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.

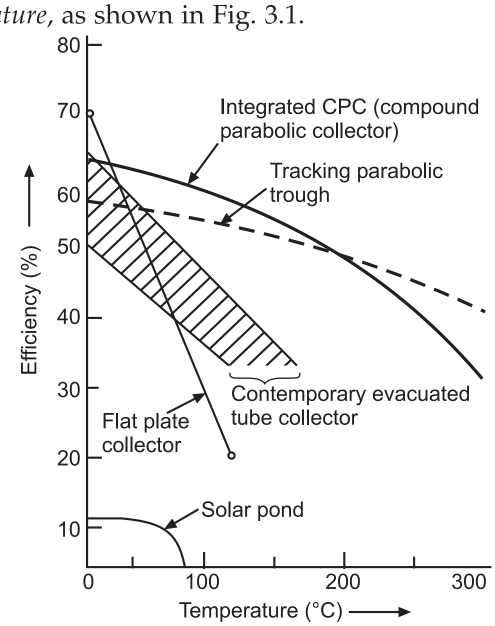

Fig. 3.1. Efficiency for solar collectors (Halcrow/ITP, 1983b).

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°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 effec*t' 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).

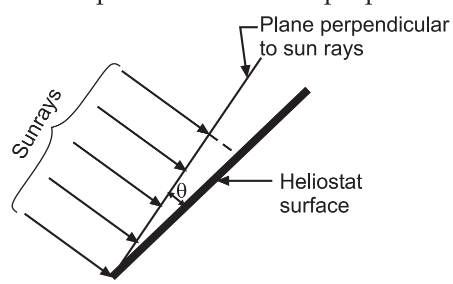

Fig. 3.2. Exhibiting cos θ loss.

- 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.

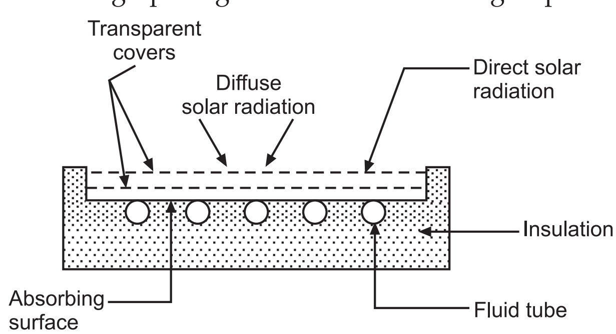

Fig. 3.3. Flat-plate solar collector.

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.

- 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 polystrene, 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

$$\alpha + \rho + \tau = 1 \qquad ...(3.1)$$

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 loses 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* $\varepsilon\sigma T^4$, 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

$$\alpha I = \varepsilon\sigma T^4 \qquad ...(3.2)$$

or,

$$\frac{\alpha I}{\varepsilon} = \sigma T^4 \qquad ...(3.3)$$

From equation (3.3), it is evident that comparatively higher equilibrium temperature will be obtained where the quantity $\frac{\alpha}{\varepsilon}$ *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 $I = 800\ \mathrm{W/m^2}$, 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

$$\alpha I + \alpha' I' = h_c(T - T_a) + \varepsilon\sigma T^4 \quad \text{...(3.4)}$$

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:

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

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

= Energy absorbed in the metal surface — Heat losses from the surface directly and indirectly to the surroundings.

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

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

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

A_{cs} = Collector *surface area* ($\mathrm{m^2}$),

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

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°C),

t_{fi} = collector fluid inlet temperature (°C), and

t_a = Ambient air temperature (°C).

Introducing heat "*removal factor* F_R" in (Eqn. (3.6), we get,

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

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*.

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

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

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

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

If, $$\frac{t_{f_i} - t_a}{I_{cs}} = 0 \text{ i.e. } t_{f_i} = t_a\text{, then}$$

$$\eta_c = F_R (\tau\alpha)_e \quad (...3.10)$$

This is the effective *optical efficiency*.

