3

Solar Radiation and Its Measurement

3.1 A PERSPECTIVE

The sun is a hydrodynamic spherical body of extremely hot ionized gases (plasma), generating energy by the process of thermonuclear fusion. The temperature of the interior of the sun is estimated at 8×10^6 K to 40×10^6 K, where energy is released by fusion of hydrogen to helium.

Energy radiated from the sun is electromagnetic waves reaching the planet earth in three spectral regions, ultraviolet 6.4% ($\lambda < 0.38$ µm), visible 48% (0.38 µm $< \lambda <$ 0.78 µm) and infrared 45.6% ($\lambda > 0.78$ µm) of total energy. Due to the large distance between the sun and the earth (1.495×10^8 km) the beam radiation received from the sun on the earth is almost parallel.

3.2 SOLAR CONSTANT

The sun, being at a very large distance from the earth, solar rays subtend an angle of only 32 minutes on earth, as shown in Figure 3.1. Energy flux received from the sun before entering the earth's atmosphere, is a constant quantity.

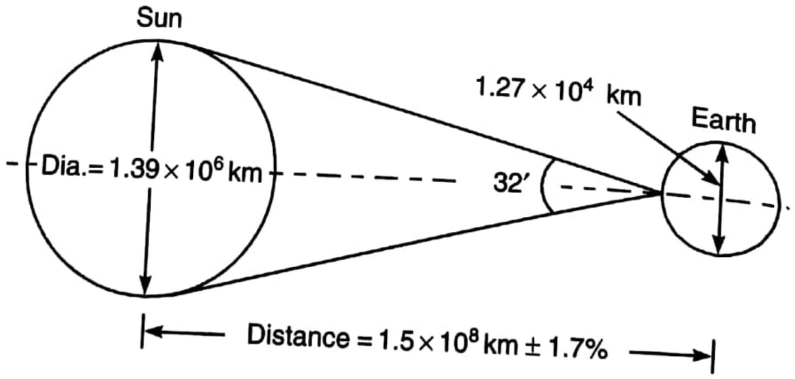

Figure 3.1 Sun–Earth geometry.

The solar constant, I_{sc}, is the energy from the sun received on a unit area perpendicular to the solar rays at the mean distance from the sun outside the atmosphere. Based on the experimental measurements, the standard value of the solar constant is 1367 W/m^2 or 1.958 langley per minute (1 langley/min is the unit, equivalent to 1 cal/cm^2/min). In terms of other units, I_{sc} = 432 Btu/ft^2/h or 4.921 MJ/m^2/h.

3.3 SPECTRAL DISTRIBUTION OF EXTRATERRESTRIAL RADIATION

Extraterrestrial radiation is the measure of solar radiation that would be received in the absence of atmosphere. A typical spectral distribution of extraterrestrial radiation is shown in Figure 3.2. The curve rises sharply with the wavelength and reaches the maximum value of 2074 W/m^2/µm at a wavelength of 0.48 µm. It then decreases asymptotically to zero, showing that 99% of the sun's radiation is obtained up to a wavelength of 4 µm.

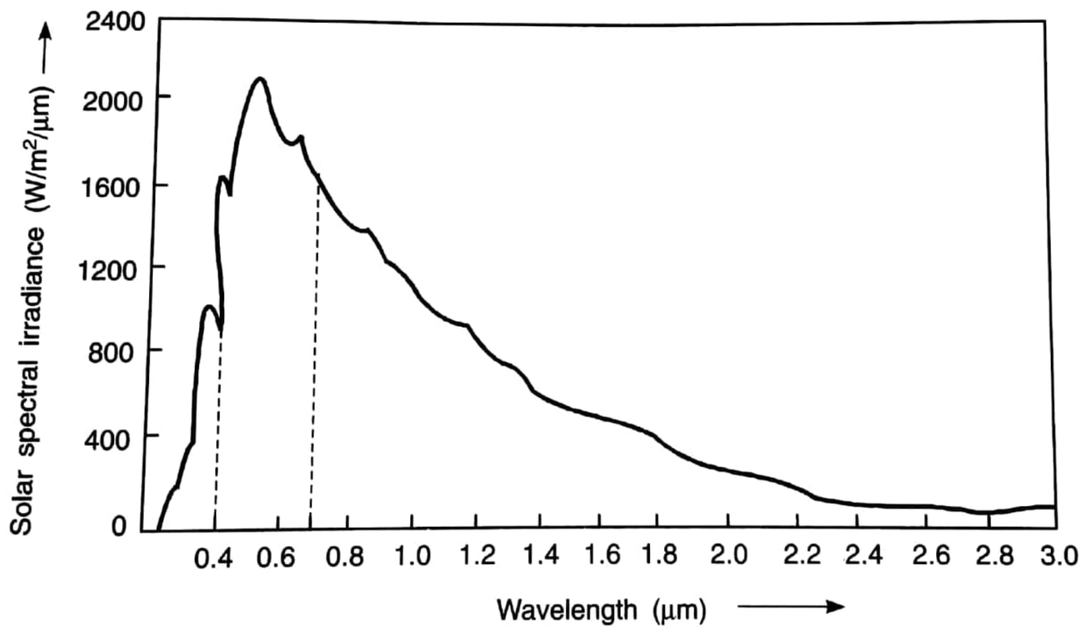

Figure 3.2 Spectral distribution of extraterrestrial radiation.

The distance between the sun and the earth varies due to the elliptical motion of the earth. Accordingly, the extraterrestrial flux also varies, which can be calculated (on any day) by the equation

$$I_n = I_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right) \tag{3.1}$$

where n is the day of the year counted from the first day of January.

Solar radiation reaching the earth is essentially equivalent to blackbody radiation. Using the Stefan–Boltzmann law, the equivalent blackbody temperature is 5779 K for a solar constant of 1367 W/m^2.

3.4 TERRESTRIAL SOLAR RADIATION

For utilisation of solar energy, a study is required to be carried out of radiations received on the earth's surface. Solar radiations pass through the earth's atmosphere and are subjected to scattering and atmospheric absorption. A part of scattered radiation is reflected back into space.

Short wave ultraviolet rays are absorbed by ozone and long wave infrared rays are absorbed by CO_2 and water vapours. Scattering is due to air molecules, dust particles and water droplets that cause attenuation of radiation as detailed in Figure 3.3. Minimum attenuation takes place in a clear sky when the earth's surface receives maximum radiation.

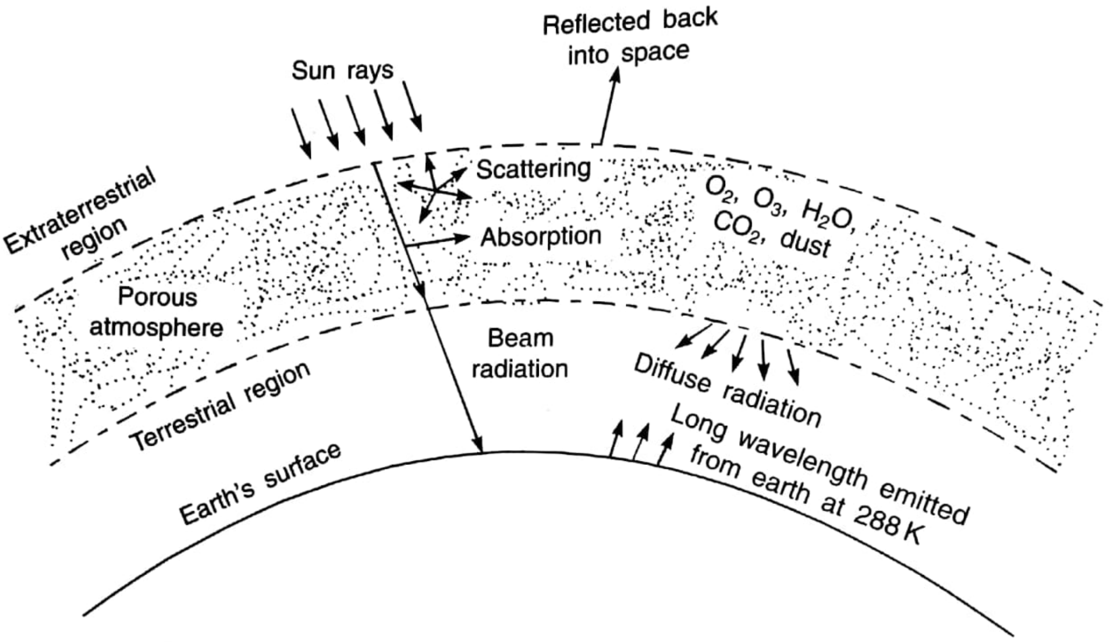

Figure 3.3 Solar radiation atmospheric mechanisms.

