# CHAPTER 3

# SOLAR THERMAL ENERGY COLLECTORS

## 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*.

- 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.

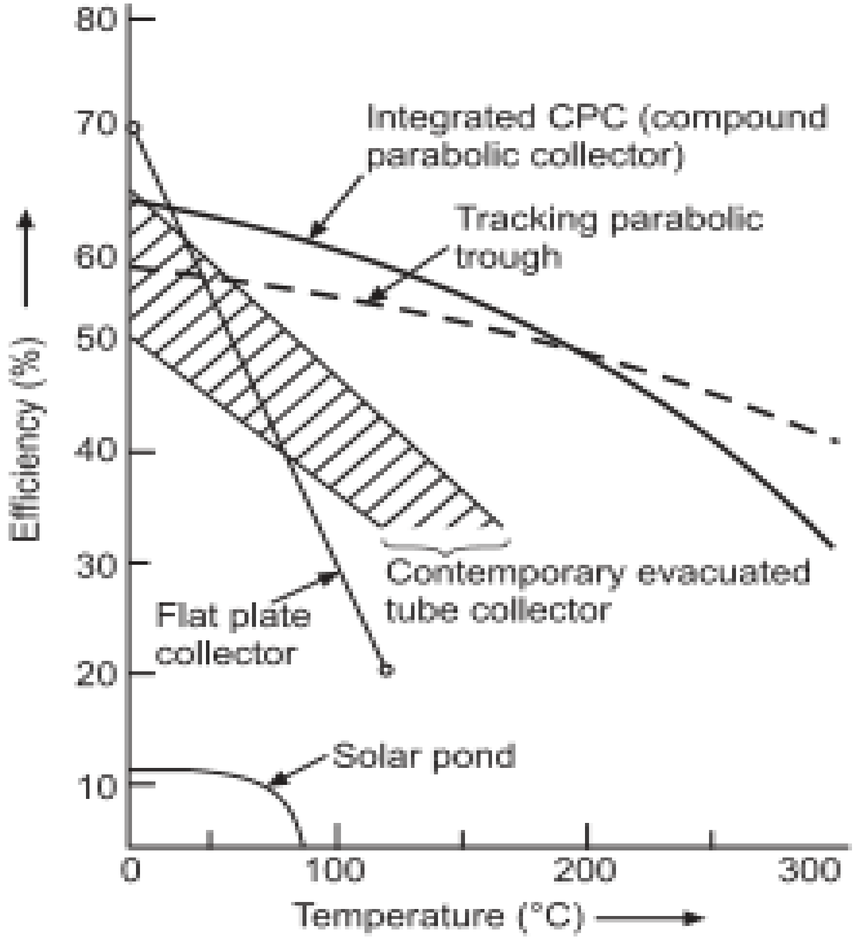


**Fig. 3.1.** Efficiency for solar collectors (Halcrow/ITP, 1983b).

### 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°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°C)
   (*i*) Steam engines and turbines
   (*ii*) Stirling engine
   (*iii*) Thermo-electric generators.
   } ...*Parabolloid 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 *parabolloid reflector* as an array of mirrors reflecting to a central target, and requiring *two directional diurnal tracking*.

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

1. *Non-availability and high cost of materials required*. These materials must be easily shapeable, yet have a long life; they must be 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:

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

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 θ. Hence solar power collected in proportional to cos θ (Fig. 3.2).

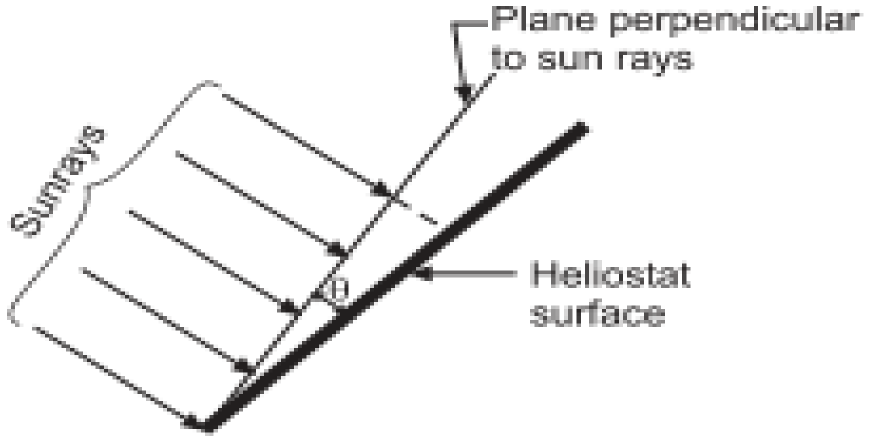


**Fig. 3.2.** Exhibiting cos θ loss.

- 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 looses 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.

