12. Name the method used for conversion of thermal energy into hydrogen energy:
    (a) Electrolysis (b) Hydrolysis
    (c) Thermolysis (d) None of the above

13. What is the main difficulty in storing hydrogen in liquid form?
    (a) It is difficult to maintain it due to refrigeration requirement.
    (b) It is very heavy in liquid form.
    (c) It is very light in liquid form.
    (d) It is very difficult to liquify it.

14. What is the main difficulty in storing hydrogen in a metal-hydride form?
    (a) Releasing hydrogen from metal hydride
    (b) Very little amount of hydrogen can be stored
    (c) These metals are difficult to obtain
    (d) Weight and cost of metal as well as heat management

15. In a reversible chemical-energy storage, the input energy is in the form of
    (a) Electrical energy (b) Thermal energy
    (c) Chemical energy (d) Mechanical energy

16. The main drawback of electromagnetic energy storage is that it requires
    (a) a very bulky inductor coil (b) a very strong magnetic field
    (c) A very strong electrostatic field (d) a superconducting material

17. Ultra-capacitors have capacities in the range of
    (a) Few microfarads (b) Few farads
    (c) Several thousand farads (d) Several hundred microfarads

18. The energy density of an ultra-capacitor is in the range of
    (a) 3–4 Wh/kg (b) 3–4 kWh/kg
    (c) 60–70 Wh/kg (d) 110–130 Wh/kg

19. Which of the following statements is not true for solid medium sensible heat storage?
    (a) No freezing problem (b) No corrosion problem
    (c) Low cost (d) Simultaneous charging and discharging are possible

20. Phase-change energy storage with solid-to-gas and liquid-to-gas transformations are not employed in spite of large latent heats because it
    (a) has low heat storage capacity
    (b) makes use of toxic materials
    (c) requires large change in volume that makes the system impracticable
    (d) requires a prohibitively wide temperature range

4 Solar Energy — Basics

Introduction

The sun radiates energy uniformly in all directions in the form of electromagnetic waves. The sun provides the energy needed to sustain life in our solar system. It is a clean, inexhaustible, abundantly and universally available source of renewable energy. The major drawbacks of solar energy are that it is a dilute form of energy, which is available intermittently and uncertainly, and not steadily and continuously. However, it is more predictable than wind energy. Also, peak solar insolation (incident solar radiation) often coincides with peak daytime demand; it can be well matched to suit commercial power needs. The output of the sun is 2.8×10^{23} kW/year. The energy reaching the earth is 1.5×10^{18} kWh/year.

Solar energy can be utilized directly in two ways: (i) by collecting the radiant heat and using it in a thermal system, or (ii) by collecting and converting it directly to electrical energy using a photovoltaic system. The former is referred as 'Solar Thermal' and the latter as 'Solar Photovoltaic' (SPV) system.

Solar energy is also used by various well-known natural effects and appears in nature in some other forms of energy. These are indirect forms of solar energy. Thus, solar energy is the mother of all forms of energy: conventional or non-conventional, renewable or non-renewable, the only exception being nuclear energy. Various sources of energy find their origin in the sun, as mentioned below:

1. Wind energy
2. Biomass energy
3. Tidal energy
4. Ocean wave energy
5. Ocean thermal energy
6. Fossil fuels and other organic chemicals
7. Hydro energy

Warming the body during winter is perhaps the earliest use of direct solar heat that man has made. Drying of clothes, timber, fodder, salt water (to get salt) and agricultural produce remain the most extensive use of direct solar energy in the history of mankind. All other devices for harnessing direct solar energy are of fairly recent origin.

Archimedes (212 BC), it is said, set the Roman fleet on fire by concentrating solar radiation using a large number of small plane mirrors at a distance of several hundred feet from the fleet. Antoine Lavoisier (1740–1794), achieved temperatures up to 1700°C by concentrating the sun's rays through a magnifying glass. Solar steam boilers were developed in late 19th century to produce steam to run steam engines. In the 1870s, a large-scale project using solar energy was installed in Chile where 6000 gallons of fresh water was produced per day in a desalination plant by collecting solar energy in an area of 50,000 sq. ft. In subsequent years, the development of solar energy declined due to availability of cheap fossil fuels. However, after the oil crisis of 1973, solar energy (as well as other non-conventional energy sources) received renewed interest from mankind.