The terms pertaining to solar radiation are now defined as below:

Beam radiation (I_b): Solar radiation received on the earth's surface without change in direction, is called *beam* or *direct radiation.*

Diffuse radiation (I_d): The radiation received on a terrestrial surface (scattered by aerosols and dust) from all parts of the sky dome, is known as *diffuse radiation.*

Total radiation (I_T): The sum of beam and diffuse radiations ($I_b + I_d$) is referred to as total radiation. When measured at a location on the earth's surface, it is called *solar insolation* at the place. When measured on a horizontal surface, it is called *global radiation* (I_g).

Sun at zenith: It is the position of the sun directly overhead.

Air mass (AM): It is the ratio of the path length of beam radiation through the atmosphere, to the path length if the sun were at zenith. At sea level AM = 1, when the sun is at zenith or directly overhead; AM = 2 when the angle subtended by zenith and line of sight of the sun is 60°; AM = 0 just above the earth's atmosphere. At zenith angle θ_z, the air mass is calculated as (see Figure 3.4):

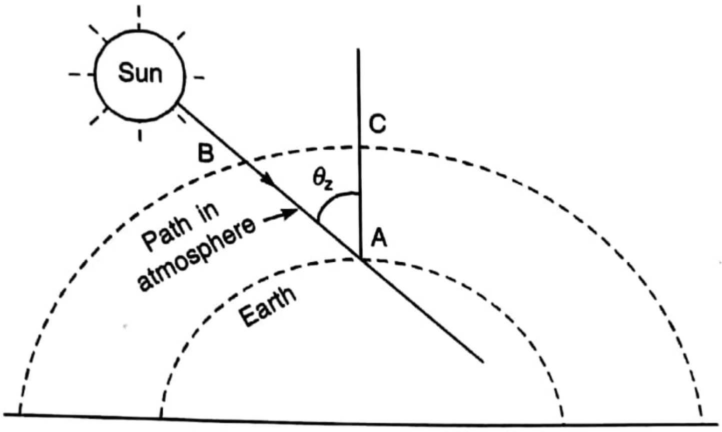

Figure 3.4 Sun rays passing through atmosphere.

$$\text{Air mass, AM} = \frac{AB}{AC} = \sec \theta_z \tag{3.2}$$

During winter, the sun is low and hence the air mass is higher and vice versa during summer.

Irradiance (W/m^2): The rate of incident energy per unit area of a surface is termed *irradiance*.

Albedo: The earth reflects back nearly 30% of the total solar radiant energy to the space by reflection from clouds, by scattering and by reflection at the earth's surface. This is called the *albedo* of the earth's atmosphere system.

3.5 SOLAR RADIATION GEOMETRY

Solar radiation varies in intensity at different locations on the earth, which revolves elliptically around the sun. For the calculation of solar radiation, the position of a point P on the earth's surface with regard to sun's rays can be located, if the latitude ϕ, the hour angle ω for the point and the sun's declination δ are known. These basic angles for a location P on the northern hemisphere are shown in Figure 3.5 and defined as follows:

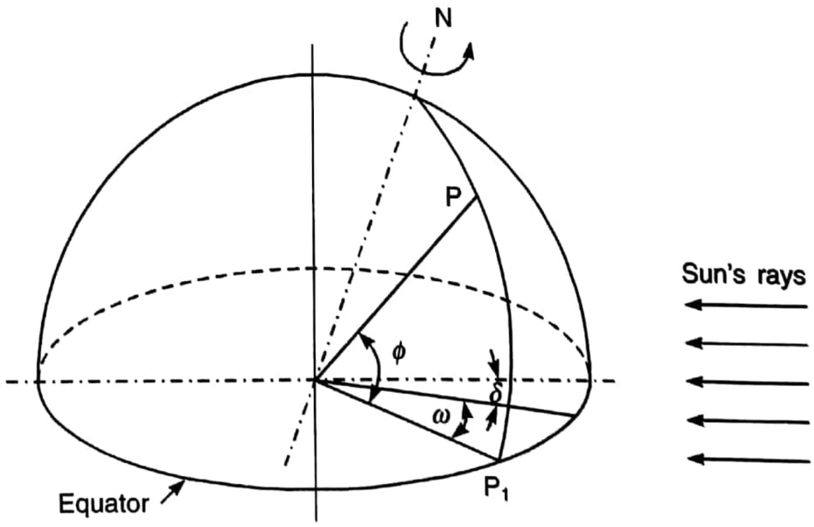

Figure 3.5 Latitude ϕ, hour angle ω and sun's declination δ.

Latitude (ϕ): The latitude ϕ of a place is the angle subtended by the radial line joining the place to the centre of the earth, with the projection of the line on the equatorial plane. Conventionally, the latitude for northern hemisphere is measured positive.

Declination (δ): Declination δ is the angle subtended by a line joining the centres of the earth and the sun with its projection on the earth's equatorial plane. Declination occurs as the axis of the earth is inclined to the plane of its orbit at an angle 66½°, as shown in Figure 3.6.

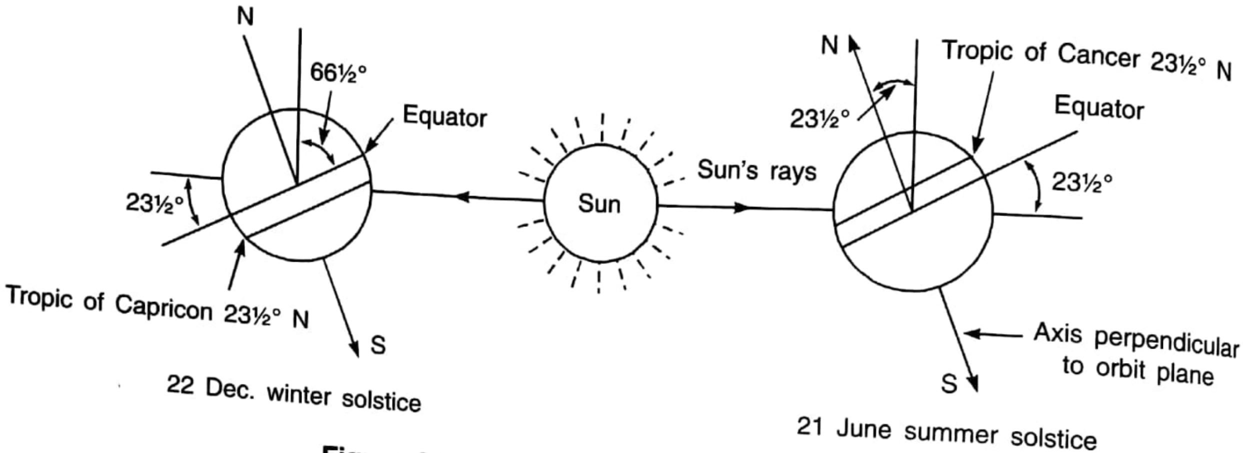

Figure 3.6 Tropics and northern hemisphere.

The declination angle changes from a maximum value of +23.45° on June 21 to a minimum of –23.45° on December 22. The declination is zero on two equinox days, i.e., March 22 and September 22. The angle of declination may be calculated as suggested by Cooper (1969)

$$\delta \text{ (in degrees)} = 23.45 \sin\left[\frac{360}{365}(284 + n)\right] \tag{3.3}$$

where n is the total number of days counted from first January till the date of calculation. [For example for June 21, 2004, $n = 31 + 29 + 31 + 30 + 31 + 21 = 173$]

The variation of declination angle δ with the nth day of the year is shown in Figure 3.7.

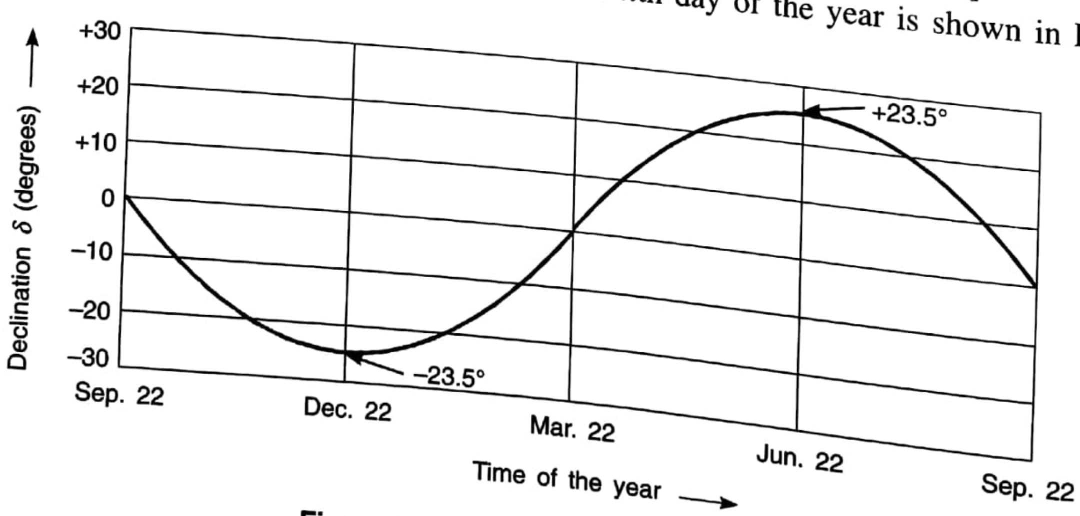

Figure 3.7 Variation of declination angle.