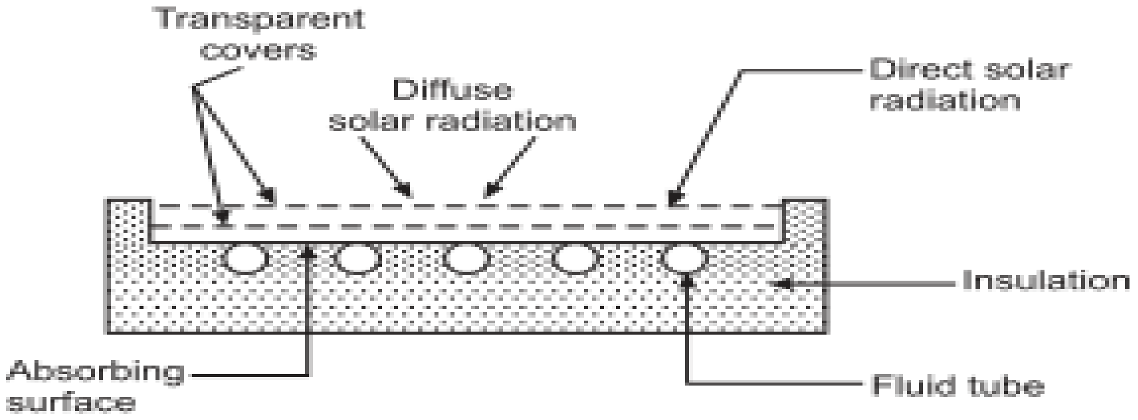


**Fig. 3.3.** Flat-plate solar collector.

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.

### 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).

**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.

## 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*

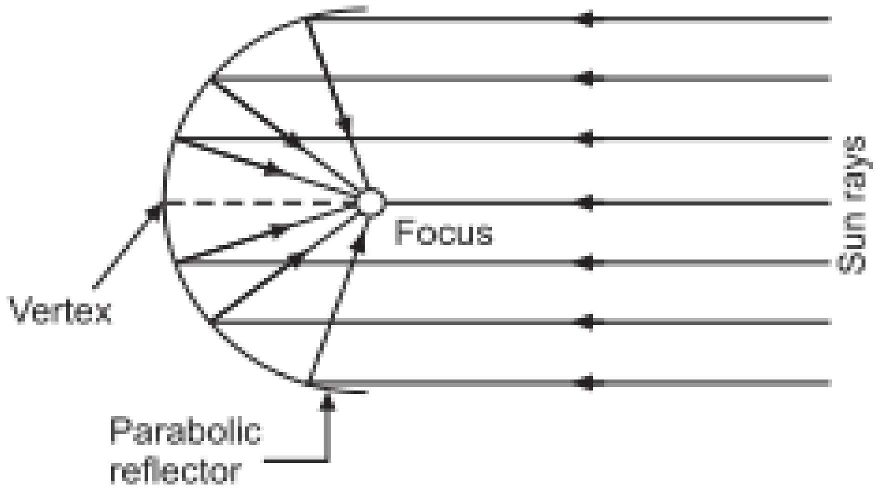


**Fig. 3.4.** Cross-section of parabolic trough collector.

*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].

