may consist of a heat pipe that is thermally bonded to collecting this, possibly in an evacuated glass tube.

Efficiencies in excess of 40% or an output temperature of 200°C can be reached (Collins and Duff, 1983).

3.3.5. Performance Analysis of Flat-plate Collector**Analysis:**

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

Using the above symbols we can write

$$\alpha + \rho + \tau = 1 \quad \dots(3.1)$$

The absorbed part of the solar radiations, which is equal to α , is responsible for increasing the temperature of the body. However, the body also loses energy by conduction, convection and radiation. The *equilibrium temperature of the body will be that at which the heat losses from the body are equal to the absorbed radiations*.

For analysis purposes, if we represent the body by a flat a plate and assume that the *convection and conduction losses are negligible to begin with*, then at equilibrium temperature the absorbed solar radiations should be equal to the radiation losses from the flat plate. The *radiation losses are equal to $\epsilon\sigma T^4$* , where ϵ and T are the emission coefficient and absolute temperature respectively of a flat plate and σ is the Boltzman's constant.

Therefore, at equilibrium

$$\alpha I = \epsilon\sigma T^4 \quad \dots(3.2)$$

$$\text{or,} \quad \frac{\alpha I}{\epsilon} = \sigma T^4 \quad \dots(3.3)$$

From equation (3.3), it is evident that comparatively higher equilibrium temperature will be obtained where the quantity $\frac{\alpha}{\epsilon}$ i.e., the ratio of absorption coefficient to emission coefficient of the flat plate is *more*. However, this has been demonstrated by an equation obtained under *idealised condition*. In the realistic conditions too, its nature will remain the same, but it will get *modified* by other influencing factors.

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

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

A flat plate painted black is placed on a well insulated base. If it is exposed to solar radiations where $I = 800 \text{ W/m}^2$, a typical summer value for a tropical region, we obtain from equation (3.3) the equilibrium temperature as 70°C . In spite of the simplifications here, it is a fair estimate of the temperature reached by a black plate left for a time in the tropical sun.

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

If I' is the intensity of the diffused radiations and α' the absorption coefficient, then equation (3.2) becomes

$$\alpha I + \alpha' I' = h_c(T - T_a) + \varepsilon \sigma T^4 \quad \dots(3.4)$$

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

Transmissivity-absorptivity product ($\tau.\alpha$):

The effective part radiation absorbed is given by:

$$(\tau.\alpha)_e = \frac{\tau.\alpha}{1 - (\tau - \alpha)\rho_d} \quad \dots(3.5)$$

The value of ρ_d for an incident angle of 60° is about 0.16, 0.24 and 0.2 for *one, two and three glass covers* respectively.

Performance:

The "performance of a flat-plate collector" is described by an energy balance that indicates the distribution of incident solar energy into useful energy gain and various losses.

Under steady conditions:

Useful heat delivered by a solar collector

$$= \text{Energy absorbed in the metal surface} - \text{Heat losses from the surface directly and indirectly to the surroundings.}$$

Useful heat output of a flat-plate collector is given by:

$$Q_c = A_{cs} [I_{cs}(\tau\alpha)_e - U_{oc}(t_{fi} - t_a)] \text{ watts} \quad \dots(3.6)$$

Q_c = Useful heat output of flat-plate collector (W),

A_{cs} = Collector surface area (m^2),

I_{cs} = Intensity of solar radiation incident on the collector surface (W/m^2),

τ = Transmission coefficient (i.e., fraction of incoming solar radiation that reaches the absorbing surface)

α = Absorption coefficient (i.e. fraction of the solar radiation reaching the surface that is absorbed)

$(\tau\alpha)_e$ = Effective product of transmittivity of the transparent cover and absorptivity of the absorber,

U_{oc} = Overall total heat loss coefficient of the collector (W/m^2C),

t_{fi} = collector fluid inlet temperature ($^{\circ}C$), and

t_a = Ambient air temperature ($^{\circ}C$).

Introducing heat “removal factor F_R ” in (Eqn. (3.6), we get,

$$Q_c = A_{cs} [I_{cs} F_R (\tau\alpha)_e - F_R U_{oc} (t_{fi} - t_a)] \text{ watts} \quad \dots(3.7)$$

The “**efficiency** of a solar collector (η_c)” is defined as the ratio of the useful heat output of the collector to the solar energy flux incident on the collector.

$$\text{Mathematically,} \quad \eta_c = \frac{Q_c}{A_{cs} I_{cs}} \quad \dots(3.8)$$

Inserting the value of Q_c from Eqn. (3.7) in Eqn. (3.8), we get:

$$\eta_c = F_R (\tau\alpha)_e - F_R U_{oc} \left(\frac{t_{fi} - t_a}{I_{cs}} \right) \quad \dots(3.9)$$

Eqn. (3.9) indicates that if the efficiency is plotted against $\left(\frac{t_{fi} - t_a}{I_{cs}} \right)$, a straight line will result, with a slope of $F_R U_{oc}$ and Y-intercept of $F_R (\tau\alpha)_e$,

$$\text{If,} \quad \frac{t_{fi} - t_a}{I_{cs}} = 0 \text{ i.e. } t_{fi} = t_a, \text{ then} \quad \eta_c = F_R (\tau\alpha)_e \quad \dots(3.10)$$

This is the effective optical efficiency.

- The energy balance equation on the whole collector can be written as:

$$A_{cs} [I_{cs} F_R (\rho\alpha)_b + I_{cs} F_R (\tau\alpha)_d] = Q_u + Q_l + Q_s \quad \dots(3.11)$$

where, Q_u = Rate of useful heat transfer to a working fluid in the solar heat exchanger,

Q_l = Rate of energy losses from the collector to the surroundings by re-radiation, convection and by conduction through supports for the absorber plate and so on. The losses due to reflection from the covers are included in the $(\tau\alpha)$ terms, and

Q_s = Rate of energy storage in the collector.

Suffices, b and d stand for beam and diffuse radiations respectively.

The outlet temperature of collector heat transfer fluid, t_{fo} ($^{\circ}C$)

The outlet temperature of collector heat transfer fluid t_{fo} is given by:

$$t_{fo} = t_{fi} + \frac{Q_c}{\dot{m} c_p} \quad \dots(3.12)$$

where,

t_{fi} = Collector fluid inlet temperature ($^{\circ}C$),

Q_c = Useful heat output of collector (W),

\dot{m} = Mass flow rate of collector fluid (kg/s), and

c_p = Specific heat of collector fluid (J/kg K).

The stagnant temperature (t_s) of the collector is defined as the temperature of the absorber which is achieved when there is no flow of heat transfer fluid in the collector and therefore, its useful heat output and efficiency both are equal to zero. Hence, for Eqn. 3.7, we get:

$$O = A_{cs} [I_{cs} F_R (\tau\alpha)_e - F_R U_{oc} (t_{fi} - t_a)]$$

or,

$$I_{cs} F_R (\tau\alpha)_e = F_R U_{oc} (t_{fi} - t_a)$$

or,

$$t_s = t_{fi} = t_a + I_{cs} \frac{F_R (\tau\alpha)_e}{F_R U_{oc}} \quad \dots(3.13)$$

It is evident from Eqn. (3.13) that t_s will be high, if I_{cs} and $(\tau\alpha)_e$ are *high* and $F_R U_{oc}$ is *low*.

Factors affecting the performance of a flat-plate collector:

The following *factors* affect the performance of a flat-plate collector:

1. Incident solar radiation.
 2. Number of cover plates.
 3. Spacing between absorber plate and glass cover.
 4. Tilt of the collector.
 5. Selective surface.
 6. Fluid inlet temperature.
 7. Dust on cover plate.
1. **Incident solar radiation.** The collector's efficiency is *directly* related to solar radiation falling on it and *increases* with rise in temperature.
 2. **Number of cover plates.** The *increase* in number of cover plates *reduces* the internal connective heat losses but also *prevents* the transmission of radiation inside the collector.
 3. **Spacing between absorber plate and glass cover.** The *more the space* between the absorber and the cover plate, the *less is the internal heat loss*.
 4. **Tilt of the collector.** In order to achieve better performance, flat-plate collector should be *tilted at an angle of latitude of the location*.
— The collector is placed with south facing at northern hemisphere to receive maximum radiation throughout the day.
 5. **Selective surface.** The selective surface should be able to *withstand high temperature*, should *not oxidise* and should be *corrosion resistant*.
 6. **Fluid inlet temperature.** With the increase in the inlet temperature of the fluid, there is an increase in operating temperature of the collector and this leads to *decrease in efficiency*.
 7. **Dust on cover plate.** The collector's efficiency *decreases* as dust particles *increase* on the cover plate. Thus, *frequent cleaning* is required to get the maximum efficiency of the collector.

Example 3.1. The following data relate to an evacuated tube collector:

The intensity of solar radiation on the collector's surface	= 800 W/m ² ;
The inlet temperature of the fluid	= 38 °C;
The ambient air temperature	= 25 °C
Effective optical efficiency	= 0.76
Effective heat loss coefficient	= 1.65 W/m ² K
Mass flow rate of water	= 0.019 kg/s/m ²
Specific heat of water at constant pressure	= 4187 J/kg K

Calculate the following:

- (i) Useful heat output, per m^2 of the surface area.
- (ii) Outlet temperature of the fluid.
- (iii) Stagnation temperature.

Solution. Given: $I_{cs} = 800 \text{ W/m}^2$; $A_{cs} = 1 \text{ m}^2$; $t_{fi} = 38^\circ\text{C}$; $t_a = 25^\circ\text{C}$; $F_R (\tau\alpha)_e = 0.76$; $F_R U_{oc} = 1.65 \text{ W/m}^2\text{K}$; $\dot{m} = 0.019 \text{ kg/s/m}^2$, $c_p = 4187 \text{ J/kg K}$.

(i) Useful heat output; Q_c :

$$Q_c = A_{cs} [I_{cs} F_R (\tau\alpha)_e - F_R U_{oc} (t_{fi} - t_a)] \text{ watts} \quad \dots [\text{Eqn. (3.7)}]$$

$$= 1 \times [800 \times 0.76 - 1.65 (38 - 25)] = 586.5 \text{ W (Ans.)}$$

(ii) Outlet temperature of the fluid, t_{fo} :

$$t_{fo} = t_{fi} + \frac{Q_c}{\dot{m} c_p} \quad \dots [\text{Eqn. (3.12)}]$$

$$= 38 + \frac{586.5}{0.019 \times 4187} = 45.4^\circ\text{C (Ans.)}$$

Example 3.2. The following data relate to a flat plate collector used for heating the building:

Location and latitude = Baroda, 22°N ; Day and time: January 22, 11:30 – 12:30 (IST); Annual average intensity of solar radiation = $340 \text{ W/m}^2 \text{ hr}$; Tilt of the collector = latitude + 14° ; Number of glass covers = 2; Heat removal factor for collector = 0.82; Transmittance of glass = 0.87; Absorptance of glass = 0.89; Top loss coefficient for collector = $7.9 \text{ W/m}^2 \text{ hr } ^\circ\text{C}$; Collector fluid inlet temperature = 48°C ; Ambient temperature = 16°C .

Calculate the following:

- (i) Solar altitude angle;
- (ii) Incident angle;
- (iii) Efficiency of the collector.

Solution. Given: $\phi = 22^\circ$; Day and time: Jan. 22, 11:30 – 12:30 (IST);

$$H_b = 340 \text{ W/m}^2 \text{ hr}; \beta = \phi + 14^\circ = 22^\circ + 14^\circ = 36^\circ;$$

ρ_d (diffuse reflectance for two glass covers) = 0.24; $F_R = 0.82$; τ (for glass) = 0.87; α (glass) = 0.89; Top loss coefficient for collector, $U_{oc} = 7.9 \text{ W/m}^2 \text{ hr } ^\circ\text{C}$; $t_{fi} = 48^\circ\text{C}$; $t_a = 16^\circ\text{C}$.

(i) Solar altitude angle, α :

$$\text{Solar declination, } \delta = 23.45 \sin \left[\frac{360}{365} (284 + n) \right] \quad \dots [\text{Eqn. (2.3)}]$$

$$\therefore \delta = 23.45 \sin \left[\frac{360}{365} (284 + 22) \right] = -19.93^\circ$$

Solar hour angle $\omega = 0$, (at mean of 11:30 and 12:30).

Solar altitude angle α is given by:

$$\sin \alpha = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega \quad \dots [\text{Eqn. (2.10)}]$$

$$= \sin 22^\circ \sin (-19.93^\circ) + \cos 22^\circ \cos (-19.93^\circ) \cos 0^\circ$$

$$= -0.1277 + 0.8716 = 0.7439$$

$$\therefore \alpha = 48.6^\circ \text{ (Ans.)}$$

(ii) Incident angle, θ :

$$\theta = \frac{\pi}{2} - \alpha = 90^\circ - 48.06^\circ = 41.94^\circ \text{ (Ans.)}$$

(iii) **Efficiency of the collector, η_c :**

Tilt for the beam radiation (R_b) is given by:

$$\begin{aligned} R_b &= \frac{\sin \delta \sin(\phi - \beta) + \cos \delta \cos \omega \cos(\phi - \beta)}{\sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega} \quad \dots[\text{Eqn. (2.29(a)}] \\ &= \frac{\sin(-19.93^\circ) \sin(22^\circ - 36^\circ) + \cos(-19.93^\circ) \cos 0^\circ \cos(23^\circ - 36^\circ)}{\sin 22^\circ \sin(-19.93^\circ) + \cos 22^\circ \cos(-19.93^\circ) \cos 0^\circ} \\ &= \frac{-0.0825 + 0.9121}{-0.1277 + 0.8716} = 1.115 \end{aligned}$$

Effective transmittance absorptance product is given by;

$$(\tau.\alpha)_e = \frac{\tau.\alpha}{1 - (1 - \alpha)\rho_d} \quad \dots[\text{Eqn. (3.5)}]$$

(where, ρ_d = diffuse reflectance for two glass covers = 0.24)

$$= \frac{0.87 \times 0.89}{1 - (1 - 0.89) \times 0.24} = 0.795$$

Beam solar radiation intensity, $H_b = 340 \text{ W/m}^2\text{hr}$...(Given)

$$\begin{aligned} \text{Now, solar radiation, } H &= H_b R_b (\tau.\alpha)_e \\ &= 340 \times 1.115 \times 0.795 = 301.38 \text{ W/m}^2\text{hr} \end{aligned}$$

$$\begin{aligned} \text{Useful gain, } Q_c &= F_R [H - U_{oc}(t_{fi} - t_a)] \\ &= 0.82 [301.38 - 7.9 (48 - 16)] = 39.83 \text{ W/m}^2\text{hr} \end{aligned}$$

$$\therefore \text{Collector efficiency, } \eta_c = \frac{Q_c}{H_b R_b} = \frac{39.83}{340 \times 1.115} = 0.105 \text{ or } 10.5\% \text{ (Ans.)}$$

3.4. CONCENTRATING (OR FOCUSING) COLLECTORS

Concentrating collector is a device to collect solar energy with high intensity of solar radiation on the absorbing surface by the help of reflector or refractor.