THE SUN AS A SOURCE OF ENERGY

4.1 The sun, which is the largest member of the solar system, is a sphere of intensely hot gaseous matter having a diameter of 1.39×10^9 m, and, at an average distance of 1.495×10^{11} m from the earth. As observed from the earth, the sun rotates on its axis about once in every four weeks, though it does not rotate as a solid body. The equator takes about 27 days and the polar region takes about 30 days for each rotation. At the innermost region, the core, the temperature is estimated between 8×10^6 to 40×10^6 °K. The core has a density of about 100 times that of water and a pressure of 10^9 atm. Such a high inner temperature is maintained by enormous energy released due to continuous fusion reaction. Thus, the sun is a big natural fusion reactor with its constituent gases as the 'containing vessel' retained by gravitational forces. Several fusion reactions have been suggested to be the source of the energy radiated by the sun. The most important of them is a reaction in which four hydrogen atoms (protons) combine to form one helium atom. The mass of the helium nucleus is less than that of four protons, the difference of mass having been converted to energy in a fusion reaction as follows:

$$4({}_1H^1) \longrightarrow {}_2He^4 + 26.7 \text{ MeV}$$

The surface of the sun is maintained at a temperature of approximately 5800°K.

THE EARTH

4.2 The earth is shaped as an oblate spheroid—a sphere flattened at the poles and bulged in the plane normal to the poles. However, for most practical purposes, the earth may be considered as a sphere with a diameter of about 1.275×10^7 m. The earth makes one rotation about its axis every 24 hours and completes a revolution about the sun in a period of approximately 365.25 days. Its axis is inclined at an angle of 23.5°. As a result, the length of days and nights keep changing. The earth reflects about 30% of the sunlight that falls on it. This is known as the earth's *albedo*.

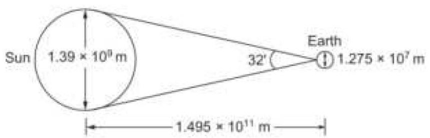

Fig. 4.1 *Sun–earth relationship*

The geometry of the earth–sun relationship is shown in Fig. 4.1. The eccentricity of the earth's orbit is such that the distance between the sun and the earth varies by ±1.7%. The sun subtends an angle of 32' on the earth

at an average sun – earth distance of 1.495×10^{11} m, a distance of one *astronomical unit.*

SUN, EARTH RADIATION SPECTRUMS

4.3 The energy radiated away from a black body at temperature T and wavelength λ can be obtained from Planck's black-body radiation formula:

$$W_\lambda = \frac{2\pi\pi b^2\lambda^{-5}}{e^{\frac{hc}{\lambda kT}} - 1} \text{ (W/m}^2\text{/unit wavelength in m)} \qquad (4.1)$$

where $b = 6.63 \times 10^{-34}$ watt-sec² (Planck's constant) and

$k = 1.38 \times 10^{-23}$ Joules/K (Boltzmann's constant)

Using this formula, the energy-density distribution of solar radiation at the surface of the sun considering the surface temperature to be 5760°K can be calculated. Also, the same for the earth surface can be found out assuming the average earth temperature to be 288°K (15°C). The comparison of these radiations from the sun and the earth is shown in Fig. 4.2. It is clear from Fig. 4.2 (a) and (b) that the radiation emitted from the sun at about 5760°K lies in the range of short wavelengths, peaking around 0.48 μm and that from the earth at 288°K (15°C) lies in the range of long wavelengths, peaking around 10 μm.