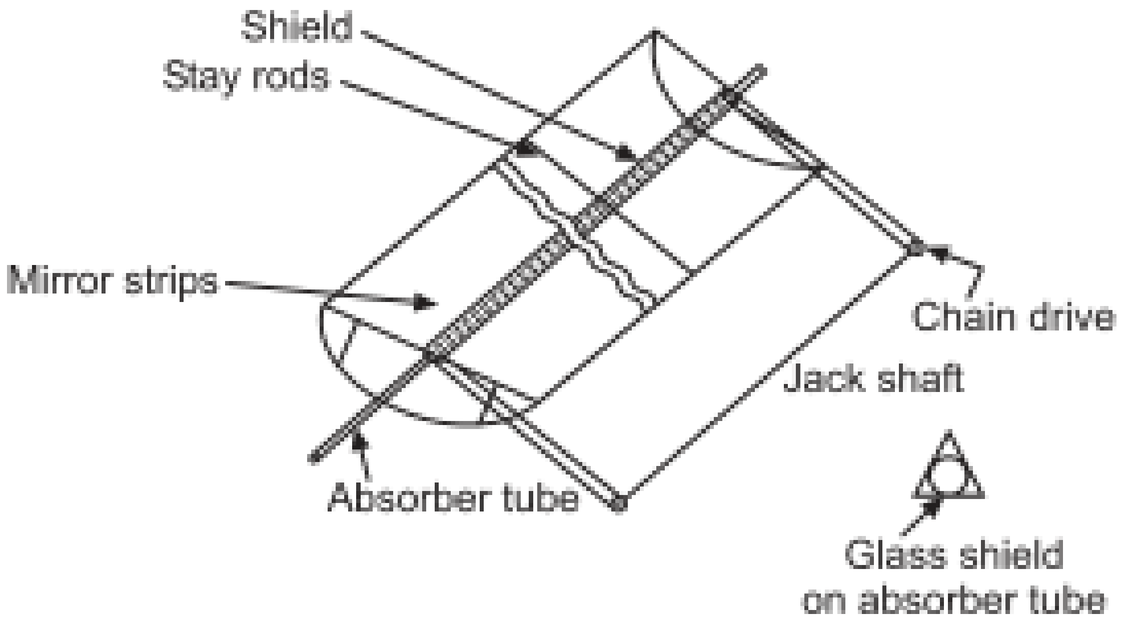


**Fig. 3.5.** Cylindrical parabolic system.

### 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*.

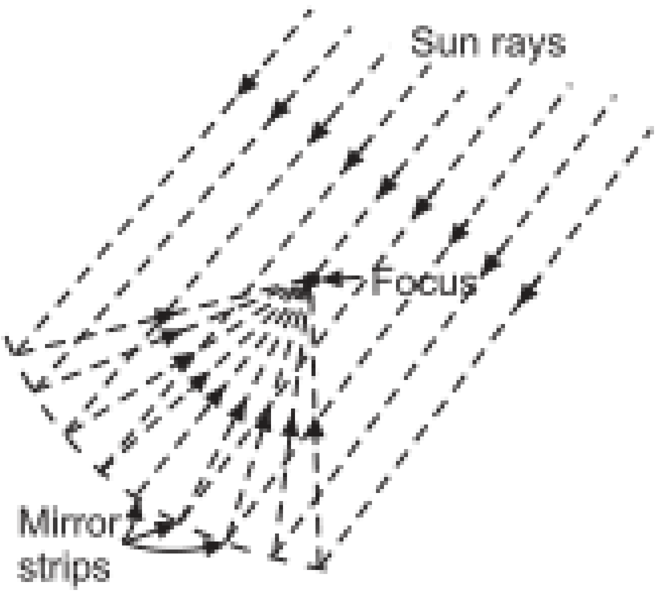


**Fig. 3.6.** Mirror strip collector.

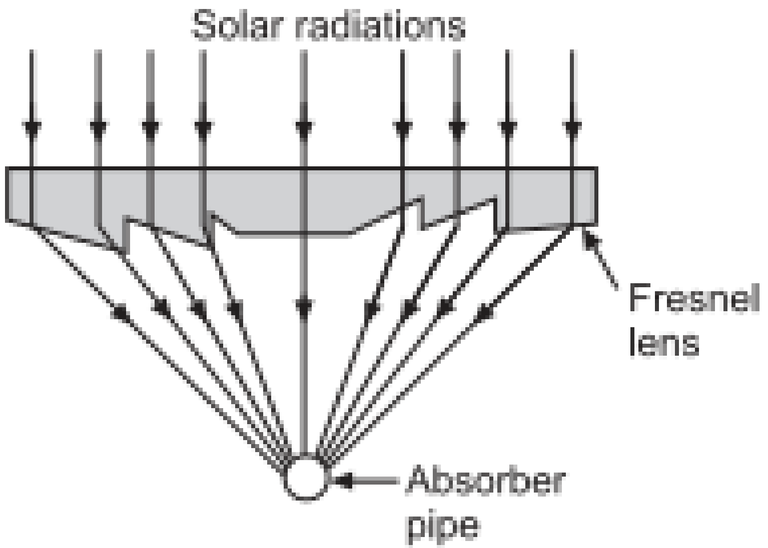


**Fig. 3.7.** Fresnel lens collector.

### 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 continously* 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.