Hour angle (ω): Hour angle ω is the angle through which the earth must rotate to bring the meridian of the point directly under the sun (Figure 3.5). It is the angular measure of time at the rate of 15° per hour. Hour angle is measured from noon, based on local apparent time being positive in the afternoon and negative in the forenoon.

Altitude angle (α): It is a vertical angle between the direction of the sun's rays (passing through the point) and its projection on the horizontal plane (Figure 3.8).

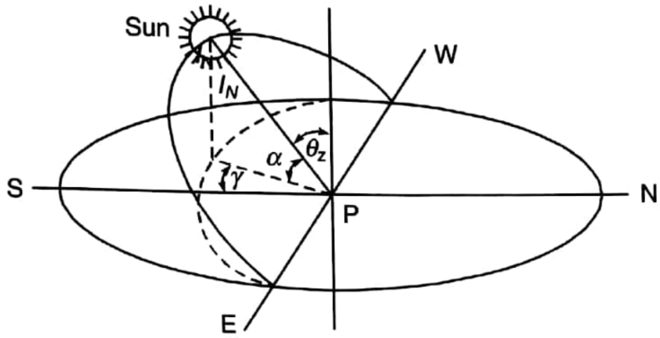

Figure 3.8 Sun's zenith, altitude and azimuth angles (northern hemisphere).

Zenith angle (θ_z): It is the vertical angle between the sun's rays and the line perpendicular to the horizontal plane through the point. It is the complimentary angle of the sun's altitude angle. Thus,

$$\theta_z + \alpha = \frac{\pi}{2}$$

Surface azimuth angle (γ): It is an angle subtended in the horizontal plane of the normal to the surface on the horizontal plane (Figure 3.8). By convention, the angle is taken positive if the normal is west of south and negative when east of south in northern hemisphere, and vice versa for southern hemisphere.

Tilted surface

The basic angles for a location P on a tilted surface are shown in Figure 3.9.

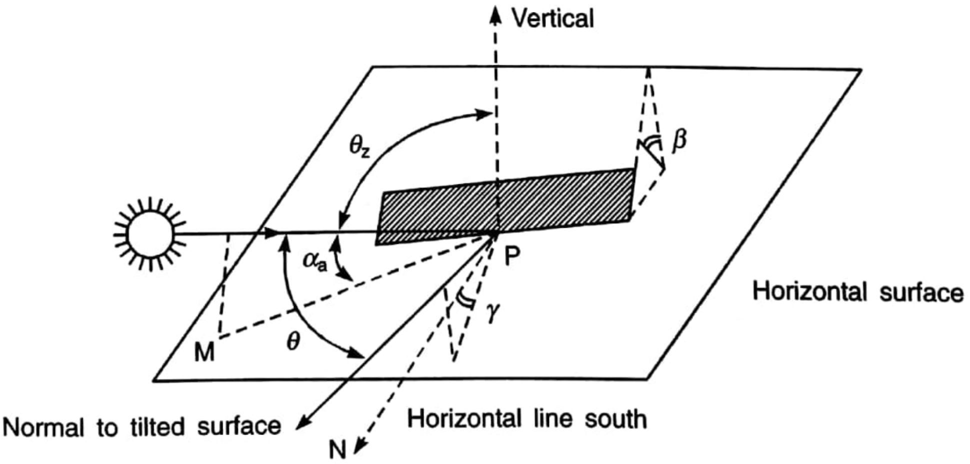

Figure 3.9 Diagram showing the angle of incidence θ, the zenith angle θ_z, the solar altitude angle α_a, the slope β, and the surface azimuth angle γ for a tilted surface.

Slope (β): It is an angle made by the plane surface with the horizontal surface. The angle is taken as positive for a surface sloping towards south, and negative for a surface sloping north (Figure 3.9).

3.6 COMPUTATION OF COS θ FOR ANY LOCATION HAVING ANY ORIENTATION

To compute the beam energy falling on a surface having any orientation, the incident beam flux I_b is multiplied by cos θ, where θ is the angle between the incident beam and the normal to the tilted surface (Figure 3.9). The angle θ depends on the position of the sun in the sky.

A general equation showing the relation of angles is

$$\begin{aligned}\cos\theta &= \sin\phi(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta)\\ &\quad + \cos\phi(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta)\\ &\quad + \cos\delta\sin\gamma\sin\omega\sin\beta \end{aligned} \tag{3.4}$$

Use of Eq. (3.4) can be demonstrated as:

(i) For a vertical surface, $\beta = 90°$. Therefore,

$$\cos\theta = \sin\phi\cos\delta\cos\gamma\cos\omega - \cos\phi\sin\delta\cos\gamma + \cos\delta\sin\gamma\sin\omega \tag{3.5}$$

(ii) For a horizontal surface, $\beta = 0°$. Therefore,

$$\cos\theta = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega \tag{3.6}$$

In this case, the angle θ is the zenith angle θ_z (shown in Figure 3.9).

(iii) In northern hemisphere the sun during winter is towards south. For a surface facing due south, $\gamma = 0°$. Therefore,

$$\begin{aligned}\cos\theta &= \sin\phi(\sin\delta\cos\beta + \cos\delta\cos\omega\sin\beta)\\ &\quad + \cos\phi(\cos\delta\cos\omega\cos\beta - \sin\delta\sin\beta)\\ &= \sin\delta\sin(\phi - \beta) + \cos\delta\cos\omega\cos(\phi - \beta)\end{aligned} \tag{3.7}$$

(iv) For a vertical surface facing due south, $\beta = 90°$, $\gamma = 0°$. Therefore,

$$\cos\theta = \sin\phi\cos\delta\cos\omega - \cos\phi\sin\delta \tag{3.8}$$

Solar azimuth angle (γ_s)

It is an angle in the horizontal plane between the line due south and projection of beam radiation on the horizontal plane. Conventionally, the solar azimuth angle is considered positive if the projection of the sun beam is west of south and negative if east of south in the northern hemisphere.

3.7 SUNRISE, SUNSET AND DAY LENGTH

The times of sunrise and sunset and the duration of the day-length depend upon the latitude of the location and the month in the year. At sunrise and sunset, the sunlight is parallel to the ground surface with a zenith angle of 90°. The hour angle pertaining to sunrise or sunset (ω_s) is obtained from Eq. (3.6) as

$$\cos \omega_s = -\tan \phi \tan \delta$$

or

$$\omega_s = \cos^{-1}(-\tan \phi \tan \delta) \qquad (3.9)$$

The value of hour angle corresponding to sunrise is positive, and negative corresponding to sunset. The total angles between sunrise and sunset is given by

$$2\omega_s = 2\cos^{-1}(-\tan \phi \tan \delta) \qquad (3.10)$$

Since 15° of hour angle corresponds to one hour, the corresponding day-length (T_d) in hours is given by

$$T_d = \frac{2}{15}\cos^{-1}(-\tan \phi \tan \delta) \qquad (3.11)$$

Local apparent time (LAT)

The time used for calculating the hour angle ω is the 'local apparent time' which is not the same as the 'local clock time'. It can be obtained from the local time observed on a clock by applying two corrections. The first correction arises due to the difference between the longitude of a location and the meridian on which the standard time is determined. This correction has a magnitude of 4 minute for each degree difference in longitude. The other correction is known as the 'equation of time correction' which is required due to the fact that the earth's orbit and the rate of rotation are subject to certain fluctuations. This correction is applied by results of experimental observations as plotted in Figure 3.10.

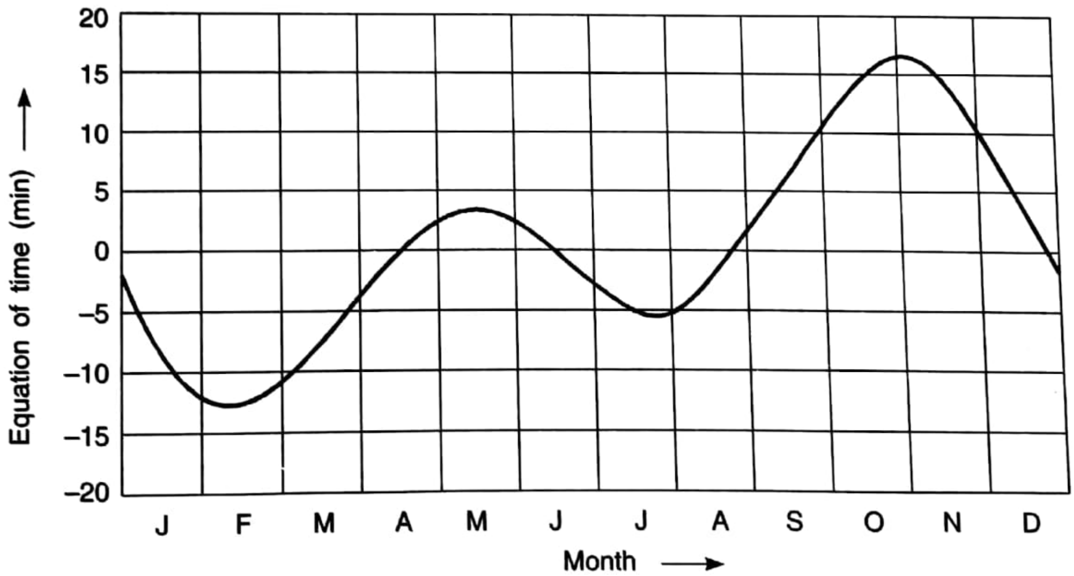

Figure 3.10 Graph for the 'equation of time correction'.