3.4.1. Need of Orientation in Concentrating Collectors

Such collectors generally use optical system in the form of reflectors or refractors. A concentrating collector is a special form of flat-plate collector modified by introducing a reflecting (or refracting) surface (*concentrator*) between the solar radiations and the absorber. These types of collectors can have radiation increase from low value of 1.52 to high values of the order of 10,000. In these collectors radiation falling on a relatively large area is focused on to a receiver (or absorber) of considerably smaller area. As a result of the energy concentration, fluids can be heated to temperatures of 500°C or more.

Orientation of sun from earth changes from time to time. So to harness maximum solar rays it is necessary to keep our collector facing to sun rays direction. This is the reason why orientation in concentrating collector is necessary. This is achieved by the use of “Tracking device”.

3.4.2. Types of Concentrating Collectors

The different types of focusing/concentrating type collectors are:

1. Parabolic trough collector.
2. Mirror strip collector.
3. Fresnel lens collector.
4. Flat-plate collector with adjustable mirrors.
5. Compound parabolic concentrator (CPC).
6. Parabolic dish collector.

3.4.3. Advantages and Disadvantages of Concentrating Collectors

Advantages:

1. *High concentration ratio.*
2. *High fluid temperature can be achieved.*
3. *Less thermal heat losses.*
4. *System's efficiency increases at high temperatures.*
5. *Inexpensive process.*

Disadvantages:

1. *Non-uniform flux on absorber.*
2. *Collect only beam radiation components* because diffuse radiation components *cannot be reflected, hence these are lost.*
3. *Need costly tracking device.*
4. *High initial cost.*
5. *Need maintenance* to retain the quality of reflecting surface against dirt and oxidation.

3.4.4. Parabolic Trough Collector

Fig 3.4. shows the *principle of the parabolic trough collector* which is often used in *focusing collectors*. Solar radiation coming from the particular direction is *collected over*

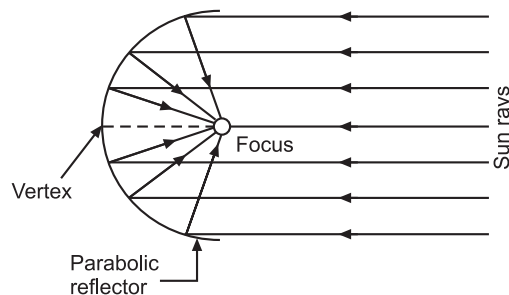


Fig. 3.4. Cross-section of parabolic trough collector.

the area of reflecting surface and is concentrated at the focus of the parabola, if the reflector is in the form of a trough with parabolic cross-section, the solar radiation is focused along a line. Mostly cylindrical parabolic concentrators are used in which absorber is placed along focus axis [Fig. 3.5].

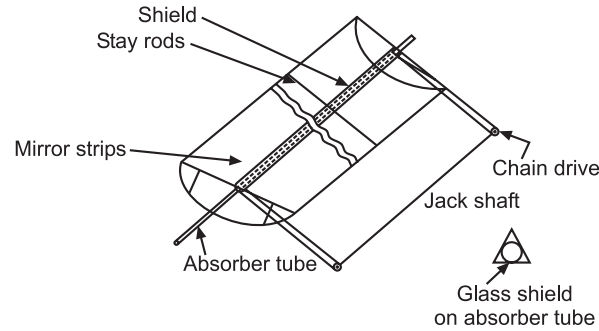


Fig. 3.5. Cylindrical parabolic system.

3.4.5. Mirror Strip Collector

Refer to Fig. 3.6. A mirror strip collector has a number of planes or slightly curved or concave mirror strips which are mounted on a base. These individual mirrors are placed at such angles that the reflected solar radiations fall on the same focal line where the pipe is placed. In this system, *collector pipe is rotated so that the reflected rays on the absorber remain focused with respect to changes in sun's elevation.*

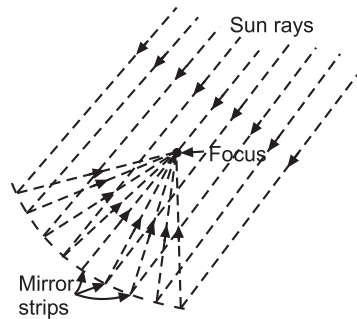


Fig. 3.6. Mirror strip collector.

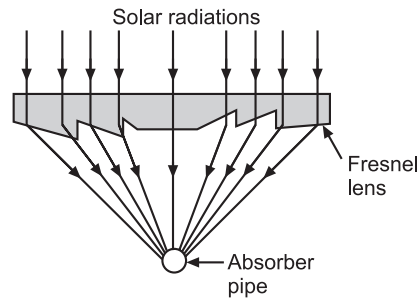


Fig. 3.7. Fresnel lens collector.

3.4.6. Fresnel Lens Collector

In this collector a *Fresnel lens* is used in which *linear grooves are present on one side and flat surface on the other*. The solar radiations which fall normal to the lens are *refracted* by the lens and are focused on the absorber (tube) as shown in Fig. 3.7. Both glass and plastic can be used as refracting materials for Fresnel lenses.

3.4.7. Flat-plate Collector with Adjustable Mirrors

Fig. 3.8. shows a flat-plate collector with adjustable mirrors. It consists of a flat-plate collector facing south, with mirrors attached to its north and south edges. If the mirrors are set at the proper angle, they reflect solar radiation on to the absorber plate. Thus, the latter receives *reflected radiation in addition* to that normally falling on it. In order to make the mirrors *effective*, the *angles should be adjusted continuously* as the sun's altitude changes. Since the mirrors can provide only a relatively small increase in the solar radiation falling on the absorber, flat-plate collectors with mirrors are not widely used.

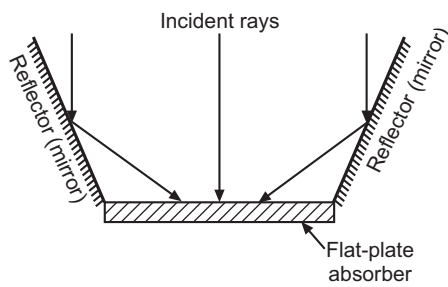


Fig. 3.8. Flat-plate collector absorber with adjustable mirrors.

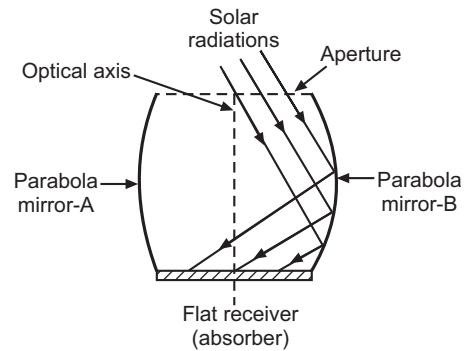


Fig. 3.9. Compound parabolic concentrator (CPC).

3.4.8. Compound Parabolic Concentrator (CPC)

Fig. 3.9 shows the compound parabolic concentrator. It was designed by Winston (and Baranov). It consists of two parabolic segments, oriented such that focus of one is located at the bottom end point of the other and vice versa. The receiver is a flat surface *parallel to the aperture joining of two foci of the reflecting surfaces*.

For thermal and economic reasons the *fin and the tubular type of absorbers are preferable*. It is claimed that Winston collectors are capable of competitive performance at high temperatures of about 300°C required for power generation, if they are *used with selectively coated, vacuum enclosed receivers*.

The maximum concentration ratio available with paraboloidal system is of the order of 10,000.

Advantages:

1. *High concentration ratio.*
2. *No need of tracking.*
3. *Efficiency for accepting diffuse radiation is much larger than conventional concentrators.*

3.4.9. Paraboloidal Dish Collector

Refer to Fig. 3.10. In this type of collector all the radiations from the sun are focussed at a point. This collector can generate temperature up to 300°C and contraction ratio from 10 to few thousands. Its diameter is of the range between 6 to 7 m and can be commercially manufactured.

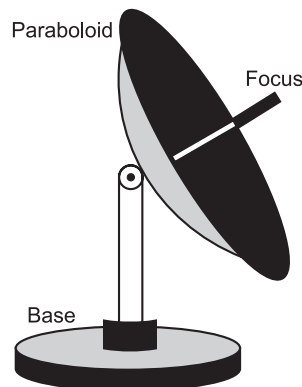


Fig. 3.10. Paraboloidal dish collector.

3.4.10. Comparison between Flat-Plate and Concentrating Collectors

The comparison between flat-plate and concentrating collectors is given below:

S.No.	Aspects	Flat-plate collector	Concentrating collector
1.	Absorber area	Large	Small (comparatively)
2.	Insolation intensity	Less	More
3.	Working fluid temperature	Low temperatures attained	High temperatures attained
4.	Material required by reflecting surfaces	More	Less
5.	Use for power generation	Cannot be used	Can be used
6.	Need of tracking system	No	Yes
7.	Flux received on the absorber	Uniform	Non-uniform
8.	Collection of beam and diffuse solar radiation components	Beam as well as diffuse solar radiation components collected.	Only beam component collected (because diffuse component cannot be reflected and is thus lost).

3.4.11. Performance Analysis of a Concentrating Collector

The useful heat output of a concentrating collector (Q_C) is given by:

$$Q_C = F_R A_{ua} [I_{bc} \eta_{opt} - (U_{oc}/C) (t_{in} - t_a)] \quad \dots(3.14)$$

where, F_R = Heat removal factor of the collector,

A_{ua} = Unshaded aperture area (m^2),

I_{bc} = Intensity of beam solar radiation incident on the concentrator aperture (W/m^2),

η_{opt} = Optical efficiency of the collector,

U_{oc} = Overall/total heat loss coefficient ($W/m^2\text{ }^\circ\text{C}$),

C = Correction factor,

t_{in} = The inlet temperature of the collector ($^\circ\text{C}$), and

t_a = Ambient temperature.

The “**optical efficiency**” of a concentrating collector (η_{opt}) is defined as the ratio of the solar radiation absorbed by the absorber to the beam solar radiation on the concentrator. It is given by:

$$\eta_{opt} = \eta_{opt\ 0^\circ} C_{opt} = \rho \gamma \tau \alpha_a \cdot C_{opt} \quad \dots(3.15)$$

where, $\eta_{opt\ 0^\circ}$ = Optical efficiency of the collector at 0° -incident angle of beam radiation,

C_{opt} = Correction factor for deviation of incidence angle from 0° ;

ρ = Mirror reflectivity,

γ = Intercept factor (It is defined as the ratio of radiation intercepted by absorber to the total radiation),

τ = Transmittivity of transparent cover of the absorber, and

α_a = Absorptivity of the absorber.

∴ The “efficiency” of a concentrating collector (η_c) is given by:

$$\eta_c = \frac{Q_c}{A_a I_{bc}}$$

$$\text{or, } \eta_c = F_R \eta_{opt} - \frac{F_R U_{oc}}{C I_{bc}} (t_{in} - t_a) \quad \dots(3.16)$$

The outlet enthalpy (h_{out}) of heat transfer fluid in a concentrating collector with a phase change (vapourisation) of fluid is given by:

$$h_{out} = h_{in} + \frac{Q_c}{\dot{m}} \text{ (J/kg)} \quad \dots(3.17)$$

where, h_{in} = Inlet enthalpy of heat transfer fluid (J/kg),
 Q_c = Useful heat output of collector (W), and
 \dot{m} = Mass flow rate of heat transfer fluid (kg/s).

3.5. SOLAR-THERMODYNAMIC CONVERSION

3.5.1. Introduction

Since several years, this has been scientists’s endeavour to *convert heat into mechanical energy*, which in turn, may be *used to generate electricity*. Several ambitious solar power systems were constructed during 19th and 20th centuries.

Carnot discovered the following formula for the theoretical maximum efficiency for *converting heat energy into mechanical energy*:

$$\text{Carnot efficiency, } \eta_{\text{carnot}} = \frac{T_h - T_c}{T_h} \quad \dots(3.18)$$

where, T_h = Absolute temperature of the *heat source*, and
 T_c = Absolute temperature of the *heat sink*.

In practice, however, it is *not possible* even with a good design to obtain an efficiency *nearly as high as the theoretical one*. In most cases, the true thermal efficiency for converting heat to work will be 30 to 60 per cent of η_{carnot} . Whereas thermodynamics dictate that to achieve maximum conversion efficiency, the difference in operating temperature should be *as large as possible* (Fig. 3.11), the *efficiency of a solar collector decreases with increasing temperature*.

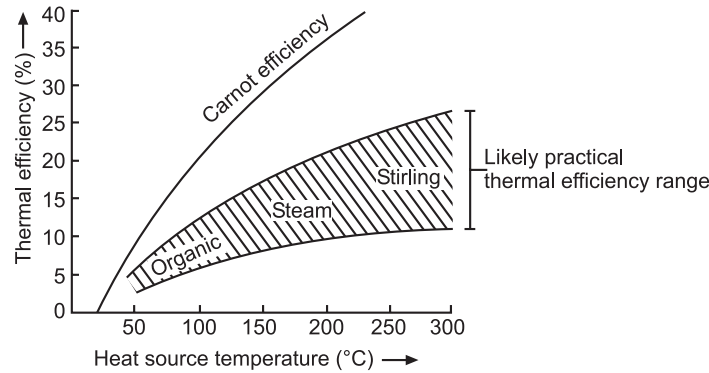


Fig. 3.11. Comparison of theoretical efficiency with those obtained in practice at a sink temperature of 25°C (Halcrow/ITDG 1981 b)

- The type of solar collector required is governed by the choice of heat engine. The “medium temperature steam engines and high-temperature engines” need linear focusing, parabolic dish or heliostat devices that concentrate the sun’s direct beam.
- In case of “gas-cycle engines” which demand high temperature, the solar collector should be parabolic dish or heliostat (power tower) devices.

Practically, so far, only the Rankine and Stirling cycles have been used for small scale applications.

3.5.2. Rankine-cycle Engines

The Rankine and similar vapour-cycle engines can be of two types: (i) Low-temperature ORC engines that use organic fluids with low boiling points; (ii) Medium-temperature vapour cycles, which generally use water as the working fluid. “Rankine cycle engines” are the most well-developed of the heat engines used in solar-thermodynamic systems.