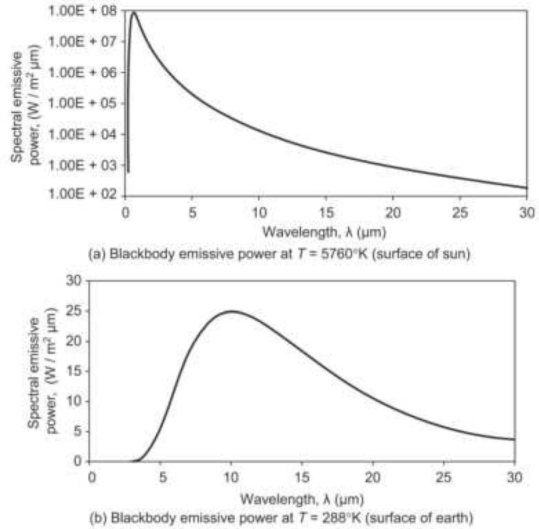

Fig. 4.2 *Radiant powers per unit wavelength at the surface of the sun and earth*

The term *irradiance* is defined as the measure of power density of sunlight received at a location on the earth and is measured in W/m^2. *Irradiation* is the measure of energy density of sunlight and is measured in kWh/m^2. It is generally denoted by the symbol H. Irradiance and irradiation apply to all components of solar radiation.

4.4 EXTRATERRESTRIAL AND TERRESTRIAL RADIATIONS

The intensity of solar radiation keeps on attenuating as it propagates away from the surface of the sun, though the wavelengths remain unchanged. Solar radiation incident on the outer atmosphere of the earth is known as *extraterrestrial radiation*, I_{ext}. The *solar constant*, I_{sc} is defined as the energy received from the sun per unit time, on a unit area of surface perpendicular to the direction of propagation of the radiation at the top of the atmosphere and at the earth's mean distance from the sun. The World Radiation Center (WRC) has adopted the value of the solar constant as 1367 W/m^2 (1.940 cal/cm^2 min, 432 Btu/ft^2 h or 4.921 MJ/m^2 h). This has been accepted universally as a standard value of solar constant.

The extraterrestrial radiation deviates from the solar-constant value due to two reasons. The first is the variation in the radiation emitted by the sun itself. The variation due to this reason is less than ±1.5% with different periodicities. The second is the variation of the earth–sun distance arising from the earth's slightly elliptic path. The variation due to this reason is ± 3% and is given by

$$I_{ext} = I_{sc}[1.0 + 0.033 \cos (360\, n/365)] \text{ W/m}^2 \tag{4.2}$$

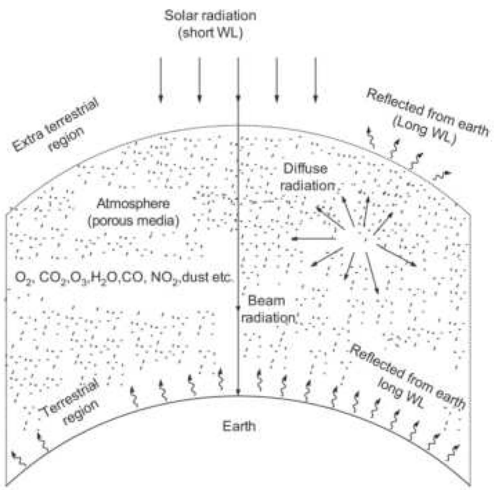

Fig. 4.3 *Propagation of solar radiation through the atmosphere*

The extraterrestrial radiation, being outside the atmosphere, is not affected by changes in atmospheric conditions. While passing through the atmosphere, it is subjected to mechanisms of atmospheric absorption and scattering depending on atmospheric conditions, depleting its intensity. The solar radiation that reaches the earth surface after passing through the earth's atmosphere is known as *terrestrial radiation*. The term *solar insolation* (incident solar radiation) is defined as the solar radiation received on a flat horizontal surface on the earth. The positions of extraterrestrial and terrestrial regions are indicated in Fig. 4.3.