Therefore,

$$\text{Local apparent time (LAT)} = \text{Standard time} \pm 4\,(\text{Standard time longitude} - \text{Longitude of location}) + (\text{Time correction}) \qquad (3.12)$$

The positive sign in the first correction is for the western hemisphere while the negative sign is applicable for the eastern hemisphere.

EXAMPLE 3.1

Determine the local apparent time corresponding to 13 : 30 IST on July 1, at Delhi (28°35′ N, 77°12′ E). The 'equation of time correction' on July 1 from Figure 3.10 is −4 minutes. In India, the standard time is based on 82°30′ E.

Solution

$$\begin{aligned}
\text{Local apparent time} &= 13.50 \text{ h} - 4\,[(82.50) - (77.2)] \text{ min} + (-4 \text{ min}) \\
&= 13.50 \text{ h} - 4\,(82.50 - 77.2) \text{ min} - 4 \text{ min} \\
&= 13.50 \text{ h} - 21.20 \text{ min} - 4 \text{ min} \\
&= 13.50 \text{ h} - 25.20 \text{ min} \\
&= 13.50 \text{ h} - 0.42 \text{ h} \\
&= 13.08 \text{ h} = 13 \text{ h } 4 \text{ min } 48 \text{ s}
\end{aligned}$$

3.8 EMPIRICAL EQUATION FOR ESTIMATING THE AVAILABILITY OF SOLAR RADIATION

The measurement of solar radiation at every location is not feasible, so engineers have developed empirical equations by utilising the meteorological data like the number of sunshine hours, the days-length and the number of clear days. For accurate calculations, the hourly, the daily and the monthly time scales are used. Angstrom (1924) suggested a linear equation as follows for determining the amount of sunshine at a given location.

$$\frac{H_g}{H_c} = a + b\left(\frac{D_L}{D_{max}}\right) \tag{3.13}$$

where

H_g = monthly average of daily global radiation on a horizontal surface at a given location, in $MJ/m^2/day$

H_c = monthly average of daily global radiation on a horizontal surface at the same location on a clear sky day, in $MJ/m^2/day$

D_L = monthly average measured solar day length, in hours

D_{max} = monthly average of the longest day-length, in hours

a, b = constants for the location.

It is difficult to define a clear sky day, so it was proposed that H_c in Eq. (3.13) should be replaced by H_o. Here, H_o is the monthly average of daily extra terrestrial radiation that would fall on a horizontal surface at the given location. Thus,

$$\frac{H_g}{H_o} = a + b\left(\frac{D_L}{D_{max}}\right) \tag{3.14}$$

The values of a and b obtained for 20 Indian cities by conducting a city-wise regression analysis are given in Table 3.1.

Table 3.1 Constants *a* and *b* in Eq. (3.14) for 20 Indian cities

Location	*a*	*b*	*Mean error per cent*
Ahmedabad	0.28	0.48	3.0
Bangalore	0.18	0.64	3.9
Bhavnagar	0.28	0.47	2.8
Bhopal	0.27	0.50	–
Kolkata	0.28	0.42	1.3
Goa	0.30	0.48	2.1
Jodhpur	0.33	0.46	2.0
Kodaikanal	0.32	0.55	2.9
Chennai	0.30	0.44	3.5
Mangalore	0.27	0.43	4.2
Minicoy	0.26	0.39	1.4
Nagpur	0.27	0.50	1.6
New Delhi	0.25	0.57	3.0
Pune	0.31	0.43	1.9
Roorkee	0.25	0.56	–
Shillong	0.22	0.57	3.0
Srinagar	0.35	0.40	4.7
Trivandrum	0.37	0.39	2.5
Vidisha	0.27	0.50	–
Vishakhapatnam	0.28	0.47	1.2

The value of H_o can be obtained by the following empirical equation

$$H_o = \frac{24}{\pi} I_{sc}\left(1 + 0.033 \cos \frac{360n}{365}\right)(\omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s) \tag{3.15}$$

where

I_{sc} = solar constant per hour = 1367 W/m^2 in SI units

ω_s = sunset hour angle

n = day of the year.

EXAMPLE 3.2

At Nagpur, the following observations were made:

Theoretical maximum possible sunshine hours = 9.5 h

Average measured length of a day during April = 9.0 h

Solar radiation for a clear day, H_o = 2100 kJ/m^2/day

Constants: a = 0.27, b = 0.50.

Calculate the average daily global radiation.

Solution

$$H_g = H_o\left[a + b\left(\frac{D_L}{D_{max}}\right)\right]$$

$$= 2100\left[0.27 + 0.50\left(\frac{9.0}{9.5}\right)\right]$$

$$= 1554 \text{ kJ/m}^2\text{/day}$$

Monthly average daily diffuse radiation

As a result of study of field data conducted by Liu and Jordan, they arrived at a result that the daily diffuse to global radiation ratio could be correlated with the daily global to extraterrestrial radiation ratio. It was expressed by a cubic equation

$$\frac{H_d}{H_g} = 1.390 - 4.027\,K_T + 5.531\,K_T^2 - 3.108\,K_T^3 \tag{3.16}$$

where

H_d = monthly average for daily diffuse radiation on a horizontal surface, in kJ/m^2/day

$$K_T = \frac{H_g}{H_o} = \text{monthly average clearness index.} \tag{3.17}$$

It was indicated by Kreith that Eq. (3.16) was obtained with a value of 1394 W/m^2 for the solar constant.

When the Indian data was analyzed, two linear equations were finalized.

$$\frac{H_d}{H_g} = 1.411 - 1.696\,K_T \tag{3.18}$$

$$\frac{H_d}{H_g} = 1.354 - 1.570\,K_T \tag{3.19}$$

The above equations provide similar results, and are valid for

$$0.3 < \left(\frac{H_d}{H_g}\right) < 0.7$$

Solar radiation on an inclined surface

The total solar radiation incident on a surface has three components.

(i) Beam solar radiation

(ii) Diffuse solar radiation

(iii) Reflected solar radiation from ground and surroundings.

To obtain maximum solar energy, flat plate collectors always face the sun using a sun tracking equipment. It, therefore, infers that the solar radiation collecting appliances are tilted at an angle to the horizontal. However, the measuring instruments generally measure the values of solar radiation falling on a horizontal surface. Thus, mathematical analysis is necessary to convert the values measured on horizontal surfaces to the corresponding values obtainable on the inclined surfaces.

Beam radiation

Generally, the inclined surface faces south to obtain maximum solar radiation even during winter, i.e., $\gamma = 0°$. Therefore,

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

While for a horizontal surface ($\theta = \theta_z$), and therefore,

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

The ratio of beam radiation falling on an inclined surface to that falling on a horizontal surface is termed *tilt factor for beam radiation*. It is represented by the notation R_b. Thus,

$$R_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\sin\delta\sin(\theta - \beta) + \cos\delta\cos\omega\cos(\phi - \beta)}{\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega} \quad (3.20)$$

Other equations for R_b can be derived complying to conditions, when the inclined surface is oriented in different directions with $\gamma \neq 0°$.

Diffuse radiation

The ratio of diffuse radiation falling on a tilted surface to that falling on a horizontal surface is known as *tilt factor for diffuse radiation*, symbolized by R_d. Considering the sky as an isotropic source of diffuse radiation, R_d for an inclined surface with a slope β may be calculated from

$$R_d = \frac{1 + \cos\beta}{2} \quad (3.21)$$

where $(1 + \cos\beta)/2$ is the *radiation shape factor* for an inclined surface with reference to the sky.

Reflected radiation

Since $(1 + \cos\beta)/2$ is the *radiation shape factor* for an inclined surface with reference to the sky, so $(1 - \cos\beta)/2$ is the radiation shape factor for the surface with respect to surroundings. Accepting that the beam and diffuse radiation after reflection from the ground is diffuse and isotropic, and the reflectivity is ρ, the *tilt factor for reflected radiation* is expressed as:

$$R_r = \frac{\rho(1 - \cos\beta)}{2} \quad (3.22)$$

Total radiation

The total radiation flux falling on an inclined surface at any instant is expressed as:

$$I_T = I_b R_b + I_d R_d + (I_b + I_d) R_r \quad (3.23)$$

Dividing Eq. (3.23) by I_g, we get the ratio of solar flux reaching on an inclined surface at any instant to that on a horizontal surface. That is,

$$\frac{I_T}{I_g} = \left(1 - \frac{I_d}{I_g}\right) R_b + \frac{I_d}{I_g} R_d + R_r \qquad (\because \quad I_g = I_b + I_d) \tag{3.24}$$

For evaluating R_r, the diffuse reflectivity ρ can be taken as 0.2 for the surface of concrete or grass and 0.7 for a surface with snow cover.