- The components of this engine can be powered by flat-plate collectors for tasks such as operating a “water pump”. The working fluid is evaporated by solar heat in a boiler before passing to the expander, from which mechanical work is extracted.

- Following “working fluids” are suitable for operations at “lower temperatures”:

Water, Freons (F-11 widely used); Ammonia, Ethylene; Ethane, Propylene; Sulphur dioxide:

3.5.3. High-temperature Gas-Cycle Engines

High-temperature engines (including using the Brayton, Stirling and Ericsson cycles) have high Carnot efficiencies and their technology is being developed mostly for large scale-systems in the range of 7kW to 10 MW. Rankine-cycle steam turbines which were developed for conventional power stations, have been adopted for high-temperature solar applications. However, ORC engines are now frequently used, with toluene as the working fluid.

HIGHLIGHTS

1. The factors which adversely affect the collector’s efficiency are; Shadow, Cosine loss, Dust etc.
2. Solar collectors are mainly of two types:
 - (i) Non-concentrating or flat-plate solar collector, (ii) Concentrating or focusing type solar collector.
3. The performance of a flat-plate collector is described by an energy balance that indicates the distribution of incident solar energy into useful energy gain and various losses.

Useful heat output of a flat-plate collector is given by:

$$Q_c = A_{cs}[I_{cs} F_R (\tau\alpha)_e - F_R U_{oc} (t_f - t_a)] \text{ watts}$$

where, Q_c = Useful heat output (W),

A_{cs} = Collector surface area (m^2),

I_{cs} = Intensity of solar radiation incident on the collector surface (W/m^2),

τ = Transmission coefficient,

α = Absorption coefficient,

$(\tau\alpha)_e$ = Effective product of transmissivity of the transparent cover and absorptivity of the absorber,

U_{oc} = Overall heat loss coefficient of the collector ($W/m^2\text{°C}$),

t_{fi} = Collector fluid inlet temperature ($^{\circ}\text{C}$),

t_a = Ambient air temperature ($^{\circ}\text{C}$), and

F_R = Heat removal factor.

Stagnation temperature (t_s) of the collector is given by:

$$t_s = t_{in} = t_a + I_{cs} \cdot \frac{F_R(\tau\alpha)_e}{F_R U_{oc}}$$

4. *Concentrating collector* is a device to collect solar energy with high intensity of solar radiation on the absorbing surface by the help of reflector or refractor.
5. The useful heat output of a concentrating collector (Q_c) is given by:

$$Q_c = F_R A_{ua} [I_{bc} \eta_{opt} - (U_{oc}/C) (t_{in} - t_a)]$$

where, F_R = Heat removal factor,

A_{ua} = Unshaded aperture area (m^2),

I_{bc} = Intensity of beam solar radiation incident on the concentrator aperture (W/m^2),

η_{opt} = Optical efficiency of the collector,

U_{oc} = Overall/total heat loss coefficient ($W/m^2\text{°C}$),

C = correction factor,

t_{in} = The inlet temperature of the collector ($^{\circ}\text{C}$), and

t_a = Ambient temperature.

Efficiency of a concentrating collector (η_c) is given by:

$$\eta_c = F_R \eta_{opt} - \frac{F_R U_{oc}}{C I_{bc}} (t_{in} - t_a)$$

Here, $\eta_{opt} = \eta_{opt 0^\circ} C_{opt} \rho \gamma \tau \alpha_a C_{opt}$.

where, $\eta_{opt 0^\circ}$ = Optical efficiency of the collector at 0° incident angle of beam radiation, C_{opt} = Correction factor for derivation of incidence angle from 0° , ρ = Mirror reflectivity, γ = Intercept factor, τ = Transmissivity of transparent cover of the absorber, and α_a = Absorptivity of the absorber.

THEORETICAL QUESTIONS

1. List the advantages, disadvantages and applications of solar thermal energy.
2. What is Green-house effect? Explain briefly.
3. What are the characteristic features of a collector system?
4. Explain briefly the factors which adversely affect the efficiency of a collector system.
5. How are solar collectors classified?
6. Give brief description of a flat-plate collector.
7. Discuss briefly selective coatings/surfaces.
8. State the advantages, disadvantages and applications of flat-plate collectors.
9. Explain briefly "Evacuated collectors"
10. What do you mean by performance of a flat-plate collector? Explain briefly.
11. Explain briefly the factors which affect the performance of a flat-plate collector.
12. What is a concentrating collector?

13. Why is there a need of orientation in concentrating collectors?
14. Explain briefly, with neat sketches, any two of the following concentrating collectors:
 - (i) Parabolic trough collector
 - (ii) Fresnel lens collector
 - (iii) Flat-plate collector with adjustable mirrors
 - (iv) Paraboloidal dish collector.
15. Give the comparison between flat-plate collectors and concentrating collectors.

UNSOLVED EXAMPLES

1. An evacuated tube collector is working under the following conditions:
 The intensity of solar radiation on the collector surface = 760 W/m^2 ; the collector fluid inlet temperature = 43°C ; the ambient air temperature = 26°C ; effective optical efficiency $F_R(\tau\alpha)_e = 0.77$; effective heat loss coefficient = $F_R U_C = 1.65 \text{ W/m}^2\text{C}$; mass flow rate of water = 0.017 kg/s/m^2 ; specific heat of water at constant pressure, $c_p = 4187 \text{ J/kg}^\circ\text{C}$.
 Calculate the Following:
 - (i) Useful heat output.
 - (ii) Outlet temperature of water.
 - (iii) Stagnation temperature.

[Ans. (i) 557.15 W/m^2 (ii) 50.83°C (iii) 380.66°C]
2. Following data relate to a flat-plate collector used for heating the building:
 Location and latitude = Baroda, 22°N ; day and time = January 1, 11:30 to 12:30 (IST); annual average intensity of solar radiation = $350 \text{ W/m}^2 \text{ hr}$; collector tilt = latitude + 15° ; No. of glass covers = 2; heat removal factor for collector = 0.81; transmittance of the glass = 0.88; absorption of the glass = 0.90; top loss coefficient for collector = $7.88 \text{ W/m}^2\text{C}$; collector fluid temperature = 60°C ; ambient temperature = 15°C .
 Calculate:
 - (i) Solar altitude angle.
 - (ii) Incident angle.
 - (iii) Collector efficiency.

[Ans. (i) 44.7° ; (ii) 45.3° ; (iii) 6%]
3. The following data relate to a flat-plate collector used for heating:
 Location and latitude = Coimbatore, $11^\circ 00' \text{ N}$; day and time = March 22, 2.30 – 3.30 (LST); average intensity of solar radiation = 560 W/m^2 ; collector tilt = 26° ; number of glass covers = 2; heat removal factor for collector = 0.82; transmittance of glass = 0.88; absorptance of the plate = 0.93; top loss coefficient for collector = $7.95 \text{ W/m}^2\text{C}$; collector fluid inlet temperature = 75°C ; ambient temperature = 25°C .
 Calculate:
 - (i) Solar latitude angle.
 - (ii) Incident angle.
 - (iii) Collector efficiency.

[Ans. (i) 43.9° ; (ii) 46.1° ; (iii) 8.87%]

Rankine cycle heat engine. Hot water from the bottom level of the pond is pumped to the evaporator where the *organic working fluid is vapourized*. The vapour then flows under high pressure to the *turbine* where it expands and work thus obtained *runs an electric generator producing electricity*. The exhaust vapour is then *condensed* in a condenser and the *liquid is pumped back to the evaporator* and the cycle is repeated.

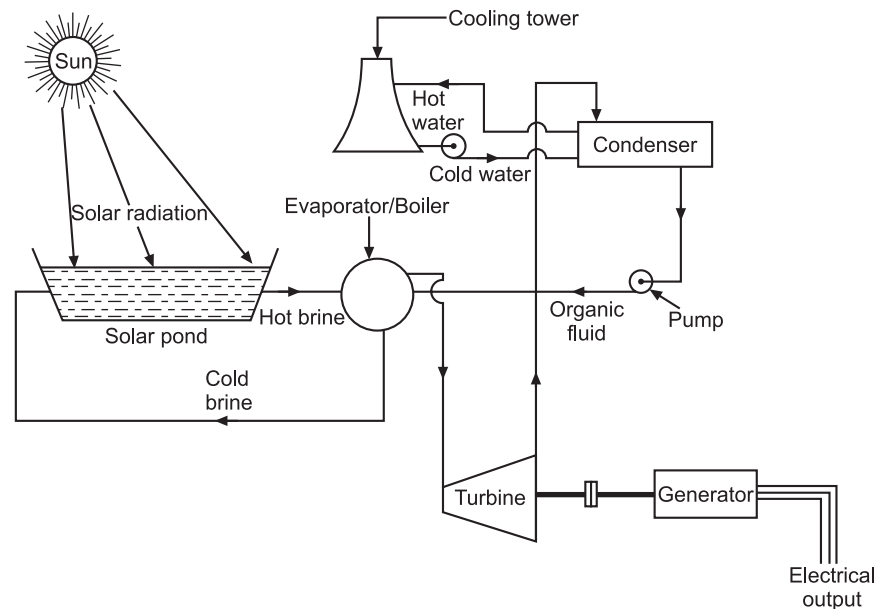


Fig. 4.4. Solar pond electric power plant.

B. SOLAR ENERGY APPLICATIONS

4.10. INTRODUCTION TO SOLAR ENERGY APPLICATIONS

The solar energy applications may be considered under the following *three* general categories:

1. *Direct thermal applications*
2. *Solar electric applications*
 - Solar thermal electric conversion
 - Photovoltaic conversion
 - Thermoelectric conversion
 - Ocean thermal energy conversion
3. *Biomass energy applications.*

Based on the above classification, some of the commonly used direct solar energy applications are enumerated and discussed henceforth:

1. Solar water heating.
2. Solar heating and cooling.
3. Solar distillation.
4. Solar pumping.

5. Solar drying.
6. Solar cooking.
7. Solar Green-house.
8. Solar power plant.
9. Solar photovoltaic system.

4.11. SOLAR WATER HEATING

Solar water heating is one of the most common applications of solar energy.

4.11.1. Natural Circulation Solar Water Heater

A natural circulation solar water is usually used in most “domestic systems”.

A simple solar water heater with natural circulation is shown in Fig. 4.5.

Construction. It consists of a *flat-plate solar collector*, normally single glazed, and insulated *storage tank* kept at a height. It is installed on a roof with the collector facing the sun and connected to cold water mains. The collector comprises *copper tubes welded to a copper sheet* (both coated with a highly absorbing *black coating*) with a *toughened glass sheet* on top and insulating material on the rear.

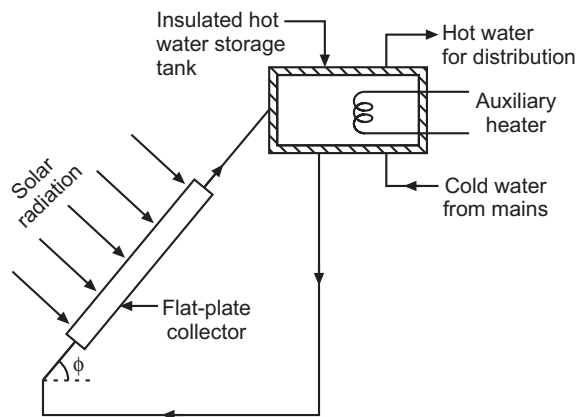


Fig. 4.5. Natural circulation solar water heater.

Working. The collector collects the sun radiation due to which water flowing through the tubes absorbs solar heat and is stored in a tank. The water circulation is entirely based on the density difference between the solar-heated water in the collector and the cold water in the storage tank. Hot water for use is taken out from the top of the tank.

To provide heat during long, cloudy periods, an *electrical immersion heater* (i.e. ‘auxiliary heater’) can be used as a back-up for the solar system. A non-freezing fluid may be used in the collector circuit.

- Most domestic systems are of capacity ranging from 100 to 150 litres of hot water per day.

4.11.2. Forced-Circulation Solar Water Heater

Solar water heaters of this type which are suited to supply large quantity of hot water, are suitable for *industries, hospitals, hostels and offices*. Fig. 4.6. shows a forced-circulation solar water heater with a *pump*. Water is pumped through flat-plate solar collector(s) where it is heated and flows back into the storage tank. Whenever hot water is withdrawn for use, cold water takes its place. When the difference in water temperature at the collector(s) outlet and that at the storage tank exceeds 7°C, the pump motor is activated by a differential thermostate. A non-return/check valve is needed to prevent reverse circulation and resultant night time thermal losses from the collector.

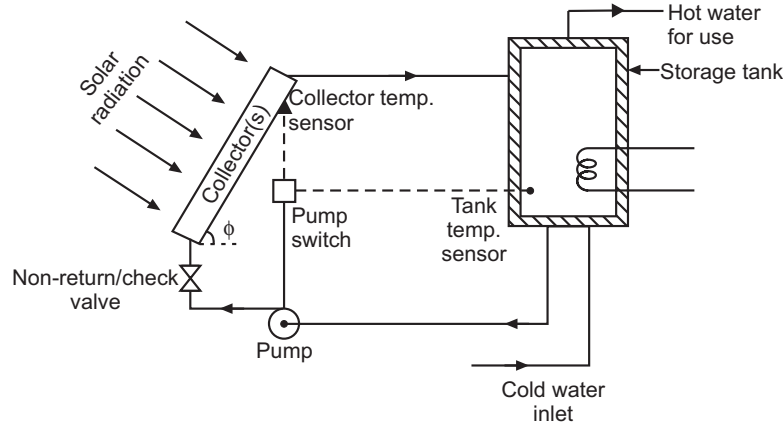


Fig. 4.6. Forced-circulation water heater.

4.12. SPACE HEATING (or Solar Heating of Buildings)

All solar heating systems may be divided into the following *two* categories:

1. **Active systems.** These systems generally consist of the following *components*:
 - (i) *Separate solar collectors*, which may heat either *water* or *air*,
 - (ii) *Storage devices* which can accumulate the collected energy for use at nights and during *inclement days*, and
 - (iii) A *back-up system* to provide heat for protracted periods of bad weather.
2. **Passive systems.** In such systems solar radiation is collected by some element of structure itself, or admitted directly into building through large, south facing windows.

Fig. 4.7. shows a **basic space heating system**.