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

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

  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} (0°C)

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

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

where, t_{fi} = Collector fluid inlet temperature (°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, $$t_s = t_{fi} = t_a + I_{cs} \frac{F_R(\tau\alpha)_e}{F_R U_{oc}} \quad ...(3.13)$$

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

(*i*) Useful heat output; Q_c:

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

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

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

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

$$= 38 + \frac{586.5}{0.019 \times 4187} = \mathbf{45.4\ °C\ (Ans.)}$$

Example 3.2. *The following data relate to a flate 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 W/m^2 hr; Tilt of the collector = latitude + 14°; Number of glass covers = 2; Heat removal factor for collector = 0.82; Transmittance of glass = 0.87; Aborptance of glass = 0.89; Top loss coefficient for collector = 7.9 W/m^2 hr °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:* ϕ = 22° ; Day and time: Jan. 22, 11:30 – 12:30 (IST);

H_b= 340 W/m^2 hr ; $\beta = \phi + 14° = 22° + 14° = 36°$;

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 W/m^{2}hr °C; t_{fi} = 48°C; t_a = 16 °C.

(*i*) **Solar altitude angle, α:**

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

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

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

Solar altitude angle α is given by:

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

$$= \sin 22°\,\sin(-19.93°) + \cos 22°\,\cos(-19.93°)\,\cos 0°$$

$$= -0.1277 + 0.8716 = 0.7439$$

$$\therefore \qquad \alpha = \mathbf{48.6°\ (Ans.)}$$

(*ii*) **Incident angle, θ:**

$$\theta = \frac{\pi}{2} - \alpha = 90° - 48.06° = \mathbf{41.94° \ (Ans.)}$$

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

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

$$R_b = \frac{\sin\delta \sin(\phi-\beta) + \cos\delta \cos\omega \cos(\phi-\beta)}{\sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega} \quad \text{...[Eqn. (2.29(a)]}$$

$$= \frac{\sin(-19.93°) \sin(22°-36°) + \cos(-19.93°) \cos 0° \cos(23°-36°)}{\sin 22° \sin(-19.93°) + \cos 22° \cos(-19.93°) \cos 0°}$$

$$= \frac{-0.0825 + 0.9121}{-0.1277 + 0.8716} = 1.115$$

Effective transmittance absorptance product is given by;

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

(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 W/m^{2}hr ...(Given)

Now, solar radiation, $H = H_b R_b \, (\tau.\alpha)_e$

$= 340 \times 1.115 \times 0.795 = 301.38$ W/m^{2}hr

Useful gain, $Q_c = F_R [H - U_{oc}(t_{fi} - t_a)]$

$= 0.82 \, [301.38 - 7.9 \, (48 - 16)] = 39.83$ W/m^{2}hr

$\therefore$ Collecton efficiency, $\eta_c = \dfrac{Q_c}{H_b R_b} = \dfrac{39.83}{340 \times 1.115} =$ **0.105 or 10.5% (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*

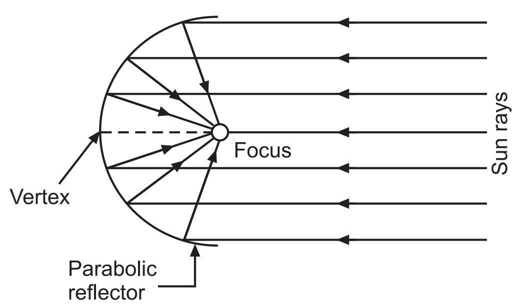

Fig. 3.4. Cross-section of parabolic trough collector.

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].

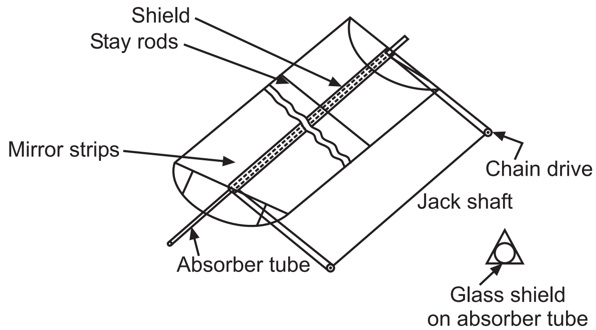

Fig. 3.5. Cylindrical parabolic system.

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*.

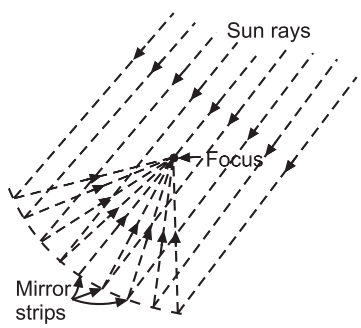

Fig. 3.6. Mirror strip collector.