The monthly average of daily radiation reaching a tilted surface is required in dealing with liquid flat-plate collectors and in other applications. Liu and Jordan have suggested that the ratio of the daily radiation falling on an inclined surface (H_T) to the daily global radiation on an horizontal surface (H_g) can be represented by an equation similar to Eq. (3.24). Thus,

$$\frac{H_T}{H_g} = \left(1 - \frac{H_d}{H_g}\right) R_b + \frac{H_d}{H_g} R_d + R_r \tag{3.25}$$

For a surface facing south ($\gamma = 0°$), Liu and Jordan proposed:

$$R_b = \frac{\omega_{si} \sin\delta \sin(\phi - \beta) + \cos\delta \sin\omega_{si} \cos(\phi - \beta)}{\omega_{sh} \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_{sh}} \tag{3.26}$$

$$R_d = \frac{1 + \cos\beta}{2} \tag{3.27}$$

$$R_r = \rho\left(\frac{1 - \cos\beta}{2}\right) \tag{3.28}$$

where ω_{si} and ω_{sh} in Eq. (3.26) are sunrise or sunset hour angles (in radians) for an inclined surface and a horizontal surface respectively.

EXAMPLE 3.3

Find the angle subtended by beam radiation with the normal to a flat-plate collector at 9 a.m. for the day on November 3, 2003. The collector is in Delhi (28° 35′ N, 77° 12′ E), inclined at an angle of 36° with the horizontal and is facing due south.

Solution

Given $\gamma = 0°$ and $n = 307$ for November 3, 2003

From Eq. (3.3),

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + 307)\right]$$

$$= 23.45 \sin 582.9°$$

$$= 23.45\,(-0.681) = -15.96°$$

At 9.00 a.m. (local apparent time) $\omega = 45°$. From Eq. (3.7),

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

or $\cos\theta = \sin(-15.96°)\sin(28.58° - 36°) + \cos(-15.96°)\cos 45° \cos(28.58° - 36°)$

$= (-0.275)(-0.129) + 0.961 \times 0.707 \times 0.99$

$= 0.709$

$\therefore \quad \theta = 44.85°$

EXAMPLE 3.4

Compute the monthly average hourly solar flux received on a flat-plate collector facing due south ($\gamma = 0°$) having a slope of 12°. The collector is located at a place 15° 00′ N on 20th day of October. The data given are:

Time 11 : 12 h (local apparent time)
H_g = 2408 kJ/m²/h
H_d = 1073 kJ/m²/h
Ground reflectivity, $\rho = 0.25$, $\omega = 7.5°$

Solution

Given $\gamma = 0°$ and $n = 293$ for 20th October.

From Cooper's equation, given in Eq. (3.3)

$$\delta = 23.45 \sin\left[\frac{360}{365}(284 + 293)\right]$$

$$= -11.40°$$

Substituting the given data in Eq. (3.20), we have

$$R_b = \frac{\sin(-11.4°)\sin(15° - 12°) + \cos(-11.40°)\cos 7.5° \cos(15° - 12°)}{\sin 15° \sin(-11.4°) + \cos 15° \cos(-11.40°)\cos 7.5°}$$

$$= 1.08$$

From Eqs. (3.21) and (3.22),

$$R_d = \left(\frac{1 + \cos 12°}{2}\right) = 0.989$$

$$R_r = 0.2\left(\frac{1 - \cos 12°}{2}\right) = 0.0022$$

Equation (3.25) is valid for evaluating the average daily radiation reaching on an inclined surface if the value of ω is taken at the middle of the hour. Similarly, the monthly average hourly value H_T can be calculated by using a representative day of the month. The modified form of Eq. (3.25) becomes

$$\frac{H_T}{H_g} = \left(1 - \frac{H_d}{H_g}\right)R_b + \frac{H_d}{H_g}R_d + R_r$$

Thus,

$$\frac{H_T}{H_g} = \left(1 - \frac{1073}{2408}\right) 1.08 + \frac{1073}{2408} 0.989 + 0.0022$$

$$= 1.04165$$

Therefore,

$$H_T = 2508 \text{ kJ/m}^2\text{/h}$$

3.9 SOLAR RADIATION MEASUREMENTS

The solar radiation data bank is required for many purposes, e.g. solar energy appliances, hydrology and weather forecast. A few instruments used to measure solar radiation are discussed below:

Pyranometer

The pyranometer measures global or diffuse radiation on a horizontal surface. It covers total hemispherical solar radiation with a view angle of 2π steradians.

The pyranometer designed by the Eppley laboratories, USA, operates on the principle of thermopile. It consists of a black surface which heats up when exposed to solar radiation. Its temperature rises until the rate of heat gain from solar radiation equals the heat loss by conduction, convection and radiation. On the black surface the hot junctions of a thermopile are attached, while the cold junctions are placed in a position such that they do not receive the radiation. An electrical output voltage (0 to 10 mV range) generated by the temperature difference between the black and the white surfaces indicates the intensity of solar radiation. The output can be obtained on a strip chart or on a digital printout over a period of time. This is a measure of global radiation.

The pyranometer can also measure diffuse sky radiation by providing a shading ring or disc to shade the direct sun rays. The shading ring is provided with an arrangement such that its plane is parallel to the plane of the sun's path across the sky. Consequently, it shades the thermopile element at all times from direct sunshine and the pyranometer measures only the diffuse radiation obtained from the sky. A continuous record can be obtained either on an electronic chart or on an integrated digital printout system. As the shading ring blocks a certain amount of diffuse sky radiation besides direct radiation, a correction factor is applied to the measured value.

Data acquisition system for measurement of solar radiation

This system does not require an instrument operator to measure the radiation data. With a personal computer (PC), the system uses an analog-to-digital conversion (ADC) card, which serves as a vital interface between the sensor and the PC to obtain analog data from the sensor. The data so received is processed in the PC with an appropriate software.

The radiation falling on the pyranometer generates thermo-electric emf which is fed into one of the channels of the ADC card provided with the PC. The numerical value of the instantaneous voltage in the digital form is stored in a Programmable Peripheral Interface (PPI). A printout of the solar flux can be obtained by processing the data. The block diagram of such a radiation measuring system is shown in Figure 3.11.

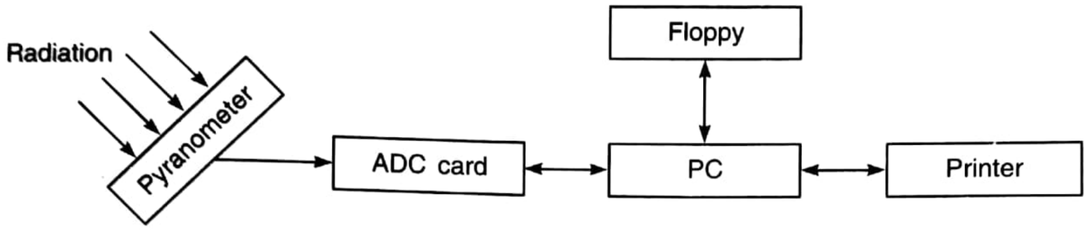

Figure 3.11 Block diagram of a radiation measuring system.

Pyrheliometer

A pyrheliometer is an instrument which measures beam radiation on a surface normal to the sun's rays. The sensor is a thermopile and its disc is located at the base of a tube whose axis is aligned in the direction of the sun's rays. Thus, diffuse radiation is blocked from the sensor surface. The pyrheliometer designed by Eppley Laboratories, USA, consists of bismuth silver thermopile, with 15 temperature-compensated junctions connected in series. It is mounted at the end of a cylindrical tube, with a series of diaphragms (the aperture is limited to an angle of 5.42°). The instrument is mounted on a motor-driven heliostat which is adjusted every week to cover changes in the sun's declination. The output of the pyreheliometer can either be recorded on a strip chart recorder or integrated over a suitable time period. The pyrheliometer readings give data for atmospheric turbidity and provide a clearness index.

Sunshine recorder

The duration in hours of bright sunshine in a day is measured by a sunshine recorder. It consists of a glass sphere installed in a section of spherical metal bowl, having grooves for holding a recorder card strip. The glass sphere is adjusted to focus sun rays to a point on the card strip. On a bright sunshine day, the focused image burns a trace on the card. Through the day the sun moves across the sky, the image moves along the strip. The length of the image is a direct measure of the duration of bright sunshine.