The *collector array* collect the solar radiation and heat up the water. This heated water is stored in the *tank* and the energy is transferred to the air circulating in the building *by water to air heat exchanger*. Two *pumps* are provided for *forced circulation* between the collectors and the tank, and between the tank and heat exchanger.

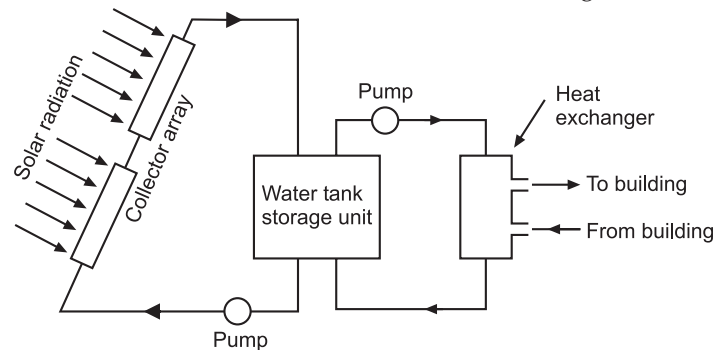


Fig. 4.7. Basic space heating system.

Limitations of uses of solar water heating system:

1. The energy received from the sun in cloudy days is almost nil and so the output of solar collector(s) will be almost zero and hence the system cannot provide the necessary service required.

2. For the functioning of the system, it is necessary to have continuous cold water supply at a height of around 2.5 m.
3. The insulation of the tank must be good, to ensure availability of 'heated water during the day' for use during night and next morning.
4. Owing to the deposit of *hard water scale* in the collector, the efficiency of the system is likely to *reduce*.
5. Sometimes hot water supply may *stop* due to *vapour locking* in pipeline.

4.13. SPACE COOLING (or Solar Cooling of Buildings)

4.13.1. Introduction

Solar energy can be used in *airconditioning* and *refrigeration*. The principles of the following two cycles are used for refrigeration using solar energy.

1. Absorption cycle
2. Vapour compression cycle

1. Absorption cycle:

In this cycle, two working fluids are used:

- (i) A *refrigerant*, and
- (ii) *Absorbent-refrigerant solution*.

The **absorbent cooling** is based on the principle that the refrigerant can be bound by a liquid or solid solvent, known as **absorbent** to release heat during operation, while it absorbs heat during evaporation, thus producing a "cooling effect."

Common refrigerant-absorbent combinations are:

- (i) Lithium bromide (Li) – Water (LiBr–H₂O).
- (ii) Ammonia-water (NH₃–H₂O).
 - "*LiBr–H₂O system*" is simple and requires lower generator temperature of the order of 85°C to 95°C which are *achievable* by a flat-plate collector. Also it possesses *higher C.O.P.* than the NH₃–H₂O system
 - Absorption cooling with solar energy, which is regarded as *more practical*, is possible with current technology although *improvement in design would be desirable*.

2. Vapour compression cycle:

In this cycle, shaft power produced by *solar power conversion* into mechanical power by "*heat pump*" is used to drive *compressor* of refrigerator. Compressed vapour is then "*condensed*" to a liquid rejecting it through an "*expansion valve*" where it gets "*evaporated*" at *low pressure*, producing a *cooling effect*.

Liquid refrigerants are: LiBr–H₂O; NH₃–H₂O; NH₃–LiNO₃ etc.

Solid absorbents are: CaCl₂–NH₃; Silica gel–H₂O; Zeolite–H₂O etc.

4.13.2. Vapour Absorption Cooling System

Refer to Fig. 4.8. A vapour absorption cooling system consists of the following components:

- (i) *Generator (or Heat Exchanger)*; (ii) *Condenser*; (iii) *Evaporator*; (iv) *Absorber*.

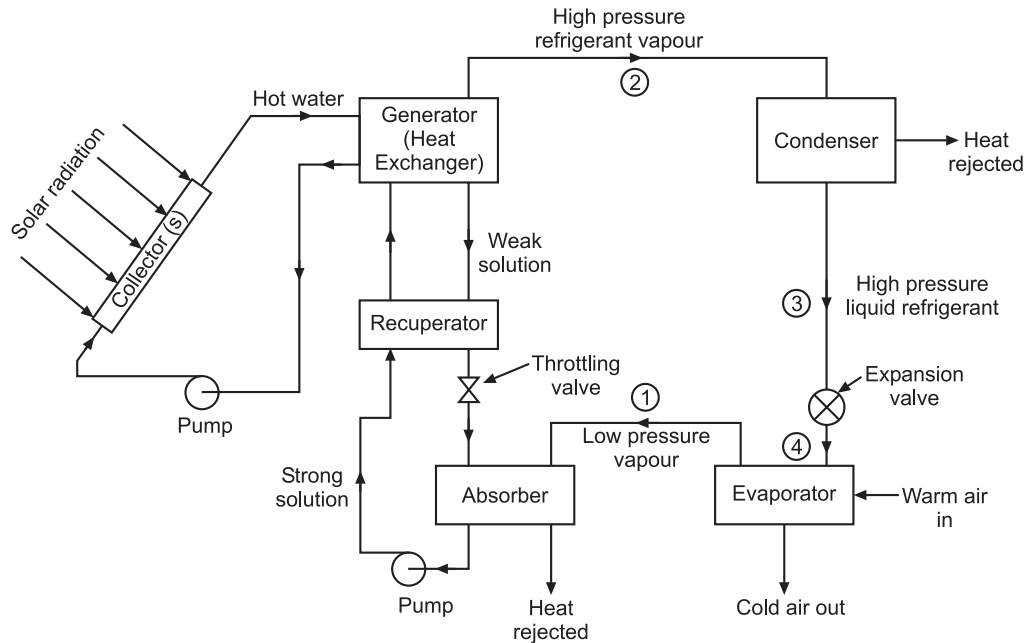


Fig. 4.8. Vapour absorption cooling system.

Working of the system:

- The low pressure refrigerant vapour leaving the **evaporator** at '1' is readily absorbed in the low temperature hot solution in the **absorber**, releasing the latent heat of condensation. The temperature of the solution tends to rise, while the absorber is cooled by the circulating water, absorbing the heat of solution, and maintaining a constant temperature.
- *Strong solution*, rich in refrigerant, is pumped (pump increases the pressure of the solution) to the **generator** where heat is supplied by the collector array. The high pressure refrigerant vapour is given off, and the weak solution returns to the **absorber** through throttling (or pressure reducing) valve.
- The high pressure refrigerant vapour from the generator at '2' is condensed in the **condenser** to a high pressure liquid at '3' refrigerant.
- The liquid refrigerant is throttled by the **expansion valve** at '4', and then evaporates, absorbing the heat of evaporation from the warm air or surroundings.

Advantages:

This system claims the following *advantages over vapour compression cycle*:

1. *No moving part in the system except the pump-motor.*
2. *Quiet in operation, very little wear, and low maintenance cost.*
3. *More compact and less bulky.*
4. The space requirements and automatic control requirements favour the absorption system more and more as the desired evaporator temperature drops.

4.14. SOLAR DISTILLATION (SOLAR STILL)

Solar still is a device which is used to convert saline water into pure water by using solar energy.

Soft drinking water, an essential requirement for supporting life, is *scarce* in arid, semi-arid and coastal areas. Saline water, at such places, is available in underground or in the ocean. This water can be *distilled utilising abundant solar radiation available in that area*, by solar still(s).

The simplest 'solar still', generally known as, 'basin type solar still' is shown in Fig. 4.9.

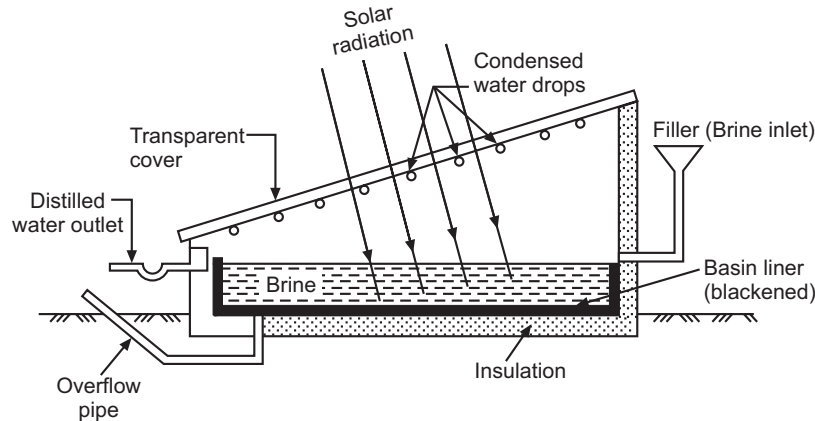


Fig. 4.9. Basin type solar still.

Construction. It is a shallow basin having blackened surface called *basin liner*. The filler supplies the saline water to the basin and an *overflow pipe* allows the excess water to flow out from the basin. The top of the basin is covered with a sloping airtight *transparent cover* that encloses the space above the basin. This cover is made of glass or plastic and slope is provided towards a collection trough.

Working. Solar radiation passes through the transparent cover and is absorbed and converted into heat by the black surface of the still. The saline water is then heated and the water vapours condense over the cool interior surface of the transparent cover. The condensate flows down the sloping roof and gets collected in troughs installed at the outer frame of the solar still. The distilled water is then transferred into a storage tank.

"Desalination output" *increases* with the *rise* in ambient temperature and is independent of the salt content in raw feed water.

The "solar still performance" is expressed as the *quantity of water produced by each unit of basin area per day*.

Solar still installations may provide about 15 to 50 litres/day/10 m².

Advantages of distilling process:

1. *Low* energy consumption.
2. *Less* skilled labour required.
3. *Simple* technique required.
4. *Low* maintenance cost.

4.15. SOLAR PUMPING

Solar pumping *utilises the power generated by solar energy for water pumping, useful for irrigation*. Water pumps can be driven directly by solar heated water or fluid which operates either a heat engine or turbine. For *low heads*, a flat-plate collector is used to heat a low-boiling point liquid, the vapour of which drives the pump. For *larger heads*,

a *parabolic trough concentrator* or *parabolic bowl concentrator* is installed to drive a steam turbine, which in turn drives the pump.

Fig. 4.10 shows a typical *solar-powered water pumping system*.

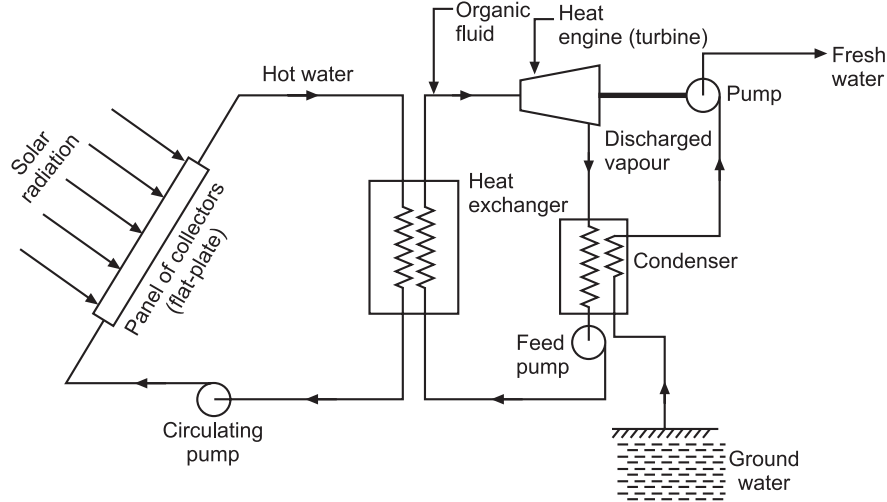


Fig. 4.10. Solar-powered water pumping system.

Working:

The panel of solar flat-plate 'collectors', on receiving solar radiation, heat water or an organic fluid (*R-115* is an acceptable working fluid as it has *low cost* and *high cycle efficiency*).

- The hot fluid then flows to a mixing/storage tank and then to a *heat exchanger* to convert the working fluid of the heat engine from liquid to vapour.
- Water or hot transport fluid is fed again into the collector circuit by a '*circulating pump*'
- The discharged vapour, from the turbine, flows into '*condenser*' where the vapour gets condensed. The working fluid is then fed into the heat exchanger by a '*feed pump*' to complete the cycle. The water, which is pumped, is used as a coolant in condenser of the turbine.
- A *high engine efficiency* is achieved if the temperature in heat exchanger or boiler is high.

4.16. SOLAR AIR HEATERS AND DRYING

4.16.1. Solar Air Heaters

A **conventional solar air heater** is essentially a *flat-plate collector* with an '*absorber plate*', a '*transparent cover system*' at the top and '*insulation*' at the bottom and on the sides. The whole assembly is encased in a sheet metal container. The working fluid is "*air*", though the passage for its flow varies according to the type of air heater.

The '*materials*' used for construction of air heaters are similar to those of liquid flat-plate collectors. '*Selective coating*' on the absorber plate can be used to improve the collection efficiency but cost effectiveness criterion should be kept in mind.

Figs. 4.11 [(i) to (iv)] shows the *basic features of non-porous absorber type air heaters*.

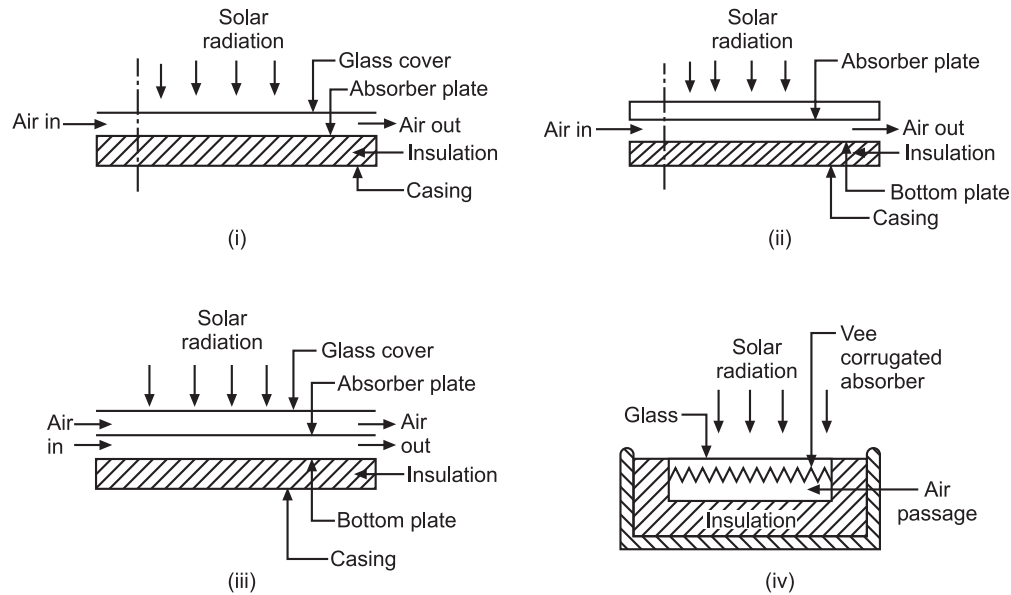


Fig. 4.11. Basic features of non-porous absorber type air heaters.