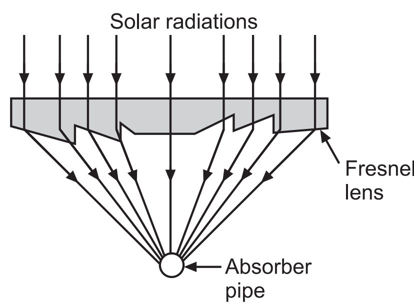

Fig. 3.7. Fresnel lens collector.

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 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.

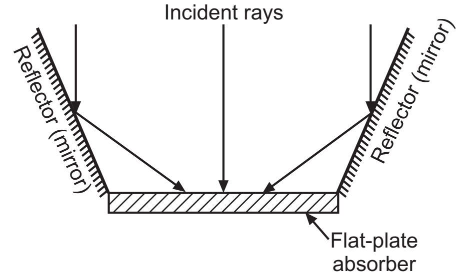

Fig. 3.8. Flat-plate collector absorber with adjustable mirrors.

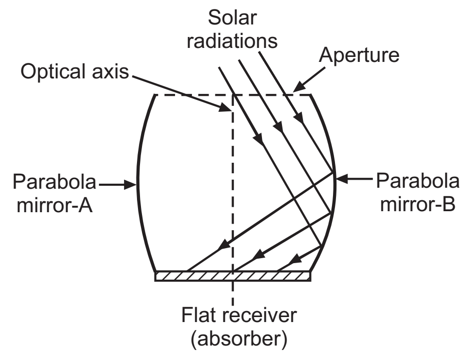

Fig. 3.9. Compound parabolic concentrator (CPC).

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.

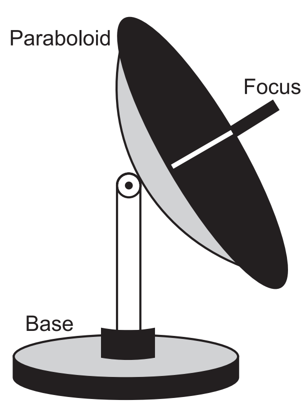

Fig. 3.10. Paraboloidal dish collector.

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).

3.4.11. Performance Analysis of a Concentrating Collector

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

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

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°C),

C = Correction factor,

t_{in} = The inlet temperature of the collector (°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:

$$\eta_{opt} = \eta_{opt\,0°}\, C_{opt} = \rho\gamma\tau\alpha_a .\, C_{opt} \quad ...(3.15)$$

where, $\eta_{opt\,0°}$ = 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:

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

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

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

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

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*:

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

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*.

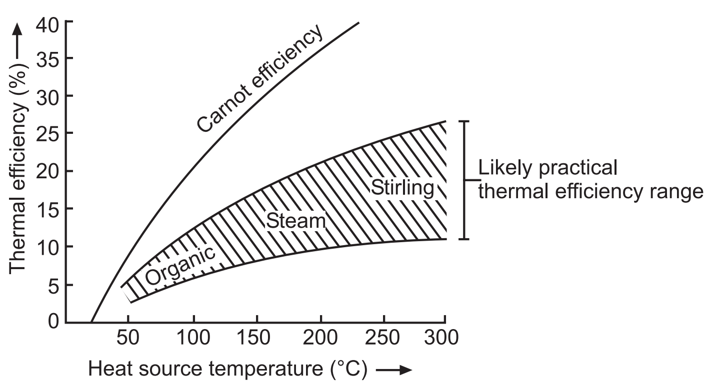

Fig. 3.11. Comparison of theoretical efficiency with those obtained in practice at a sink temperature of 25°C (Halcrow/ITDG 1981 b)

- 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 Brayon, 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 heatoutput of a flat-plate collector is given by:

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

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°C),

t_{fi} = Collector fluid inlet temperature (°C),

t_a = Ambient air temperature (°C), and

F_R = Heat removal factor.

Stagnation temperature (t_s) of the collector is gives 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:

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

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°C),

C = correction factor,

t_{in} = The inlet temperature of the collector (°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 W/m^2°C; mass flow rate of water = 0.017 kg/s/m^2; specific heat of water at constant pressure, c_p = 4187 J/kg°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 W/m^2 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 W/m^2°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°00 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 W/m^2°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%]