3.10 SOLAR RADIATION DATA FOR INDIA

India lies within the latitudes of 7° N and 37° N, with annual intensity of solar radiation between 400 and 700 cal/cm^2/day. Most parts of India receive 4–7 kWh/m^2/day of solar radiation with 250–300 sunny days in a year. The annual average daily global solar radiation in India (in kWh/m^2/day) is shown in Figure 3.12. A similar map can also be drawn for average daily diffuse radiation.

The highest annual radiation energy is received in the western Rajasthan while the north-eastern region receives the lowest annual radiation.

4

SOLAR THERMAL ENERGY COLLECTORS

4.1 INTRODUCTION

A solar thermal energy collector is an equipment in which solar energy is collected by absorbing radiation in an absorber and then transferring to a fluid. In general, there are two types of collectors:

Flat-plate solar collector: It has no optical concentrator. Here, the collector area and the absorber area are numerically the same, the efficiency is low, and temperatures of the working fluid can be raised only up to 100°C.

Concentrating-type solar collector: Here the area receiving the solar radiation is several times greater than the absorber area and the efficiency is high. Mirrors and lenses are used to concentrate the sun's rays on the absorber, and the fluid temperature can be raised up to 500°C. For better performance, the collector is mounted on a tracking equipment to face the sun always with its changing position.

In this chapter, both the above types of solar collectors are discussed in detail.

4.2 FLAT-PLATE COLLECTOR

A schematic cross-section of a flat-plate collector is shown in Figure 4.1. It consists of five major parts as mentioned below:

(i) A *metallic flat absorber plate* of high thermal conductivity made of copper, steel, or aluminium, and having black surface. The thickness of the metal sheet ranges from 0.5 mm to 1 mm.

(ii) *Tubes* or *channels* are soldered to the absorber plate. Water flowing through these tubes takes away the heat from the absorber plate. The diameter of tubes is around 1.25 cm, while that of the header pipe which leads water in and out of the collector and distributes it to absorber tubes, is 2.5 cm.

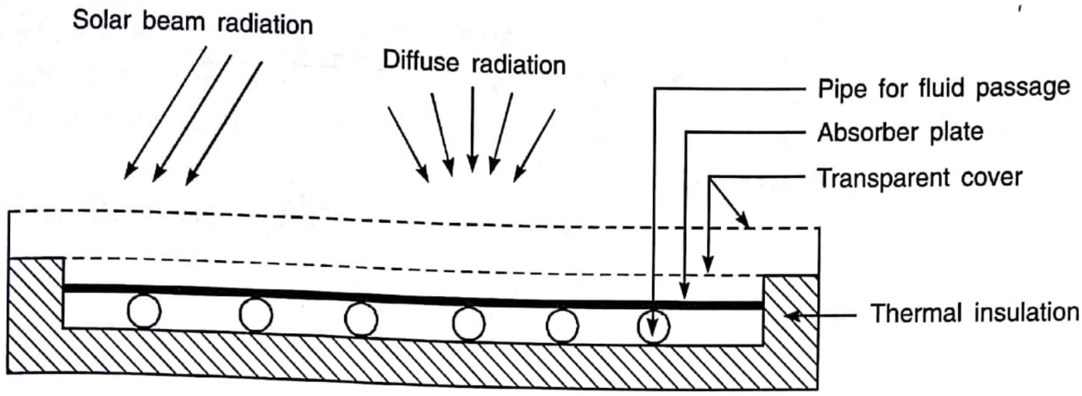

Figure 4.1 Schematic cross section of a flat-plate collector.

(iii) A *transparent toughened glass sheet* of 5 mm thickness is provided as the cover plate. It reduces convection losses through a stagnant air layer between the absorber plate and the glass. Radiation losses are also reduced as the spectral transmissivity of glass is such that it is transparent to short wave radiation and nearly opaque to long wave thermal radiation emitted by interior collector walls and absorbing plate.

(iv) Fibre glass insulation of thickness 2.5 cm to 8 cm is provided at the bottom and on the sides in order to minimize heat loss.

(v) A container encloses the whole assembly in a box made of metallic sheet or fibre glass.

In Figure 4.1, since the heat transfer fluid is liquid, so, this type of flat-plate collector is also known as liquid flat-plate collector.

The commercially available collectors have a face area of 2 m^2. The whole assembly is fixed on a supporting structure that is installed in a tilted position at a suitable angle facing south in the northern hemisphere.

For the whole year, the optimum tilt angle of collectors is equal to the latitude of its location. During winter, the tilt angle is kept 10–15° more than the latitude of the location while in summer it should be 10–15° less than the latitude.

4.3 EFFECT OF DESIGN PARAMETERS ON PERFORMANCE

There are many parameters that affect the performance of a flat-plate collector. However, four important parameters are discussed below:

4.3.1 Heat Transport System

Heat from the absorber plate is removed by continuous flow of a heat transport medium. When water is used, it flows through metal tubes that are welded to the absorber plate for effective heat transfer. Cold water enters the bottom header, flows upwards and gets warmed by the absorber. The hot water then flows out through the top header.

When air is used as the heat transfer fluid, an air stream flows at the rear side of the collector plate as shown in Figure 4.2. Fins welded to the plate increase the contact surface area. The rear side of air passages is insulated with mineral wool. Solar air heaters are utilised for drying agricultural products, space heating and seasoning of timber.

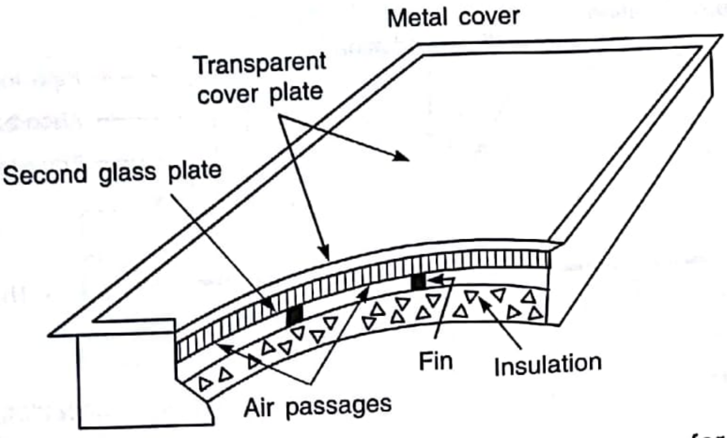

Figure 4.2 Solar collector with air as the heat transfer fluid.

4.3.2 Selective Surfaces

Absorber plate surfaces which provide high absorptivity for incoming solar radiation and low emissivity for outgoing radiation are termed *selective surfaces*. Solar radiation lies in short wavelength band up to 4 μm while the absorber plate emits long wave radiation with a maximum at 8.3 μm. Thus, a selective surface needs to have a high absorptivity for wavelengths shorter than 4 μm and a low emissivity for wavelengths longer than 4 μm. No natural surface is available which possesses selective radiation characteristics.

A selective surface is composed of a thin black metallic oxide coated on a bright metal base. Black coating is sufficiently thick to be a good solar radiation absorber. Bright metal base possesses low emissivity for thermal radiation. A successful selective surface can be developed with a black chrome ($Cr–Cr_2O_3$) coating. It is a metal dielectric Cr_2O_3 layer over a Cr particle/Cr_2O_3 composite prepared by electroplating on a steel base. An effective selective surface has solar absorptivity of about 0.95 and thermal emissivity close to 0.1. A selective surface of black chrome is durable with no degradation in performance even in humid atmosphere and operating temperature of 300°C. Selective surfaces are important for low concentration solar equipment operating at high temperatures. For high concentration devices the major requirement is high absorptance rather than low emittance.

4.3.3 Number of Covers

To minimize convection and radiation loss, a solar collector is provided with a transparent glass sheet over the absorber plate. Solar radiation incident on glass sheet passes through the glass cover. Glass sheet also absorbs heat radiation emitted by the hot absorber plate. Thus, the glass sheet cover reduces the heat loss coefficient to 10 $W/m^2 \cdot K$. Experiments show that with two glass covers, the heat loss coefficient further reduces to 4 $W/m^2 \cdot K$.

4.3.4 Spacing

The spacing between the absorber plate and the cover or between two covers also influences the performance of a flat-plate collector. The operating performance varies with the spacing as well as with tilt and service conditions and hence there is no way to specify the exact optimum spacing. However, researchers have suggested a spacing of 4 cm to 8 cm for improved performance. It is also observed that a large spacing reduces the collector area requirements.

4.4 LAWS OF THERMAL RADIATION

Solar energy reaches on the earth by radiation which is important for operation of solar collectors. Solar radiation is electromagnetic energy propagating through space at the speed of light. The sun emits radiation like a 'blackbody' whose surface temperature is 6000 K. Emission of energy with regard to wavelength is not uniform but depends on temperature. 'Planck's law' gives the relation of spectral emissive power with wavelength distribution of radiation and temperature as:

$$E_{\lambda b} = \frac{C_1}{\lambda^5} \frac{1}{(e^{C_2/\lambda T} - 1)} \tag{4.1}$$

where C_1 and C_2 are the Planck's first and second radiation constants respectively, λ is the wavelength and T is the temperature in kelvin. The numerical values of C_1 and C_2 are

$$C_1 = 3.7405 \times 10^{-16} \text{ W} \cdot \text{m}^2$$

$$C_2 = 0.01439 \text{ m} \cdot \text{K}$$

It is possible to calculate the wavelength pertaining to maximum intensity of blackbody radiation, as shown in Figure 4.3 which gives spectral radiation distribution of blackbody from a source at 6000 K, 1000 K and 400 K.