Advantages:

The solar air heaters claim the following *advantages* over other solar heat collectors:

1. The system is compact and less complicated.
2. The *pressure* inside the collector *does not become very high*.
3. Leakage of air from the duct does not pose any major problem.
4. Corrosion is completely eliminated.
5. Freezing of working fluid does not exist.

Disadvantages:

1. Poor heat transfer properties.
2. Need for handling large volumes of air.
3. The thermal capacity of air being low, it cannot be used as a storage fluid.
4. In the absence of proper design, the cost of air heater can be very high.

Important areas of applications:

The important areas of applications of non-porous absorber type air heaters are:

1. Heating and cooling buildings (such heaters are used only in *actively* heated or cooled buildings).
2. Air heaters are also used as desiccant beds for solar air-conditioning.
3. Heating of green-house.
4. Industrial processes such as drying agricultural crops and timber.

4.16.2. Solar Drying

Drying has been the oldest and most widely used application of solar energy in the developing countries. The methods have been based on open air drying.

Fig. 4.12. shows the schematic diagram of an *indirect crop dryer* (Headly and Springer design).

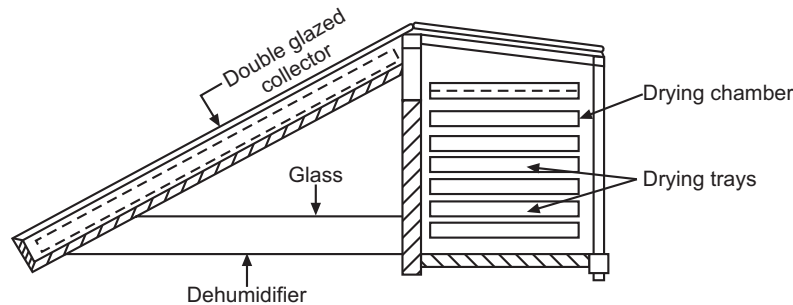


Fig. 4.12. Indirect crop dryer

In this type of dryer, ambient air is heated and is passed into drying chamber by *natural convection*. The hot air removes moisture from the crops, becomes cooler and falls to the bottom of drying chamber. By this system, yam, sweet potato, sorrel and grasses can be dried.

- For large scale drying, i.e. seasoning of timber, corn drying, tea processing, tobacco curing, fish and fruit drying, **solar kins** are used.

Advantages and disadvantages of solar drying:

Advantages:

1. Dried products improve family nutrition (Dried fruit and vegetables contain high quantities of *vitamins, minerals* and *fibre*).
2. Dried fruit can be used in stews, soups, making ice-cream and baked products.
3. Improves the bargaining position of farmers.

Disadvantages:

1. The dried product is often of poor quality as a result of grit and dirt.
2. The product is often unhygienic as a result of microorganism and insects.

4.17. SOLAR COOKING

In India, **cooking** is the common application of solar energy. Several varieties of solar cookers are available to suit different requirements.

Following types of cookers will be briefly discussed:

1. Box-type solar cooker.
2. Dish solar cooker.
3. Community solar cooker for indoor cooking.

4.17.1. Box-type Solar cooker

Fig. 4.13 shows a box-type solar cooker.

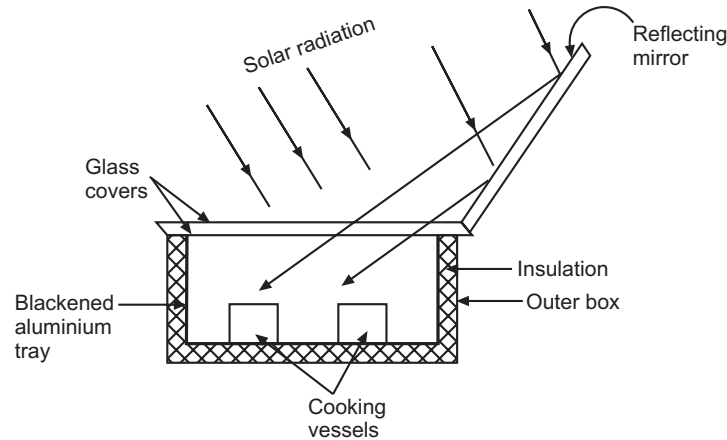


Fig. 4.13. Box-type solar cooker.

It consists of an 'outer box' made of either fibre glass or aluminium sheet, a 'blackened aluminium tray', a 'double glass lid', a 'reflector', 'insulation' and 'cooking pots'. The blackened aluminium tray is fixed inside the box, and the sides are covered with an insulation cover to prevent heat loss. The reflecting mirror provided on the box cover increases the solar energy input. Metal pots are painted black on the outside.

Food to be cooked is placed in cooking pots and cooker is kept facing the sun to cook the food. An electric heater may also be installed to serve as a back during non-shine hours.

Technical drawbacks of the design:

The Government of India is trying to introduce box-type solar cookers with financial subsidies but with poor success due to the following technical drawbacks of the design of the box-type solar cooker:

1. The temperature obtained is less than 100°C and is insufficient for chapati making and frying which are very important cooking processes.
2. There is no provision for storage of heat and cooking gas to be carried out while the sun is shining, which is an odd time for preparing breakfast and dinner.
3. Cooking has to be carried out in open without privacy and in the sun which is very inconvenient to housewife.

4.17.2. Dish Solar Cooker

In this type of cooker, a 'parabolic dish' is used to concentrate the incident solar radiation. A typical dish solar cooker has an aperture of diameter 1.4 m with focal length of 0.8 m. The 'reflecting material' is an anodized aluminium sheet having reflectivity of over 80%.

The cooker needs to track the sun (which requires power of about 0.6 kW). The temperature at the bottom of the vessel may reach up to 400°C which is sufficient for boiling, roasting and frying.

Such a cooker can meet the requirements of cooking for fifteen persons.

4.17.3. Community Solar Cooker for Indoor Cooking

A community solar cooker is a 'parabolic reflector cooker'. It has a 'large reflector' ranging from 7 to 12 m² of aperture area. The reflector is placed outside the kitchen so as to reflect

solar rays into the kitchen. A 'secondary reflector' further concentrates the rays on to the bottom of the cooking pot painted black. Temperature can reach up to 400°C and food can be cooked quickly for *fifty* persons.

4.18. SOLAR FURNACE

A **solar furnace** is an optical equipment to get high temperatures by concentrating solar radiations on to a specimen.

The "primary components" of a solar furnace are:

1. **Concentrator.** In solar furnaces, either a paraboloidal reflection concentrator or a spherical reflector concentrator is used; the *former* is considered *superior* due to acceptable spherical aberration in a spherical reflector.
2. **Heliostat.** In a solar furnace, the function of heliostats is to *orient* solar radiation *parallel* to the optical axis of the concentrator. As a guide, the size of the heliostat should be $1.4 D \times 1.4 D$ where D represents the size of aperture of concentrator.
3. **Sun tracking.** For a solar furnace to function with optimum output, it is imperative that heliostats should follow the sun from morning till evening.

In a solar furnace the temperatures may reach up to 3500°C.

Solar furnace with multiple heliostat:

The world's first 1000 kW solar furnace was operated at Odeillo, France, in 1973. Solar intensity was 1 kW/m^2 , with bright sunshine for about 1200 hours a year. It consisted of 63 heliostats installed at 8 elevations which reflected sun rays to the concentrator parallel to its optical axis as shown in Fig. 4.14. The *receiver* diameter was changed to obtain different temperatures.

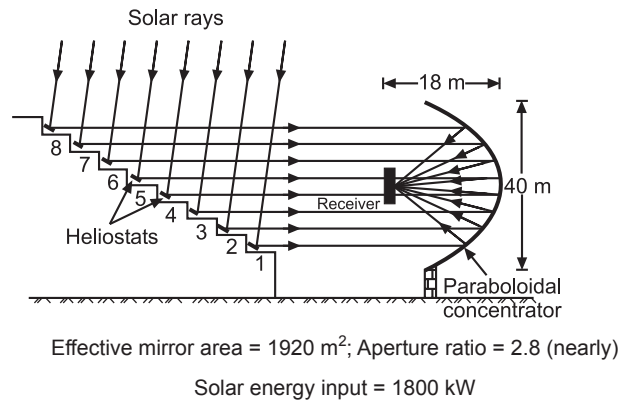


Fig. 4.14. 1000 kW solar furnace with heliostats.

Advantages and Uses of a Solar Furnace:

Advantages:

1. Simple working.
2. High heat flux is obtainable.
3. Heating without contamination.
4. Easy control of temperature.

Uses:

1. For phase and vaporisation studies.

2. Melting behaviour analysis.
3. Purification of ceramic and refractory materials.

4.19. SOLAR GREEN-HOUSES AND GLOBAL WARMING

4.19.1. Solar Green-houses

A **green-house** is an enclosed space which provides the required environment for growth and production of plants under adverse climatic conditions. Its design depends upon the local climatic conditions and the environment needed for the growth.

Plants manufacture their food by 'photosynthesis process' which maintains a balance with respiration.

The various parameters for a plant growth are:

1. **Light intensity.** For plant growth a minimum intensity of 25,000 lux is adequate. A green-house structure, with two glaziings can have maximum light intensity up to 50,000 lux on a clear day.
2. **Temperature.** Temperature is an important environmental factor for plant growth. For *winter crops*, the ideal temperature range is from 5° C to 15° C with a variation up to 3° C. For *summer crops*, the range is from 20° C to 30° C with a variation of 5° C.

The soil temperature of 20° C to 25° C, for most plants, has been reported to be optimum.

3. **Humidity.** For plant growth, relative humidity (RH) of air between 30 and 70% is good. Saplings and germinating seeds need high humidity 100% but its value (RH) *reduces* after they have grown.
4. **Air movement.** It influences transpiration, evaporation of water from soil, availability of CO₂ etc. The movement of air at a speed of 0.8 to 2 cm/s is adequate for optimum growth of the plant.

Fig. 4.15 shows a schematic diagram of a pipe-framed green-house.

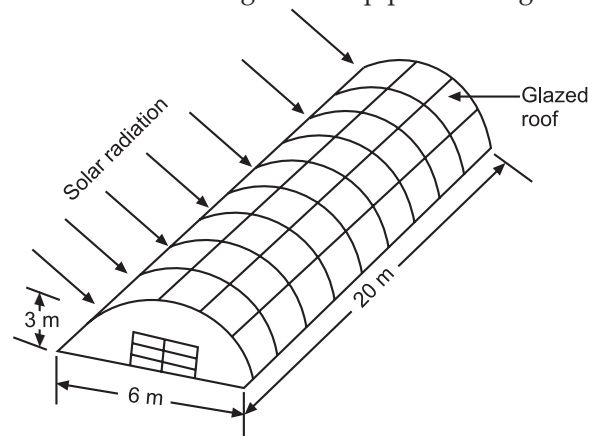


Fig. 4.15. Schematic diagram of pipe-framed greenhouse

Advantage of green-houses:

This type of structure is less expensive to build than a fully insulated structure. It provides the following *advantages* :

1. Inexpensive, good quality food can be grown.

2. An additional heat source (temperature control) is available for the house attached to it.
3. A source of moderator for the humidity (humidity control) in the house.

4.19.2. Global Warming

Global warming is the term which indicates the increase in the average temperature of the atmosphere. The increased volume of CO₂ and other green-house gases released by the burning of fossil fuels and other human activities contribute to the warming of the earth. The amount of heat trapped in the atmosphere depends mostly on the concentrations of green-house gases.

The major green-house gases are: Carbon dioxide, ozone, methane, chlorofluorocarbons (CFCs) and water vapours. Due to anthropogenic activities, there is an increase in the concentration of the green-house gases in the air, which results in the increase in average surface temperature.

Deterimental effects:

1. If the emission of green-house gases continues, the global temperature will increase.
2. With the increase in global temperature sea water will expand, which will result in rise in sea level. Heating will melt the polar ice caps resulting in further rise in sea level.
3. Results in floods.
4. Global warming will lead to changes in the rainfall pattern.

Control measures:

1. Use of renewable energy sources.
2. Afforestation.
3. Stabilization of population growth.
4. To cut down the current rate of use of CFCs and fossil fuels.

4.20. SOLAR POWER PLANTS

The solar thermal power generation involves the collection of solar heat which is utilised to increase the temperature of a fluid in a turbine operating on a cycle such as Rankine or Brayton. In another method, hot fluid is allowed to pass through a heat exchanger to evaporate a working fluid that operates a turbine coupled with a generator. These may be *classified* as : Low temperature, medium temperature and high temperature systems.

4.20.1. Low Temperature Solar Power Plant

Fig. 4.16. shows a schematic diagram of a *low temperature solar power plant*

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

4.21. SOLAR PHOTOVOLTAIC (SPV) SYSTEMS

4.21.1. Semiconductors

“Semiconductors” are solid materials, either non-metallic elements or compounds, which allow electrons to pass through them so that they conduct electricity in much the same way as a metal.

4.21.1.1 Characteristics of Semiconductors

Semiconductors possess the following *characteristics*:

1. The resistivity is usually high.
2. The temperature coefficient of resistance is *always negative*.
3. The contact between semiconductor and a metal forms a layer which has a higher resistance in one direction than the other.
4. When some suitable metallic impurity (e.g., Arsenic, Gallium etc.) is added to a semiconductor, its *conducting properties change appreciably*.
5. They exhibit a rise in conductivity in the increasing temperature, with the decreasing temperatures their conductivity falls off, and at low temperatures semiconductors become dielectrics.
6. They are usually metallic in appearance but (unlike metals) are generally hard and brittle.

Both the resistivity and the contact effect are as a rule very sensitive to small changes in physical conditions, and the *great importance* of semiconductors for a wide range of uses apart from rectification depend on the *sensitiveness*.