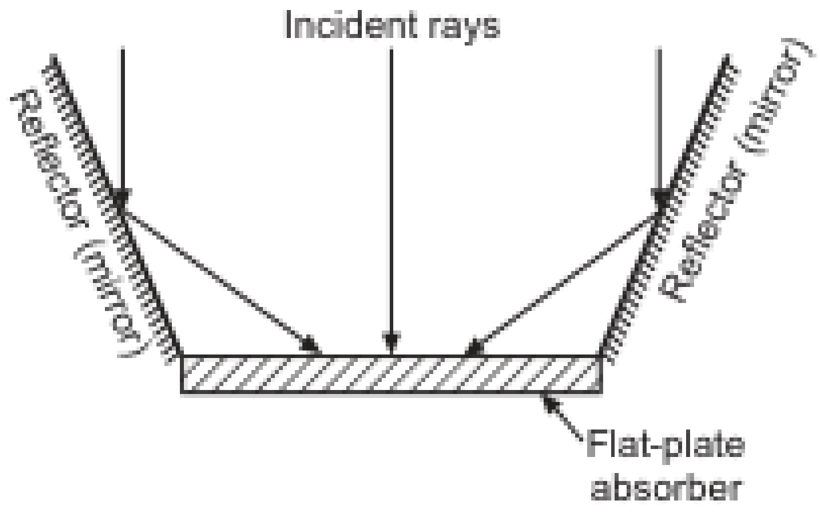


**Fig. 3.8.** Flat-plate collector absorber with adjustable mirrors.

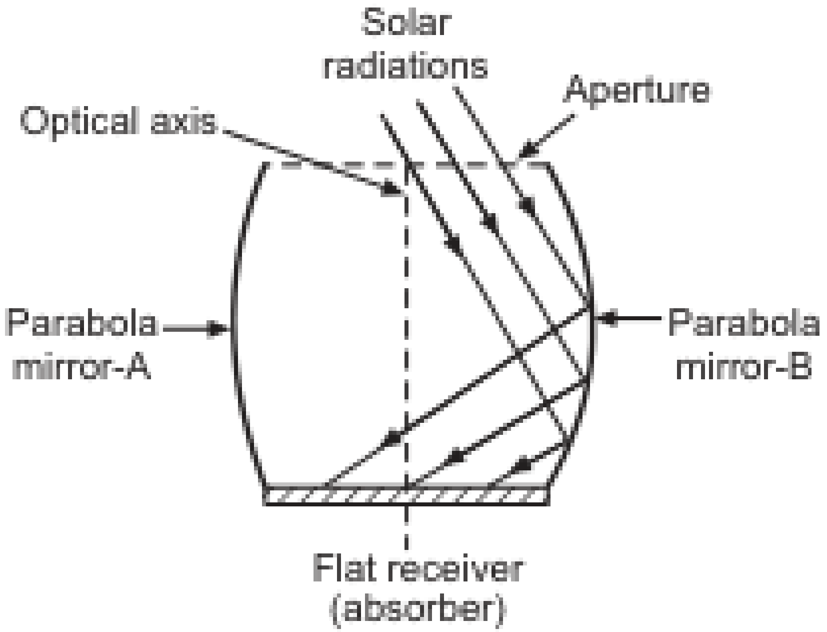


**Fig. 3.9.** Compound parabolic concentrator (CPC).

### 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* that 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.

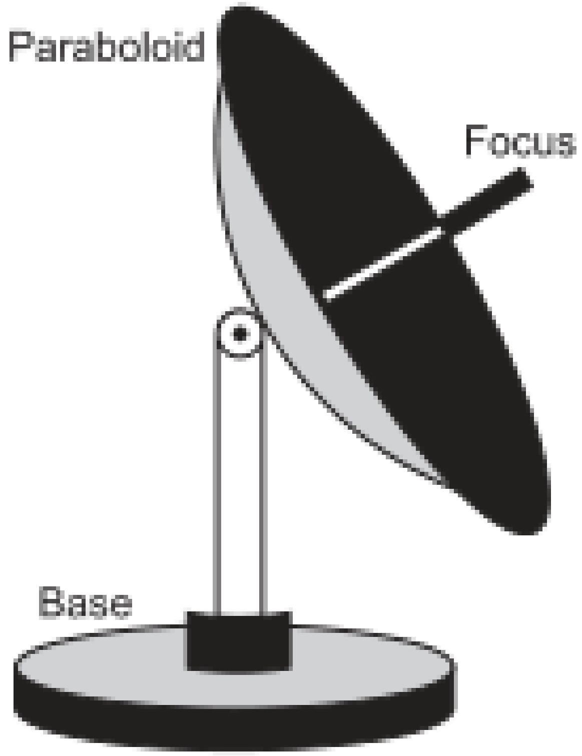


**Fig. 3.10.** Paraboloidal dish collector.

### 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). |

## 3.5. 