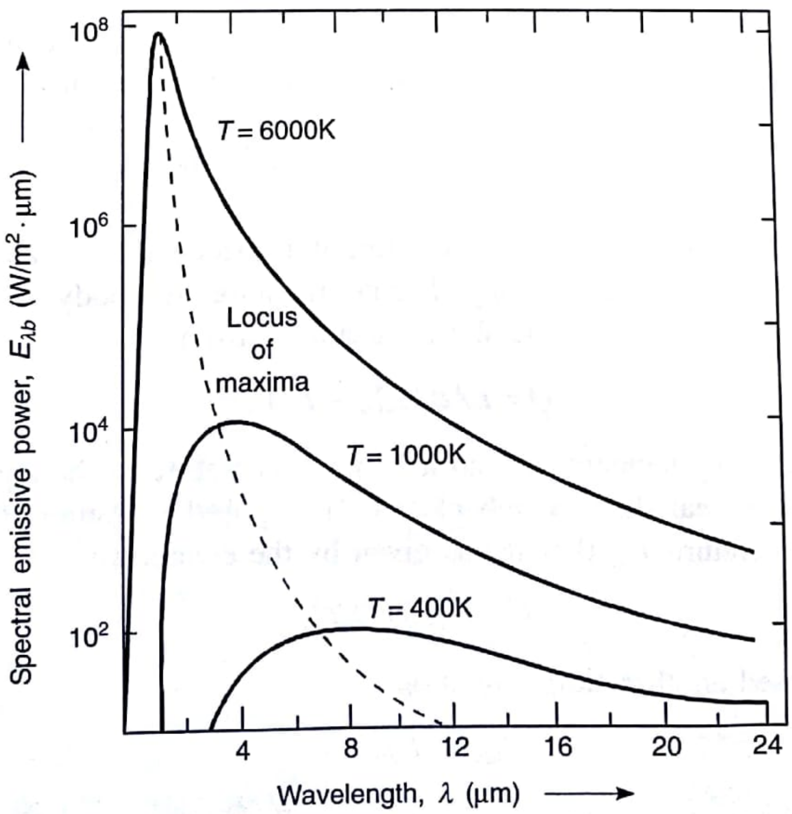

Figure 4.3 Thermal radiation graph against wavelength from a source at different temperatures.

The highest temperature 6000 K represents nearly the surface temperature of the sun (5762 K). The other two temperatures, i.e., 1000 K represents the high temperature solar heated surface while 400 K depicts the low temperature solar heated surface.

Energy emitted by a blackbody at temperature T over the wavelengths is expressed by

$$E_b = \int_0^\infty E_{\lambda b} d\lambda = \sigma T^4 \tag{4.2}$$

where $\sigma = 5.6697 \times 10^{-8}$ W/m$^2 \cdot$ K^4 and is called the Stefan–Boltzmann constant. The wavelength corresponding to maximum intensity of blackbody radiation at temperature T is expressed by Wien's Displacement law as

$$\lambda_{\max} T = 2897.8 \ \mu\text{m} \cdot \text{K} \tag{4.3}$$

It shows that an increase in temperature shifts the maximum blackbody radiation intensity towards the shorter wavelength.

The dotted line in Figure 4.3 indicates the displacement of wavelength for maximum intensity as given by Eq. (4.3). The radiation emitted by a real body is a fraction of the blackbody radiation, i.e.,

$$E = \varepsilon \sigma T^4 \tag{4.4}$$

where ε represents the emissivity of a real body surface and is always less than 1.

4.5 RADIATION HEAT TRANSFER BETWEEN REAL BODIES

Radiation exchange between two surfaces takes place from a hot to a cold body. The rate of exchange of heat energy between two closely spaced parallel bodies, one at a temperature T_1 and with emissivity ε_1 and the other at a temperature T_2 and with emissivity ε_2, is given by

$$Q_{\text{rad}} = \frac{\sigma A}{[(1/\varepsilon_1) + (1/\varepsilon_2)] - 1} (T_1^4 - T_2^4) \tag{4.5}$$

To evaluate the performance of a solar collector, it is necessary to calculate the radiation exchange between the collector and the sky. The net radiation to a body of surface area A with emittance ε and temperature T from the sky is calculated from

$$Q = \varepsilon A \sigma (T_{\text{sky}}^4 - T^4) \tag{4.6}$$

where T_{sky} is called the sky temperature and it is the temperature of the equivalent blackbody.

To estimate T_{sky}, for clear skies, Swinbank (1963) proposed a relation of sky temperature to local air ambient temperature T_{air} (kelvin) as given by the equation

$$T_{\text{sky}} = 0.0552\, T_{\text{air}}^{1.5} \tag{4.7}$$

Whiller (1967) proposed another simple relation,

$$T_{\text{sky}} = T_{\text{air}} - 12 \tag{4.8}$$

or the relation

$$T_{\text{sky}} = T_{\text{air}} - 6 \tag{4.9}$$

4.6 RADIATION OPTICS

Thermal radiation from a high temperature body to a lower temperature body causes transfer of heat through electromagnetic waves up to 0.1 μm–100 μm. The larger part of the terrestrial solar energy lies between 0.3 μm and 3 μm. Thermal radiation is in the infrared range and travels at the speed of light. When radiation strikes a body, a part is reflected, another is absorbed, and the remainder is transmitted through if the body is transparent. The law of conservation of energy dictates that the total sum of radiation components must be equal to incident radiation, i.e.,

$$I_\alpha + I_\rho + I_\tau = I \tag{4.10}$$

and

$$\alpha + \rho + \tau = 1 \tag{4.11}$$

where α, ρ and τ are absorptivity, reflectivity and transmissivity of the light-impinged body. I_α, I_ρ and I_τ are radiation components that are absorbed, reflected and transmitted respectively. The values of α, ρ and τ are always positive within the limits of 0 and 1.

For an opaque surface, $\tau = 0$, so

$$\alpha + \rho = 1$$

For a white surface which reflects all radiation, $\rho = \tau = 0$ and so $\alpha = 1$.

For a blackbody, α and τ are zero and $\rho = 1$ making it a body that absorbs all the energy incident on it.

4.7 TRANSMISSIVITY OF THE COVER SYSTEM

Transmissivity considering reflection only, when a light beam strikes a glass surface there are two losses—one is reflection loss from the top surface and the other is absorption loss as the beam passes through the glass material. First we find transmittance as if there is reflection loss only and then we find transmittance as if there is absorption loss only.

When a beam of light having intensity I_1 travelling in a transparent medium 1 strikes another transparent medium 2, a part of it is reflected and the major part is refracted (Figure 4.4).

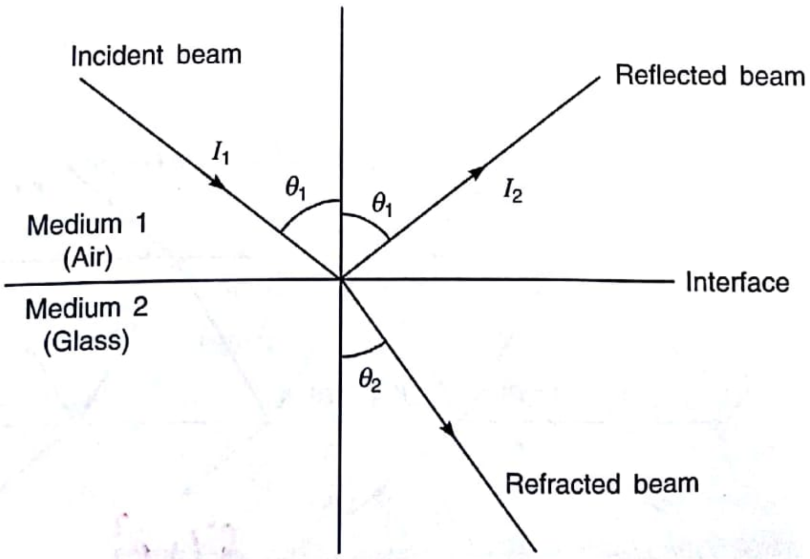

Figure 4.4 Reflection and refraction at the interface of two transparent media.

According to the Snell's law of refraction,

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} \tag{4.12}$$

where θ_1 = angle of incidence, θ_2 = angle of refraction and n_1, n_2 = refractive indices of the two media.