Examples of semiconducting materials:

Of all the elements in the periodic table, *eleven are semiconductors* which are listed below:

S. No.	Element	Symbol	Group in the periodic table	Atomic No.
1.	Boron	B	III	15
2.	Carbon	C	IV	6
3.	Silicon	Si	IV	14
4.	Germanium	Ge	IV	32
5.	Phosphorus	P	V	15
6.	Arsenic	As	V	33
7.	Antimony	Sb	V	51
8.	Sulphur	S	VI	
9.	Seleinius	Se	VI	
10.	Tellurium	Te	VI	
11.	Iodine	I	VIII	

Examples of “semiconducting compounds” are given below:

- (i) Alloys : Mg_3Sb_2 , ZnSb , Mg_2Sn , CdSb , AlSb , InSb , GeSb .
- (ii) Oxide : ZnO , Fe_3O_4 , Fe_2O_3 , Cu_2O , CuO , BaO , CaO , NiO , Al_2O_3 , TiO_2 , UO_2 , Cr_2O_3 , WO_2 , MoO_3 .

(iii) Sulphides: Cu_2S , Ag_2S , PbS , ZnS , CdS , HgS , MoS_2 .

(iv) Halides: AgI , CuI .

(v) Selenides and Tellurides.

PbS is used in photo-conductive devices, BaO in oxide coated cathodes, caesium antimonide in photomultipliers etc.

4.21.1.2 Differences between Semiconductors and Conductors

Semiconductors	Conductors
1. Their resistivity is usually high and temperature coefficient of resistance is always negative.	1. The resistivity is very low and the temperature coefficient of resistance is <i>not constant</i> .
2. Both resistivity and contact effects are very sensitive to small changes in physical conditions.	2. Both resistivity and contact effects are very sensitive to small changes in physical conditions.
3. These are materials having filled energy bands and small forbidden zones.	3. These are materials with unfilled or overlapping energy bands.
4. Moving carriers of electric current are originated due to absorption of thermal, radiant or electric energy from an external source.	4. Current carriers here are free electrons which exist whether external energy is applied or not.
5. At low temperatures, they become <i>dielectrics</i> .	5. At very low temperatures, i.e., at absolute zero temperatures they become <i>superconductors</i> .
6. They show a rise in conductivity with increase in temperature due to increase in current carriers and <i>vice versa</i> .	6. Their conductivity increases with decreasing temperature up to near absolute zero stage.

4.21.1.3 Differences between Semiconductors and Insulators

Semiconductors	Insulators
1. These are the materials whose valence electrons are bound <i>somewhat loosely</i> to their atom.	1. These are materials in which valence electrons used are bound <i>very tightly</i> to their parent atoms.
2. They require an energy <i>less</i> than insulators and more than good conductors to remove an electron from the parent atom.	2. They require <i>very large</i> electric field to remove them from the attraction of nuclei.
3. They have: (i) <i>an empty conduction band</i> (ii) <i>almost filled valence band</i> (iii) <i>very narrow energy gap</i> (of 1eV) <i>separating the two bands</i> .	3. They have: (i) <i>a full valence band</i> (ii) <i>an empty conduction band</i> (iii) <i>a large energy gap</i> . (or several eV) <i>between them</i> .

4.21.1.4. Differences between Conductors and Insulators

Conductors	Insulators
1. These are the materials in which an electromotive force causes appreciable drift of electrons.	1. The ionically and covalently bounded materials are known as insulators or poor conductors.

2. All metals are good conductors of electricity.	2. Materials like glass, plastics, ceramics, diamond, wood, asbestos, bakelite, mica, PVC, rubber and porcelain having high resistance are known as insulators.
3. The conductors do not break down under high electrical voltage.	3. These materials generally break down under high electrical voltage.
4. Metals like silver, copper and aluminium having low resistance are good conductors.	4. The energy gap in insulator is very high.

4.21.1.5. Atomic Structure

To understand how semiconductors work, it is necessary to study briefly the structure of matter. All atoms are made of electrons, protons and neutrons. Most solid materials are classed, from the stand-point of electrical conductivity, as conductors, semiconductors or insulators. *To be conductor, the substance must contain some mobile electrons—one that can move freely between the atoms.* These free electrons come only from the valence (outer) orbit of the atom. Physical force associated with the valence electrons bind adjacent atoms together. The inner electrons below the valence level do not normally enter into the conduction process.

Conductivity depends on the number of electrons in the valence orbit. Electron diagrams for three typical elements, aluminium, phosphorus and germanium are shown in Figs. 4.21, 4.22, 4.23.

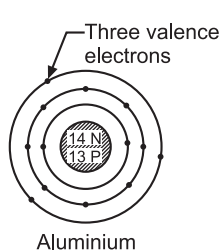


Fig. 4.21.

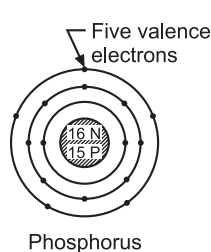


Fig. 4.22.

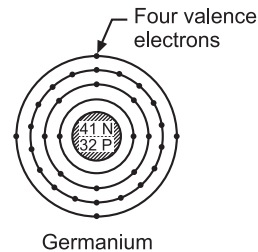


Fig. 4.23

These elements can all be used in semiconductor manufacture. The *degree of conductivity* is determined as follows:

1. Atoms with *fewer than four valence electrons* are *good conductors*.
2. Atoms with *more than four valence electrons* are *poor conductors*.
3. Atoms with *four valence electrons* are *semiconductors*.

Fig. 4.21 shows aluminium which has *three valence electrons*. When there are less than four valence electrons they are loosely held so that at least one electron per atom is normally free; hence aluminium is a good conductor. This ready availability of free electrons is also true of copper and most other metals.

Fig. 4.22 shows Phosphorus with *five valence electrons*. When there are more than four valence electrons, they are lightly held in orbit so that normally *none are free*. Hence phosphorus and similar elements are poor conductors (insulators).

Germanium (Fig. 4.23) has *four valence electrons*. This makes it neither a good conductor nor a good insulator, hence its name “semiconductor”. Silicon also has four valence electrons and is a semiconductor.

Note. The energy level of an electron increases as its distance from the nucleus increases. Thus an electron in the second orbit possesses more energy than the electron in the first orbit; electrons

in the third orbit have higher energy than in the second orbit and so on. It follows, therefore, that electrons in the last orbit will possess very high energy. These high energy electrons are less bound to the nucleus and hence they are more mobile. It is the mobility of last orbit electrons that they acquire the property of combining with other atoms. Further it is due to this combining power of last orbit electrons of an atom that they are called *valence electrons*.

4.21.1.6 Intrinsic Semiconductor

A *pure semiconductor* is called “*intrinsic semiconductor*”. Here no free electrons are available since all the co-valent bonds are complete. A *pure semiconductor, therefore, behaves as an insulator*. It exhibits a peculiar behaviour even at room temperature or with rise in temperature. The *resistance of a semiconductor decreases with increase in temperature*.

When an electric field is applied to an intrinsic semiconductor at a temperature greater than 0°K , conduction electrons move to the anode and the holes (when an electron is liberated into the conduction band a positively charged hole is created in valence band) move to cathode. Hence semiconductor current consists of movement of electrons in opposite direction.

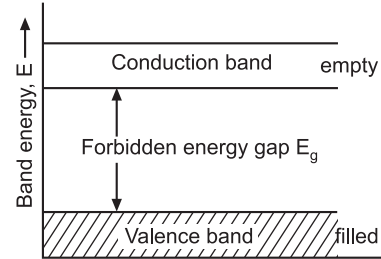


Fig. 4.24. Energy diagram for intrinsic (pure) semiconductor at absolute zero.

4.21.1.7. Extrinsic Semiconductor

In a pure semiconductor, which behaves like an insulator *under ordinary conditions*, if small amount of certain *metallic impurity* is added, it attains *current conducting properties*. The impure semiconductor is then called “*impurity semiconductor*” or “*extrinsic semiconductor*”. The process of adding impurity (extremely in small amounts about 1 part in 10^8) to a semiconductor to make it extrinsic (impurity) semiconductor is called **Doping**.

Generally following doping agents are used:

- (i) *Pentavalent atom* having five valence electrons (arsenic, antimony, phosphorus) called *donor atoms*.
- (ii) *Trivalent atoms* having three valence electrons (gallium aluminium, boron) called *acceptor atoms*.

With the addition of suitable impurities to semiconductor, two type of semiconductors are:

- (i) N-type semiconductor.
- (ii) P-type semiconductor.

N-type semiconductor:

The presence of *even a minute quantity of impurity* can produce N-type semiconductor. If the impurity atom has *one valence electron more* than the semiconductor atom which it has substituted, this *extra electron* will be loosely bound to the atom. For example, an atom of *Germanium* possesses *four valence electrons*; when it is replaced in the crystal lattice of the substance by an impurity atom of antimony (Sb) which has *five valence electrons*, the fifth valence electron (free electron) produces extrinsic N-type conductivity *even at room temperature*. Such an impurity into a semiconductor is called “*donor impurity*” (or donor). The conducting properties of germanium will depend upon the *amount of antimony (i.e., impurity) added*. This means that controlled conductivity can be obtained by proper addition of impurity. Fig. 4.25 (a) shows the loosely bound excess electron controlled by the donor atom.

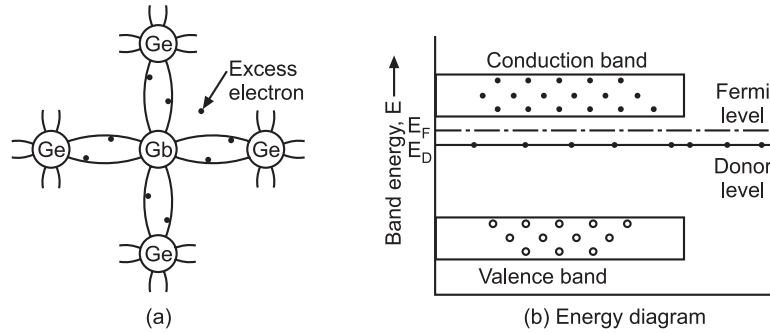


Fig. 4.25. N-type semiconductor.

- It may be noted that by giving away its one electron, the *donor atom* becomes a *positively charged ion*. But it cannot take part in conduction because it is firmly fixed or tied into the crystal lattice. In addition to the electrons and holes *intrinsically available in germanium*, the addition of antimony greatly increases the number of conduction electrons. Hence, *concentration of electrons in the conduction band is increased and exceeds the concentration of holes in the valence band*. Consequently, *Fermi level shifts upwards towards the bottom of the conduction band as shown in Fig. 4.25 (b)*. [Since the number of electrons as compared to the number of holes increases with temperature, the *position of Fermi level also changes considerably with temperature*].
- It is worth noting that even though N-type semiconductor has excess of electrons, still it is *electrically neutral*. It is so because by addition of donor impurity, number of electrons available for conduction purposes becomes more than the number of holes available intrinsically. But the *total charge of the semiconductor does not change* because the donor impurity brings in as much negative charge (by way of electrons) as positive charge (by way of protons).

Note: In terms of energy levels, the fifth antimony electron has as energy level (called donor level) just below the conduction band. Usually, the donor level is 0.01 eV below conduction band for *germanium* and 0.054 eV for *silicon*.

P-type semiconductor:

- P-type extrinsic semiconductor can be produced if the impurity atom has *one valence electrons less* than the semiconductor atom that it has replaced in the crystal lattice. This impurity atom cannot fill all the *interatomic* bonds, and the free bond can accept an electron from the neighbouring bond; leaving behind a vacancy of *hole*. Such an impurity is called an "*acceptor impurity*" (or *acceptor*). Fig. 4.26 (a) shows structure of P-type semiconductor (Germanium and Boron).
- In this type of semiconductor, conduction is by means of holes in the valence band. Accordingly, *holes form the majority carriers whereas electrons constitute minority carriers*. The process of conduction is called '*deficit conduction*'.
- Since the concentration of holes in the valence band is more than the concentration of electrons in the conduction band, Fermi level shifts nearer to the valence band [Fig. 4.26 (b)]. The acceptor level lies immediately above the Fermi level. *Conduction is by means of hole movement at the top of valence band, the acceptor level readily accepting electrons from the valence band*.

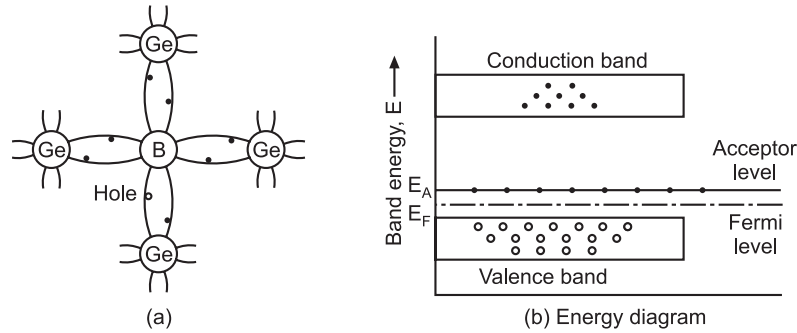


Fig. 4.26. P-type semiconductor.

It may be noted again that even though P-type semiconductor has excess of holes for conduction purposes, as a whole it is electrically neutral for the same reasons as discussed earlier.

4.21.1.8. Atomic Binding in Semiconductors

The atoms of semiconductors are arranged in an ordered array called *crystal lattice* because they have a crystalline structure e.g., *germanium* and *silicon*. Since both these materials are tetravalent having four valence electrons in their outermost shell, therefore they form *covalent bonds* with the neighbouring atoms. In order to achieve inert gas structure having 8 electrons in the outermost orbit, they *share four electrons with each other*. In case of germanium atom only four electrons out of 32 electrons take part in its electrical characteristics because the remaining 28 electrons are *tightly bound* to the nucleus. The four electrons revolving in the outermost shell are called *valence electrons*. Therefore, each atom of the semiconductor surrounded symmetrically by four other atoms forms a *tetrahedral crystal*. Hence a stable structure is formed when each shares a valence electron with each of its four neighbours.

In case of pure (intrinsic) germanium, to allow the electrons for conduction of current the *covalent bonds should be broken*. For setting the electron free, there are different ways of *rupturing the covalent bond*. This can be done by *increasing the crystal temperature above 0° K*. There are mainly two properties, *hardness* and *brittleness*, of *covalent crystals*. The *hardness* is characterised by the *great strength of the covalent bond itself*. The *brittleness* is characterised by the *fact that adjacent atom must remain in accurate alignment because the bond is strongly directional and formed along a line forming the atoms*.