4.5 SPECTRAL ENERGY DISTRIBUTION OF SOLAR RADIATION

Solar radiation covers a continuous spectrum of electromagnetic radiation in a wide frequency range. About 99% of the extraterrestrial radiation has wavelengths in the range from 0.2 to 4 μm with maximum spectral intensity at 0.48 μm (green portion of visible range). About 6.4% of extraterrestrial radiation energy is contained in the ultraviolet region ($\lambda < 0.38$ μm); another 48% is contained in the visible region (0.38 μm $< \lambda <$ 0.78 μm) and the remaining 45.6% is contained in the infrared region ($\lambda > 0.78$ μm). There is almost complete absorption of short-wave radiation in range ($\lambda < 0.29$ μm) and infrared radiation in range ($\lambda > 2.3$ μm) in the atmosphere. Thus, from the point of view of terrestrial applications of solar energy, the radiation only in the range of wavelengths between 0.29 and 2.3 μm is significant. The spectral solar-irradiation distribution, both for extraterrestrial and terrestrial radiation, is shown in Fig. 4.4. The areas under these curves indicate the total radiation intensities in W/m^2 respectively for extraterrestrial and terrestrial regions.

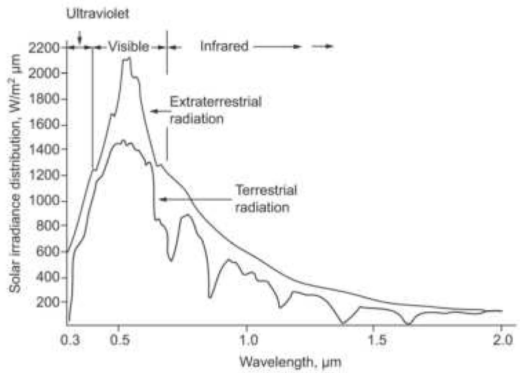

Fig. 4.4 *Spectral solar irradiation, exterrestrial and terrestrial*

4.6 DEPLETION OF SOLAR RADIATION

The earth's atmosphere contains various gaseous constituents, suspended dust and other minute solid and liquid particulate matter. These are air molecules, ozone, oxygen, nitrogen, carbon dioxide, carbon monoxide, water vapour, dust, and water droplets. Therefore, solar radiation is depleted during its passage through the atmosphere. Different molecules do different things as explained below:

1. *Absorption* Selective absorption of various wavelengths occurs by different molecules. The absorbed radiation increases the energy of the absorbing molecules, thus raising their temperatures:

(a) Nitrogen, molecular oxygen and other atmospheric gases absorb the X-rays and extreme ultraviolet radiations.
(b) Ozone absorbs a significant amount of ultraviolet radiation in the range ($\lambda < 0.38\ \mu m$).
(c) Water vapour (H_2O) and carbon dioxide absorb almost completely the infrared radiation in the range ($\lambda > 2.3\ \mu m$) and deplete to some extent the near infrared radiation below this range.
(d) Dust particles and air molecules also absorb a part of solar radiant energy, irrespective of wavelength.

2. *Scattering* Scattering by dust particles and air molecules (or gaseous particles of different sizes) involves redistribution of incident energy. A part of the scattered radiation is lost (reflected back) to space and the remaining is directed downwards to the earth's surface from different directions as *diffuse radiation.* It is the scattered sunlight that makes the sky blue. Without the atmosphere and its ability to scatter sunlight, the sky would appear black as it does on the moon.

In a cloudy atmosphere, (i) a major part of the incoming solar radiation is reflected back into the atmosphere by clouds, (ii) another part is absorbed by the clouds, and (iii) the rest is transmitted downwards to the earth surface as diffused radiation. The energy reflected back to the space by (i) reflection from clouds, (ii) scattering by the atmospheric gases and dust particles, and (iii) by reflection from the earth's surface is called the *albedo* of the earth–atmosphere system and has a value of about 30% of the incoming solar radiation for the earth as a whole. Thus, on the surface of the earth, we have two components of solar radiation: (i) *direct or beam radiation*, unchanged in direction, and (ii) *diffuse radiation*, the direction of which is changed by scattering and reflection. The total radiation at any location on the surface of the earth is the sum of beam radiation and diffused radiation, and is known as *global radiation.* These terms may be properly defined as follows:

Beam Radiation Solar radiation propagating in a straight line and received at the earth surface without change of direction, i.e., in line with the sun is called beam or direct radiation.