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*:

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

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 $\eta_{carnot}$. 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*.

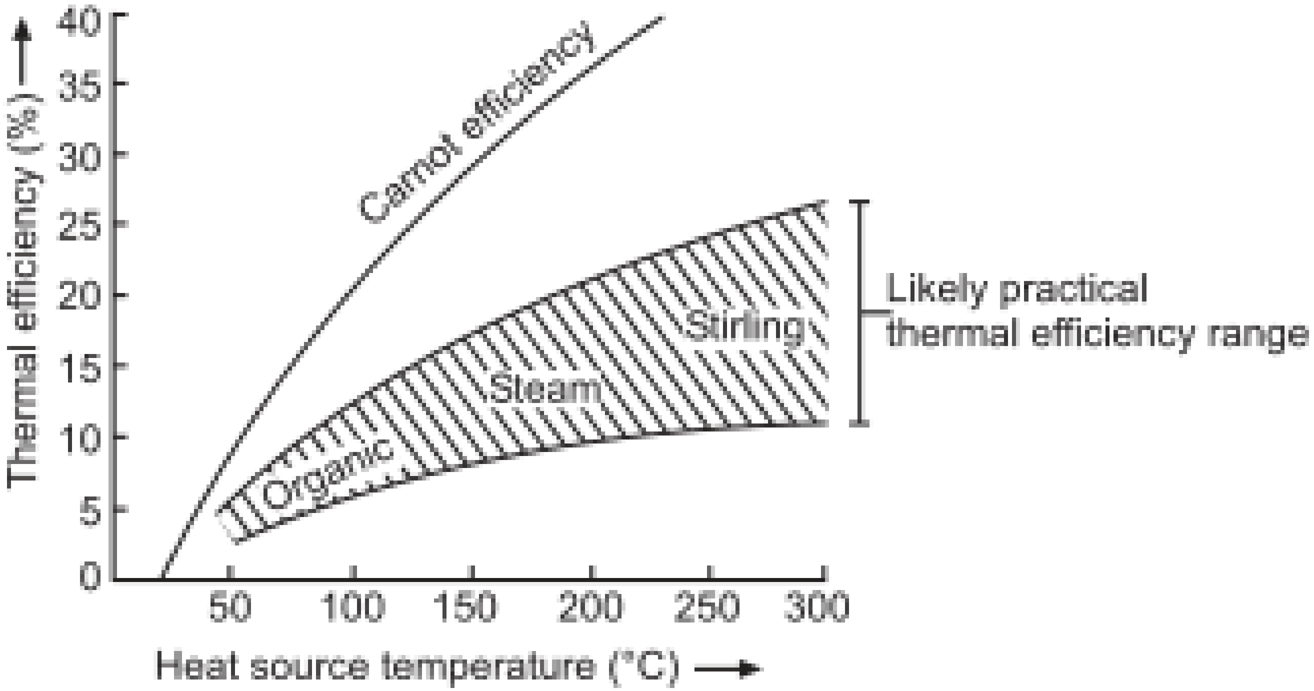


**Fig. 3.11.** Comparison of theoretical efficiency with those obtained in practice at a sink temperature of 25°C (Halcrow/ITDG 1981 b)

- 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:

# THANKS