4.21.1.9. Formation of Holes in Semiconductors

Refer to Fig. 4.27. In the semiconductor, the *hole formed is a positive charge carrier*. When a covalent bond is broken at its edge, electrons move through the crystal lattice leaving behind a hole in the bond. An electron from the side lattice jumps into the first vacant hole. Later on, an electron from another point N will jump into the hole at M and so on. Thus a hole would appear at a point (R) in the lattice opposite to the first hole (L) by a succession of electron movements. A negative charge would move from R to L. In other words, a positive charge is said to have moved from L to R. Therefore, a hole in this case is regarded as a *positive charge carrier* or an electron with a negative charge. Hence due to

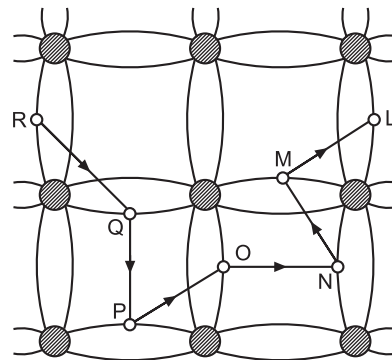


Fig. 4.27

movements of the electrons in the valence bond holes are formed. A collision is caused by each electron movement. In other words, drift velocity of electron is always more than the drift velocity of holes. Thus an *intrinsic semiconductor* is one in which number of holes produced is equal to the number of conduction electrons. Fermi level which is defined as the energy corresponding to the centre of gravity of conduction electrons and holes weighted according to their energies lies exactly in the middle of the forbidden energy gap. As the lower filled bonds of semiconductor are not of any effect, therefore, only two bands, i.e., valence and conduction bands are usually shown in the energy band diagrams.

4.21.1.10. Fermi Level in an Intrinsic semiconductor

To classify conductors, semiconductors and insulators we make use of the reference energy level, called *Fermi level*. In case of an *intrinsic semiconductor*, *Fermi level* (E_F) lies in the middle of energy gap or mid-way between the conduction and valence bands.

Let (at any temperature $T^\circ\text{K}$),

n_v = Number of electrons in the valence band.

n_c = Number of electrons in the conduction band.

N = Number of electrons in both bands.

$$= n_v + n_c$$

Assumptions:

- (i) In valence band energy of all levels is zero.
- (ii) In conduction band, energy of all levels is equal to E_g (energy at gap).
- (iii) As compared to forbidden energy gap between two bands, the widths of energy bands are small.
- (iv) All levels in a band consist of same energy due to small width of band.

Let the zero energy reference level is arbitrarily taken at the top of valence band.

\therefore No. of electrons in the conduction band, $n_c = N \cdot P(E_g)$ where $P(E_g)$ = probability of an electron having energy E_g .

Fermi-Dirac probability distribution function gives its value given below:

$$P(E) = \frac{1}{1 + e^{(E - E_F)/kT}} \quad \dots(4.1)$$

where $P(E)$ = Fermi-Dirac distribution function or probability of finding an electron having any particular value of energy E and E_F in the Fermi level.

$$\therefore P(E_g) = \frac{1}{1 + e^{(E_g - E_F)/kT}}$$

$$\therefore n_c = \frac{1}{1 + e^{(E_g - E_F)/kT}} \quad \dots(4.2)$$

Number of electrons in the valence band is

$$n_v = NP(0)$$

By putting $E = 0$ in the Fermi-Dirac probability distribution function,

$$P(0) = \frac{1}{1 + e^{(0 - E_F)/kT}} = \frac{1}{1 + e^{-E_F/kT}}$$

$$\therefore n_v = \frac{N}{1 + e^{-E_F/kT}}$$

Now
$$N = n_v + n_c = \frac{N}{1 + e^{-E_F/kT}} + \frac{N}{1 + e^{(E_g - E_F)/kT}}$$

After simplification, we get

$$E_F = \frac{E_g}{2} \quad \dots (4.3)$$

This shows that in an 'Intrinsic semiconductor', the Fermi level lies mid-way between the conduction and valence bands.

4.21.2. Photovoltaic Effect

When a solar cell (p - n junction) is illuminated, electron-hole pairs are generated and the electric current I is obtained. I is the difference between the solar light generated current I_L and the diode current I_j

Mathematically,
$$I = I_L - I_j \quad \dots(4.4)$$

or,
$$I = I_L - I_0 \left[\exp\left(\frac{eV}{kT}\right) - 1 \right] \quad \dots(4.5)$$

where,
 I_0 = Saturation current,
 e = Electron charge,
 V = Voltage across the junction,
 k = Boltzmann's constant, and
 T = Absolute temperature.

This phenomenon is known as the **Photovoltaic effect**.

4.21.3. Conversion Efficiency and Power Output of a Solar Cell

A solar cell uses a p - n junction its physical configuration. The current and voltage relationship is given by:

$$I_j = I_0 \left[\exp\left(\frac{eV}{kT}\right) - 1 \right] \quad \dots(4.6)$$

where,
 I_j = Junction current,
 I_0 = Saturation current (also called *dark current*),
 e = Electron charge,
 V = Voltage across the junction, and
 T = Absolute temperature.

Open circuit voltage V_{oc} for the *ideal cell* is given by:

$$V_{oc} = \left(\frac{kT}{e} \right) \ln \left(\frac{I_L}{I_0} + 1 \right) \quad \dots(4.7)$$

$\therefore I_L \gg I_0$, the 1 in the equation can be neglected. Then open circuit voltage (V_{oc}) becomes:

$$V_{oc} = \frac{kT}{e} \ln \left(\frac{I_L}{I_0} \right) \quad \dots (4.8)$$

In practice the 'open circuit voltage of the cell' decreases with increasing temperature.

The voltage, current and power delivered by the solar cell are influenced by the following factors:

- (i) Conditions of sunlight, intensity, wavelength and angle of incidence etc.;
- (ii) Conditions of the junction, temperature, termination, etc.
- (iii) External resistance(R).

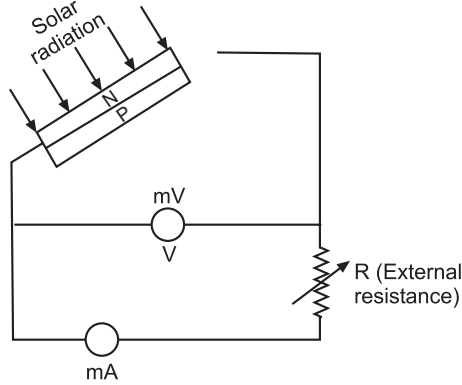


Fig. 4.28. Test condition.

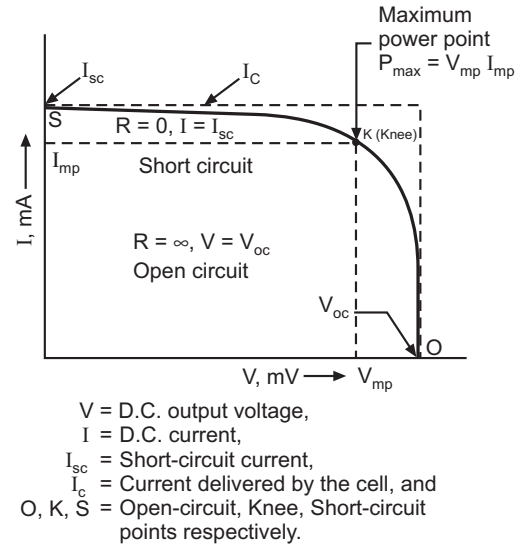


Fig. 4.29. V-I characteristics of a solar cell.

The ratings of a solar cell are specified for particular reference conditions and with the help of V - I characteristics.

Fig. 4.28 represents a test condition. Fig. 4.29 gives V - I characteristics of a typical commercially available solar cell.

- When external resistance R is **high** (mega-ohms range or infinity) the condition is called 'Open-circuit'. The open-circuit voltage V_{oc} of a solar cell is about 0.5 V.D.C. It is the *maximum voltage* across a PV (photovoltaic) cell. Open-circuit current is zero.
- If R is *reduced gradually* and the readings of the terminal voltage V and load current I are taken, we get V - I , characteristics of the PV cell (Fig. 4.29).
- As R is *reduced* from high value to low value, the terminal *voltage* of the cell *falls* and *current increases*. A *steep* characteristic OK is obtained.
- At knee point ' K ', the characteristic undergoes a smooth change and becomes *flat* for the portion Ks .
- When the external resistance is completely shorted, the short-circuit current I_{sc} is obtained. The *terminal voltage* for the short-circuit conditions is *zero* and *maximum current delivered by the cell* is I_{sc} .

The *maximum power* (P_{max}) that can be derived from the device is given by:

$$P_{max} = V_{mp} I_{mp} \quad \dots (4.9)$$

where, V_{mp} and I_{mp} are the voltage and current at maximum power point as shown in Fig. 4.29.

Maximum efficiency (η_{max}) of a solar cell is defined as the ratio of maximum electric power output to incident solar radiation.

Mathematically, $\eta_{\max} = \frac{V_{mp} I_{mp}}{I_s A_c}$... (4.10)

where, I_s = Incident solar flux, and
 A_c = Cell's area

Fill factor (FF). The *fill factor* for a solar cell is defined as *the ratio of two areas shown (Fig. 4.29)*. Mathematically,

$$FF = \frac{I_{mp} V_{mp}}{I_L V_{oc}} \quad \dots (4.10)$$

Maximum power can be defined in terms of I_L and V_{oc} and is given by

$$P_{max} = I_L \times V_{oc} \times FF \quad \dots (4.11)$$

Solar cell designers strive to *increase the FF values, to minimise internal losses.*

FF for a good silicon cell is about 0.8.

Voltage factor. The voltage factor $\frac{eV_{oc}}{E_g}$ is determined by the basic properties of the materials in the cell and is typically *about 0.5 for a 'silicon cell'* (E_g = Forbidden energy gap).

- *"Leakage" across the cell increases with temperature which reduces voltage and maximum power.*

Causes of low efficiency of a solar cell:

The efficiency of a photovoltaic cell is *15% only*. The major losses which lead to the low efficiency of the cell are:

1. As the *temperature* of the cell *rises* due to solar radiation, *leakage* across the cell *increases*. Consequently, power output, relative to solar energy input, decreases. For *silicon*, the *output decreases by 0.5% per °C*.
 2. The excess energy of active photons given to the electrons beyond the required amount to cross the band gap *cannot be recovered* as useful electric power. It appears as heat, about 33 per cent, and is lost.
 3. The electric current (generated) flows out of the top surface by a mesh of *metal contacts* provided to *reduce series resistance losses*. These *contacts cover a definite area which reduces the active surface and proves an obstacle to incident solar radiation*.
- ☞ ● To achieve maximum efficiency the semiconductor with optimum band gap should be used.

Power output of solar panel, array and module:

Let, n = Number of solar cells in a module,
 m = Number of modules in an array or a panel, and
 P_c = Power per solar cell, watts

Then, *Power per module*, $P_{mod} = nP_c$ watts ... (4.12)

and, *Power per array or panel* $P_p = m \times nP_c$ watts ... (4.13)

Voltage across panel, $V_p = \frac{P_p}{I_p}$

Current delivered by the panel, $I_p = \sqrt{\frac{P_p}{R}}$... (4.14)

4.21.4. Solar Photovoltaic Cells

The “*photovoltaic or solar cell*” is a *semiconductor device*. The ‘photovoltaic effect’ was first observed in 1839 by *Becquerel* who found that, *when light was directed on to one side of an electrochemical cell, a voltage was created*. The development of *selenium and cuprous oxide photovoltaic cells* led to many applications, including photographic exposure meters. In the late 1950s, silicon solar cells were made with a conversion efficiency high enough for power generators.

4.21.4.1. Photovoltaic materials

The solar cells are made of various materials and with different structures in order to *reduce the cost and optimize efficiency*. Various types of solar cell materials available in the market are:

- The *single crystal, polycrystalline and amorphous silicon, compound thin material and also semiconductor absorbing layer which gives highly efficient cells for specialised applications*.
- *Thin film solar cells are manufactured from CuInSe_2 , CdS , CdTe , Cu_2S , InP .*
- The *amorphous silicon thin solar cells are less expensive while crystalline silicon cells are expensive and more popular*. The amorphous silicon layer is used with both hydrogen and fluorine incorporated in the structure.
- *Higher efficiency of photovoltaic generator can be achieved by combination of different band gap materials in the tandem configurations*.

4.21.4.2. Silicon photovoltaic cell (Single crystal solar cell)

The main feature of a silicon photovoltaic cell is a *thin wafer of high purity silicon crystal, doped with a minute quantity of boron* (Fig. 4.30).

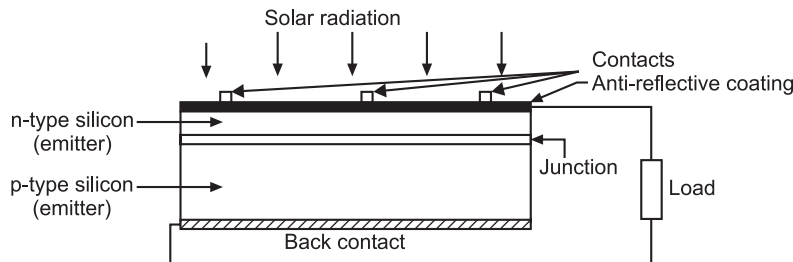


Fig. 4.30. Construction of silicon photo voltaic cell.

Phosphorous is diffused into the active surface of the slice by means of a high temperature process. The top electrical contact is made by a *metallic grid*, and the *back metal contact* covers the whole surface. The top surface usually has an anti-reflective coating (ARC).

Working theory :

— The ‘*phosphorous*’ in the silicon causes an *excess of conduction-band electrons*, and the ‘*boron*’ causes an *excess of valence electron vacancies, or holes*, which act like *positive charges*. At the “junction” between the two types of silicon, conduction electrons from the negative (*n*) region diffuse into the positive (*p*) region and combine with holes, thus *cancelling their charges*. The opposite action also occurs, with holes from the *p*-region

crossing into the *n*-region and combining electrons. The area around the junction is thus 'depleted' by disappearance of electrons and nearby holes. Layers of charged impurity atoms, positive in the *n*-region and negative in the *p*-region, are formed on either side of the junction, which sets up a 'reverse' electric field.

— When light falls on the active-surface, photons with energy exceeding a certain critical level *known as band or energy gap* (1.1 electron volt in the case of silicon) interact with the valence electrons and elevate them to the conduction band. This activity also leaves holes, so that the photons are said to generate '*electron-hole pairs*'. These electron-hole pairs are produced throughout the thickness of the silicon in concentrations that depend on the intensity and spectral distribution of the light. The electrons move throughout the crystal, and the less mobile holes also move by valence-electron substitution from atom to atom. Some *recombine, neutralising their charges and their energy is converted into heat*. Others reach the junction and are separated by the reverse field, at which point the electrons are accelerated towards the negative contact and the holes towards the positive. A *potential difference is established across the cell, and this will drive a current through an external load*.