Diffused Radiation Solar radiation scattered by aerosols, dust and molecules is known as diffused radiation. It does not have a unique direction.

Global Radiation The sum of beam and diffused radiation is referred as total or global radiation.

Even on clear days, there will be some diffused radiation depending upon the amount of dust particles, ozone and water vapour present in the atmosphere. On overcast days when the sun is not visible, all the radiation reaching the ground will be diffused radiation.

In general, the intensity of diffused radiation coming from various directions in the sky is not uniform. The diffused radiation is therefore said to be anisotropic in nature. However, in many situations (like heavy cloud cover), the intensity from all directions tends to be reasonably uniform and it thus becomes isotropic in nature.

The radiation thus available on the earth's surface is less that what is received outside the earth's atmosphere and this reduction in intensity depends on the atmospheric conditions (amount of dust particles, water vapour, ozone content, cloudiness, etc.) and the distance travelled by beam radiation through the atmosphere before it reaches a location on the earth's surface. The latter factor in turn depends on solar altitude. The path length of a solar beam through the atmosphere is accounted for in the term *air mass*, which is defined as the ratio of the path length through the atmosphere, which the solar beam actually traverses up to the ground to the vertical path length (which is minimum) through the atmosphere. Thus at sea level the air mass is unity when the sun is at its *zenith* (highest position), i.e., when the inclination angle α is 90°. Mathematically,

$$\text{Air mass, } m = \frac{\text{path length traversed by beam radiation}}{\text{vertical path length of atmosphere}}$$

The abbreviation AM_0 refers to zero atmosphere (radiation in outer space), AM_1 refers to $m = 1$ (i.e., sun overhead, $\theta_z = 0$), AM_2 refers to $m = 2$ ($\theta_z = 60°$); and so on.

From Fig. 4.5, the air mass may be written as

$$m = (BA)/(CA)$$

$$= \sec \theta_z$$

$$= \operatorname{cosec} \alpha \qquad (\text{as } \alpha + \theta_z = 90°)$$

where α is the inclination angle

and θ_z is the zenith angle

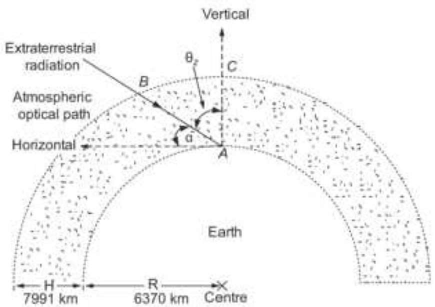

Fig. 4.5 *Direction of sun's ray with respect to atmosphere*

4.7 MEASUREMENTS OF SOLAR RADIATION

Solar radiation data are measured mainly by the following instruments:

(i) Pyranometer A pyranometer is designed to measure global radiation, usually on a horizontal surface, but can also be used on an inclined surface. When shaded from beam radiation by using a shading ring, a pyranometer measures diffused radiation.

(ii) Pyrheliometer An instrument that measures beam radiation by using a long narrow tube to collect only beam radiation from the sun at normal incidence.

(iii) Sunshine Recorder It measures the sunshine hours in a day.