Reflectivity is expressed by, $\rho = I_2/I_1$, where I_2 is the reflected beam intensity and I_1 is the incident beam radiation. Also,

$$\rho = \frac{1}{2}(\rho_1 + \rho_2) \tag{4.13}$$

where ρ_1 and ρ_2 are the reflectivities for the two components of polarization—one parallel to the plane of incidence and the other perpendicular to this plane—as given below:

$$\rho_1 = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)}$$

$$\rho_2 = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)}$$

For radiation at normal incidence, $\theta_1 = 0$ and for this case

$$\rho = \rho_1 = \rho_2 = \frac{(n_2 - n_1)^2}{(n_2 + n_1)^2} \tag{4.14}$$

Transmissivity τ can be expressed similar to that for ρ, i.e.,

$$\tau = \frac{1}{2}(\tau_1 + \tau_2) \tag{4.15}$$

where τ_1 and τ_2 are the polarization components of transmissivity.

The cover material used in solar appliances requires transmission of radiation through a slab or sheet having two interfaces per cover where reflection-refraction takes place. The cover interfaces with air on both sides. Multiple reflections and refractions will occur as shown in Figure 4.5.

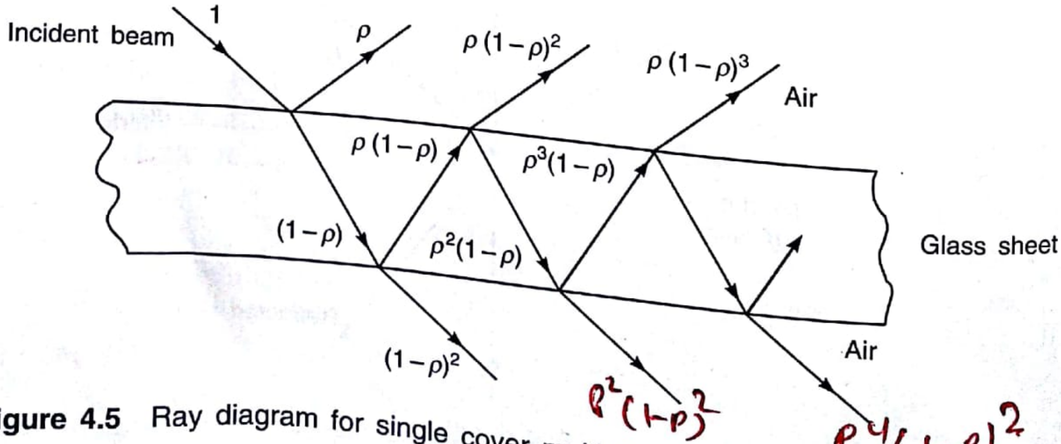

Figure 4.5 Ray diagram for single cover multiple reflections and refractions.

For each component of polarization, the incident beam depletes at the second surface. The amount of incidence beam reaching below the interface after reflection is only $(1-\rho)$, i.e., in case of a unit incident beam after reflection, only $(1-\rho)$ reaches the second interface. From this, $(1-\rho)^2$ passes through the interface and $\rho(1-\rho)$ is reflected back to the first interface, and the process is repeated. Summing up all the terms, the transmittance for a single cover is

$$\begin{aligned}\tau_1 &= (1-\rho_1)^2 + (1-\rho_1)^2\rho_1^2 + (1-\rho_1)^2\rho_1^4 + \cdots \\ &= (1-\rho_1)^2(1+\rho_1^2+\rho_1^4+\cdots) \\ &= (1-\rho_1)^2\frac{1}{1-\rho_1^2}\end{aligned}$$

or
$$\tau_1 = \frac{1-\rho_1}{1+\rho_1}$$

Similarly
$$\tau_2 = \frac{1-\rho_2}{1+\rho_2}$$

For a system of N covers and of the same material, therefore, we can write

$$\tau_1 = \frac{1-\rho_1}{1+(2N-1)\rho_2}$$

$$\tau_2 = \frac{1-\rho_2}{1+(2N-1)\rho_1} \tag{4.16}$$

4.7.1 Transmittance Considering Absorption Only

Transmissivity, based on absorption, in a transparent material sheet, can be explained by the Bouger's law, i.e.,

$$dI = -KI\,dx$$

where dI is the decrease in radiation intensity, I is the initial value of intensity, K is a constant of proportionality known as 'extinction coefficient', x is the distance travelled by radiation. Assuming that K is a constant in the solar spectrum range, then integrating the expression for dI, we get

$$\int_{I_0}^{I_L}\frac{dI}{I} = -K\int_0^L dx$$

or
$$\log I\Big|_{I_0}^{I_L} = -Kx\Big|_0^L$$

or
$$\log I_L - \log I_0 = -KL$$

or
$$I_L = I_0e^{-KL}$$

or
$$\tau_\alpha = \frac{I_L}{I_0} = e^{-KL} \tag{4.17}$$

where τ_α is the transmittance considering only absorption and L is distance travelled by radiation through the medium.

The extinction coefficient K is a physical property of the cover material. For clear white glass, the value of K is 0.04/cm, while for poor quality glass with greenish colour at its edges the value of K is 0.25/cm. A low value of K is preferred.

When the beam is incident at an angle θ_1, the path length through the cover would be $(L/\cos\theta_2)$, where θ_2 is the angle of refraction. Thus, Eq. (4.17) is modified as

$$\tau_\alpha = e^{-KL/\cos\theta_2}$$

The transmissivity of the system allowing for both absorption and reflection is given by

$$\tau = \tau_\alpha \tau_\rho$$

EXAMPLE 4.1

Estimate τ_α, τ_ρ and τ for a glass cover system with the given data:

Angle of incidence = 10°

Number of covers = 4

Thickness of each cover = 3 mm

Refractive index of glass relative to air = 1.52

Extinction coefficient of glass = 15 m^{-1}

Solution

$\theta_1 = 10°$, using Snell's law,

$$\frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2} \qquad (\theta_1 = 10°)$$

n_2/n_1 = refractive index of glass relative to air = 1.52 (given)

So,

$$\theta_2 = \sin^{-1}\left(\frac{\sin 10°}{1.52}\right) = 6.55°$$

$$\rho_1 = \frac{\sin^2(6.55° - 10°)}{\sin^2(6.55° + 10°)} = 0.044$$

$$\rho_2 = \frac{\tan^2(6.55° - 10°)}{\tan^2(6.55° + 10°)} = 0.041$$

$$\tau_{\alpha_1} = \frac{1 - 0.044}{1 + 7 \times 0.041} = 0.733$$

$$\tau_{\alpha_2} = \frac{1 - 0.041}{1 + 7 \times 0.044} = 0.742$$

$$\tau_\alpha = \frac{1}{2}(0.733 + 0.742) = 0.737$$

$$\tau_\rho = e^{-KL/\cos\theta_2}$$

Given in the problem

$$K = 15\ \text{m}^{-1}$$

$$L = 4 \times 3 \times 10^{-3}$$

$$\therefore \quad \tau_p = 0.836$$

and. $$\tau = \tau_\alpha \tau_p = 0.737 \times 0.836 = 0.616$$

4.7.2 Transmissivity–Absorptivity Product

For solar collector analysis, it is required to calculate the transmissivity–absorptivity product ($\tau\alpha$). Here, τ is the transmissivity of glass cover and α is the absorptivity of absorber plate. It is defined as the ratio of solar flux absorbed by the absorber plate to the solar flux incident on the cover system.

Solar radiation after passing through the cover system falls on the absorber plate, where some radiation is reflected back to the cover system. Out of the reflected part, a portion is transmitted through the cover system and a part gets reflected back to the absorber plate. This activity of absorption and reflection is shown in Figure 4.6 which goes on indefinitely. However, the quantities involved in the process gradually get reduced.

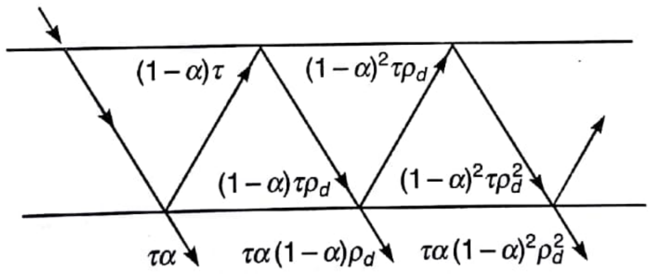

Figure 4.6 Absorption and reflection at an absorber plate.

Reflection from the absorber plate is more diffuse and let ρ_d be the reflectivity of glass cover for diffuse radiation. The fraction $(1 - \alpha)\tau$ that reaches the cover plate is diffuse radiation, $(1 - \alpha)\rho_d\tau$ is reflected back to the absorber plate.

Thus, the net radiation absorbed is the summation of

$$(\tau\alpha)_{\text{net}} = \tau\alpha + \tau\alpha(1 - \alpha)\rho_d + \tau\alpha(1 - \alpha)^2\rho_d^2 + \cdots$$

or
$$(\tau\alpha)_{\text{net}} = \frac{\tau\alpha}{1-(1-\alpha)\rho_d} \tag{4.18}$$

For an incident angle of 60°, the value of ρ_d is about 0.16, 0.24 and 0.29 for one, two and three glass covers respectively.