- Silicon voltaic cells *require the use of very pure silicon*. The best source of silicon is silica (silicon dioxide), which occurs abundantly in nature as quartz rock and sand. Quartz rocks are reduced in an arc-furnace with the help of carbon-based agents to produce 'metallurgical grade' silicon.

4.21.4.3. Polycrystalline silicon cells

The cost of production of single crystal silicon cell is *quite high* compared to the polycrystalline silicon cell. Polysilicon can be obtained in thin ribbons drawn from molten silicon bath and cooled very slowly to obtain large size crystallites. Cells are made with care so that the *grain boundaries cause no major interference with the flow of electrons and grains are larger in size than the thickness of the cell*.

Following are the *three designs* in which the polycrystalline silicon solar cell can be fabricated:

1. **p-n junction cells.** In such a cell, a polycrystalline silicon film is deposited by chemical vapour deposition on substrates like glass, graphite, metallurgical grade silicon and metal.
2. **Metal insulator semiconductor (MIS) cells.** This type of cell can be developed by inserting a thin insulating layer of SO_2 between the metal and the semiconductor.
3. **Conducting oxide-insulator semiconductor cells.**

4.21.5. Classification of Solar Cells

Solar cells can be *classified* on the basis of:

(i) Cell size; (ii) Thickness of active material; (iii) Type of junction structure; (iv) Type of active material.

1. **Cell size.** The size of the silicon solar cells can be divided into *four groups*; (i) Round single crystalline having 100 mm diameter; (ii) Square single crystalline having area of 100 cm^2 , (iii) $1000 \text{ mm} \times 1000 \text{ mm}$ square multicrystalline, and (iv) $125 \text{ mm} \times 125 \text{ mm}$ square multicrystalline.

- *Larger size solar cells* are used in *terrestrial applications*. Due to brittleness property of the silicon, *area* of silicon solar cells is *limited*.
- 2. **Thickness of active material.** Such solar cells are of *two* types: (i) Bulk material cell, and (ii) Thin film cell.
 - *Bulk material* single crystal and multicrystalline cells are most successful for terrestrial applications.
 - *Thin film cells* are *not* commercially successful.
- 3. **Type of junction structure.** These cells are *classified* as:
 - (i) *p-n* homojunction cell, (ii) *p-n* heterojunction cell, (iii) *p-n* multijunction cell, and (iv) Metal semiconductor Schottky junction.
- 4. **Type of active material.** Such cells are *classified* as: (i) Single crystal silicon cell, (ii) Multicrystalline silicon cell, (iii) Amorphous silicon cell, (iv) Gallium arsenide cell, (v) Copper indium diselenide cell, (vi) Cadmium telluride cell, and (vii) Organic P-V cell.

4.21.6. Silicon Cell Modules

- *'Solar cells'* are *electrically connected in series and parallel to give suitable voltages and currents for a particular application*. A number of cells are generally encapsulated into a *module*, which is the *building block of a photovoltaic system*.
 - A *typical module* measures about 1000 mm × 300 mm × 50 mm and contains 36 cells, which produce 30-35 W at 12 V in bright sunshine.
- Several modules combine to form a '*photovoltaic array*'. Galvanized steel, aluminium or chemically treated wood have been used to support the modules, although the latter is not recommended in developing country environments. Arrays are usually fixed in position on concrete foundations.
- *Arrays that can track the apparent motion of the sun and intercept more energy are naturally more expensive and complex.*
 - *"Photovoltaic modules"* are rated in *peak watts* (W_{pk}), which refer to the maximum power output from the module when operating at a cell temperature of 28°C (or sometimes 25°C) under a solar irradiance of 1000 W/m². It is a higher output than that usually achieved in the field.
 - If the cell efficiency is 10%, a 1-kW_{pk} array would contain a cell area of 10 m². Typically, the *packing factor* (the ratio of cell area to array area) is about 75%, giving a gross area of 13.3 m² for a 1-kW_{pk} array.
 - The *efficiency* and, consequently, the power output of the cell depends on the *electrical load* because of the relationship between current and voltage for the cells (Fig. 4.31).
 - The *efficiency of solar cells falls off about 0.5 percent /°C as the operating temperature rises*.

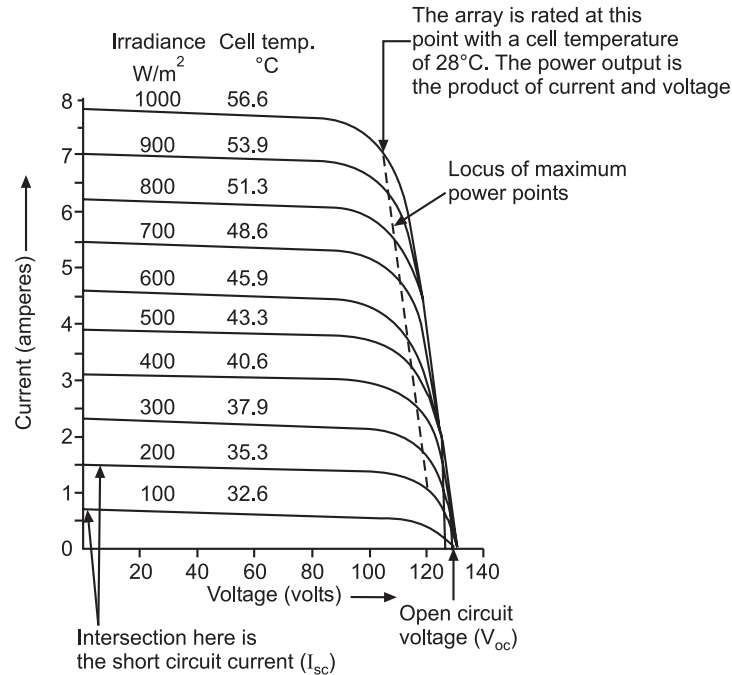


Fig. 4.31. A typical relationship between current and voltage for a photovoltaic array (ITP/Halcrow, 1983).

4.21.7. Photovoltaic (PV) Systems

Solar photovoltaic systems refer to a wide variety of solar electricity systems. Such a system *uses solar array made of silicon to convert sunlight into electricity*. Components other than PV array are collectively known as '*balance of system (BOS)*' which includes *storage batteries, an electronic charge controller and an inverter*.

These systems are of the following *two* types:

1. **Stand-alone power systems.** In such a system, the *photovoltaic array is the principal or only source of energy*. Energy is stored, often in batteries, for periods when there is insufficient solar radiation. There may also be a back-up power supply such as an engine-generator set.
2. **Grid connected power systems.** In this type of system, *load is connected to both a photovoltaic power system and an electricity grid*. In periods when there is sufficient solar radiation, the array powers the load, otherwise grid is used. In some cases, any surplus electricity produced by the array (i.e. when the load output exceeds the load) is fed back into the grid. This type includes *large MW-sized systems*.

4.21.7.1 Stand-alone power systems

A photovoltaic system can be designed to meet any electrical load. The principal components of stand-alone photovoltaic systems are shown in Fig. 4.32.

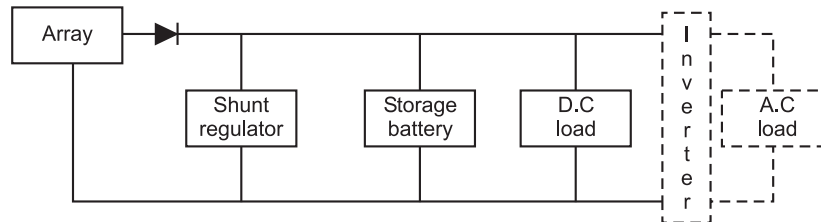


Fig. 4.32. Principal components of stand-alone photovoltaic systems.

Photovoltaic array. It consists of the required number of modules interconnected in series and parallel to give the *desired system* voltage and current.

Storage battery. The battery supplies energy to the load during *periods of little or no solar irradiance* and stores energy from the array during periods of high irradiance. This enables the systems to meet momentary peak power demands and to maintain stable voltage to the load.

Power conditioner. Because the voltage output of the photovoltaic array varies with insolation and temperature, systems with battery storage require *voltage or shunt regulator to prevent excessive overcharging of the battery*. Further controls are used, as required, to prevent discharge or to ensure that the array is operating at its *maximum power point*.

- To determine the capacity and size of a photovoltaic system, it is *necessary to select an optimum combination of battery capacity and array size for a particular location*. Methodologies for sizing systems are relatively well-developed and employ an hour-by-hour computer model of the system under consideration. The annual energy output from the system can then be calculated for a range of array sizes and battery capacities to select an optimum combination, *i.e.*, the one with the *lowest cost*.

4.21.7.2. Standards for solar photovoltaic systems

Bureau of Indian Standards (BIS) has established photovoltaic standards in India.

- For electrical safety and system reliability, PV devices need to conform to IS-12839 (1989) regulation regarding photovoltaic parts.
- Measurement of current and voltage is covered by IS-12762 (1989) and IS-12763 (1989) which deal with electrical characteristics of crystalline silicon cells.

4.21.7.3. Advantages and limitations of photovoltaic systems

Advantages and limitations of photovoltaic systems are as follows:

Advantages:

1. Systems are durable.
2. No operational cost.
3. Low maintenance.
4. More flexibility available.
5. Systems are eco-friendly.
6. Highly reliable.
7. Long effective life.
8. Absence of moving parts.
9. Can function unattended for long periods.
10. High power to weight ratio.

Limitations:

1. Weather dependent.
2. Low efficiency
3. High installation cost.

4.21.7.4. Applications of photovoltaic (PV) systems

The *applications* of photovoltaic systems are:

1. Solar street lighting system.
2. Home lighting systems.
3. Water pumping systems (for micro irrigation and drinking water supply)

4. Solar vehicles.
5. Radio beacons for ship navigation at ports.
6. Community radio and television sets.
7. Cathodic protection of oil pipelines.
8. Railway signalling equipment.
9. Weather monitoring.
10. Battery charging

4.21.8. Water Pumping Systems

The photovoltaic *water pumping systems* (major application of PV systems) essentially consist of:

- (i) A photovoltaic (PV) array,
- (ii) Storage battery,
- (iii) Power control equipment,
- (iv) Motor pump sets, and
- (v) Water storage tank.

Solar pump configurations:

Because the batteries have several disadvantages (*e.g.* power loss, increased risk of failure, shorter operational life than the rest of the solar pump and regular maintenance requirement), at present, most solar pumping systems do not include batteries, although where water storage is needed, a viable alternative may be provided.

The *four* principal combinations of motor and pump that are suitable for solar pump are:

1. Submerged motor pump set;
2. Submerged pump with surface motor;
3. Floating motor-pump set;
4. Surface motor with surface mounted pump.

These combinations are shown in Fig. 4.33.

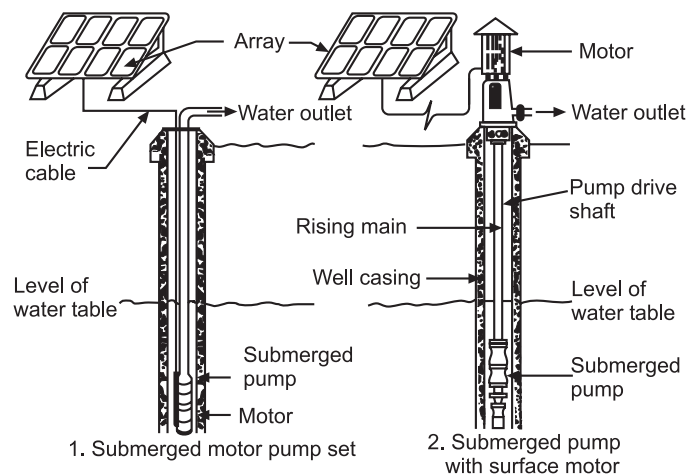


Fig. 4.33 (a). Solar pump configurations (ITP/Halcrow, 1983)

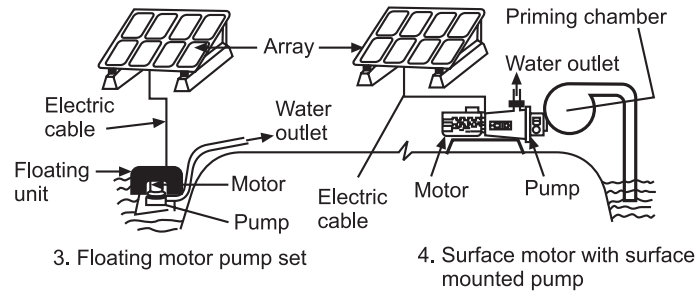


Fig. 4.33 (b). Solar pump configurations (ITP/Halcrow, 1983).

4.21.9. SPV Lighting System

Solar street light, as shown in Fig. 4.33, describes a stand-alone PV power generating device.

SPV lighting system has the following *advantages*:

1. Compact in size.
2. Highly durable.
3. Highly efficient.
4. Low maintenance.

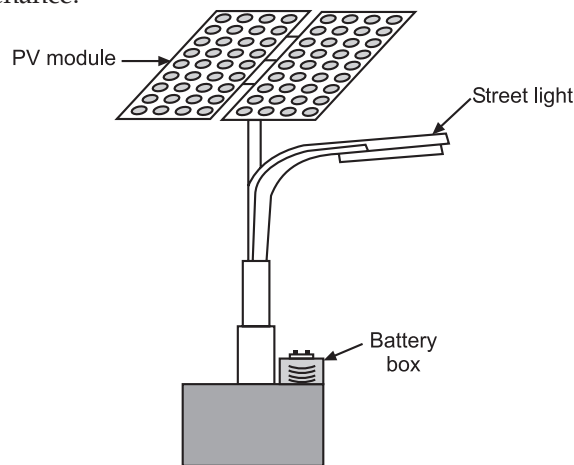


Fig. 4.34. SPV lighting system.

4.21.10. PV Hybrid System

A dedicated PV system cannot give continuous supply even with the use of the storage batteries. The stand-alone PV systems are *not reliable during the periods when the solar incidence is low and days and nights are cloudy*.

In order to meet with these difficulties, a “*hybrid system*” has been evolved to meet the load requirements regularly.

- A PV system with a diesel generator along with batteries was installed in 1987 in an island isolated from main power grid. A 100 kW solar cell module and the associated devices including the power conditioner was supplied by M/s. Hitachi. This design has the following *two features*:
 - (i) Stand-alone operation mode;
 - (ii) A parallel operation mode with a diesel unit; an additional diesel generator can also be added in the system.