4.7.1 Pyranometer

A precision pyranometer is designed to respond to radiation of all wavelengths and hence measures accurately the total power in the incident spectrum. It contains a thermopile whose sensitive surface consists of circular, blackened, hot junctions, exposed to the sun, the cold junctions being completely shaded. The temperature difference between the hot and cold junctions is the function of radiation falling on the sensitive surface. The sensing element is covered by two concentric hemispherical glass domes to shield it from wind and rain. This also reduces the convection currents. A radiation shield surrounding the outer dome and coplanar with the sensing element, prevents direct solar radiation from heating the base of the instrument. The instrument has a voltage output of approximately 9μV/W/m^2 and has an output impedance of 650 Ω. A precision spectral pyranometer (model: PSP) of Eppley Laboratory is shown in Fig. 4.6. The pyranometer, when provided

with a shadow band (or occulting disc), to prevent beam radiation from reaching the sensing element, measures the diffused radiation only. Such an arrangement of shadow band stand (model: SBS) is shown in Fig. 4.7.

Fig. 4.6 *Pyranometer (Courtesy: Eppley Laboratory)*

Fig. 4.7 *A pyranometer with shadow band (courtesy: Eppley Laboratory)*

Many inexpensive instruments are also available for measuring light intensity, including instruments based on cadmium-sulphide photocells and silicon photodiodes. These instruments give good indication of relative intensity but their spectral response is not linear, and thus they cannot be accurately calibrated.

4.7.2 Pyrheliometer

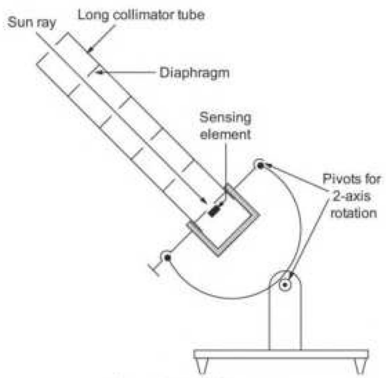

Fig. 4.8 *Pytheliometer*

The normal incidence pyranometer, shown in Fig. 4.8 uses a long collimator tube to collect beam radiation whose field of view is limited to a solid angle of 5.5° (generally) by appropriate diaphragms inside the tube. The inside of the tube is blackened to absorb any radiation incident at angles outside the collection solid angle. At the base of the tube a wire wound thermopile having a sensitivity of approximately 8 μV/W/m^2 and an output impedance of approximately 200 Ω is provided. The tube is sealed with dry air to eliminate absorption of beam radiation within the tube by water vapour. A tracker is needed if continuous readings are desired.

4.7.3 Sunshine Recorder

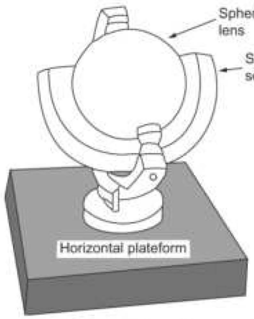

Fig. 4.9 *Sunshine recorder*

This instrument measures the duration in hours of bright sunshine during the course of a day. It essentially consists of a glass sphere (about 10 cm in diameter) mounted on its axis parallel to that of the earth, within a spherical section (bowl), as shown in Fig. 4.9. The bowl and glass sphere are arranged in such a way that the sun's rays are focused sharply at a spot on a card held in a groove in the bowl. The card is prepared from a special paper bearing a time scale. As the sun moves, the focused bright sunshine burns a path along this paper. The length of the trace thus obtained on the paper is the measure of the duration of the bright sunshine. Three overlapping pairs of grooves are provided in the spherical segment to take care of the different seasons of the year.

4.8 SOLAR RADIATION DATA

The radiation data are mostly measured on a horizontal surface. Typical records of global and diffused radiation versus solar time on a horizontal surface for a clear day and partially cloudy day are shown in Fig. 4.10. Daily radiant energy is obtained from the area under the corresponding curve. The monthly average of the daily radiation is obtained by averaging over a span of the corresponding month and expressed in kJ/m^2-day. An alternative unit for expressing solar radiation is langley per unit time, where one langley is equal to 1 cal/cm^2.

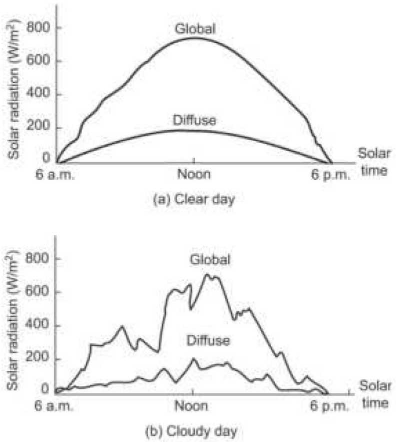

Fig. 4.10 *Daily variation of global and diffuse radiation on topical (a) clear and (b) cloudy days on horizontal surface*

Thus, solar radiation data are presented in three ways:

(i) Flow of energy per unit area per second, (kJ/m^2-s)
(ii) Flow of energy per unit area per hour, (kJ/m^2-h)
(iii) Flow of energy per unit area per day, (kJ/m^2-day)

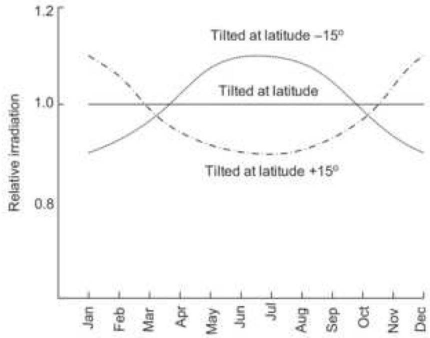

Fig. 4.11 *Relative irradiation at tilted surfaces throughout a year*

The incident solar radiation is also a function of the orientation (or tilt, due south in the northern hemisphere) of a solar collector from the horizontal. A typical pattern of relative irradiation throughout a year for three tilt angles, equal to: (i) latitude, (ii) (latitude –15°), and (iii) (latitude +15°) is shown in Fig. 4.11. The radiation pattern indicates favouring of a certain tilt during certain periods of the year. Therefore, seasonal adjustment of the tilt angle may result in enhanced radiation collection. However, the overall strategy changes from place to place and also on the type of application.

The maximum solar radiation is received on a collector surface placed normal to incident rays. But as the position of the sun in the sky changes throughout the day, the collector has to adjust itself continuously to collect maximum radiation. Therefore, maximum energy can be collected if the collector tracks the sun along two axes. However, providing for two-axis tracking is expensive and complicated. A compromising but less expensive option is to fix the collector at a suitable tilt and track the sun along a single axis only. The most cost-effective method with further compromise in the performance is to have a fix orientation for a collector and possibly with some arrangement for seasonal adjustments only.

For designing a solar system or for predicting the potential of any solar application at a location, we need monthly average, daily solar radiation data (both global and diffused) on a horizontal and possibly at certain positions of the tilt angle of the surface. These data are measured at certain measuring stations in a country (at present 16 locations in case of India) and computed for other locations. This record is produced in the form of charts and tables and an atlas is prepared to help in solar-systems design. The typical record of measured daily solar radiation data for New Delhi is shown in Tables C1, C2 and C3 in Appendix C.

4.9 SOLAR TIME (LOCAL APPARENT TIME)

Solar time is measured with reference to *solar noon*, which is the time when the sun is crossing the observer's meridian. At solar noon, the sun is at the highest position in the sky. The sun traverses each degree of longitude in 4 minutes (as the earth takes 24 hours to complete one revolution). The standard time is converted to solar time by incorporating two corrections, as follows:

$$\text{Solar time} = \text{Standard time} \pm 4\,(L_{st} - L_{loc}) + E \qquad (4.3)$$

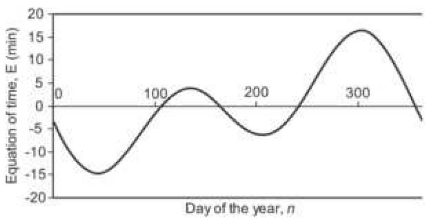

Fig. 4.12 *The equation of time as function of day of the year*

where L_{st} and L_{loc} are the standard longitude used for measuring standard time of the country and the longitude of the observer's location respectively. The (+ive) sign is used if the standard meridian of the country lies in the western hemisphere (with reference to the prime meridian) and (–ive) if that lies in the eastern hemisphere. E is the correction arising out of the variation in the length of the solar day due to variations in the earth's rotation and orbital revolution, and is called the *equation of time*. The *solar day*, which is the duration between two consecutive solar noons is not exactly of 24 hours throughout the year. E can be determined either by using the following equation or from the chart given in Fig. 4.12.

$$E = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B \quad \text{min.} \qquad (4.4)$$

where $B = (360/364)(n-81)$

n = day of the year, starting from 1st January

4.10 SOLAR RADIATION GEOMETRY

(a) Latitude (Angle of Latitude), (ϕ) The latitude of a location on the earth's surface is the angle made by a radial line joining the given location to the centre of the earth with its projection on the equator plane, as shown in Fig. 4.13 (a). The latitude is positive for northern hemisphere and negative for southern hemisphere.

(b) Declination, (δ) It is defined as the angular displacement of the sun from the plane of the earth's equator, as shown in Fig. 4.13 (b). It is positive when

measured above the equatorial plane in the northern hemisphere. The declination δ can be approximately determined from the equation

$$\delta = 23.45 \times \sin\left[\frac{360}{365}(284 + n)\right] \text{ degrees} \qquad (4.5)$$

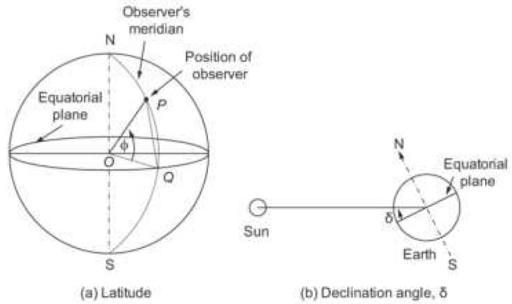

Fig. 4.13 *Latitude and declination angle*

where n is day of the year counted from 1st January.

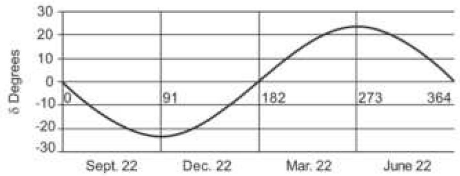

Fig. 4.14 *Variations in sun's declination*

(c) Hour Angle, (ω) The hour angle at any moment is the angle through which the earth must turn to bring the meridian of the observer directly in line with the sun's rays.

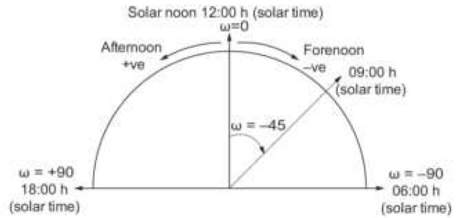

Fig. 4.15 *Hour angle*

In other words, at any moment, it is the angular displacement of the sun towards east or west of local meridian (due to rotation of the earth on its axis). The earth completes one rotation in 24 hours. Therefore, one hour corresponds to 15° of rotation. At solar noon, as the sun's rays are in line with the local meridian, the hour angle is zero. It is –ve in the forenoon and +ve in the afternoon. Thus, at 06:00 h it is –90° and at 18:00 h it is +90° as shown in Fig. 4.15.

It can be calculated as:

$$\omega = [\text{Solar Time}-12{:}00] \text{ (in hours)} \times 15 \text{ degrees} \tag{4.6}$$

(d) Inclination Angle (altitude), (α) The angle between the sun's ray and its projection on a horizontal surface is known as the inclination angle, as shown in Fig. 4.16.

(e) Zenith Angle, (θ_z) It is the angle between the sun's ray and the perpendicular (normal) to the horizontal plane. (Ref. Fig. 4.16)

(f) Solar Azimuth Angle (γ_s) It is the angle on a horizontal plane, between the line due south and the projection of the sun's ray on the horizontal plane. It is taken as +ve when measured from south towards west. (Ref. Fig. 4.16)

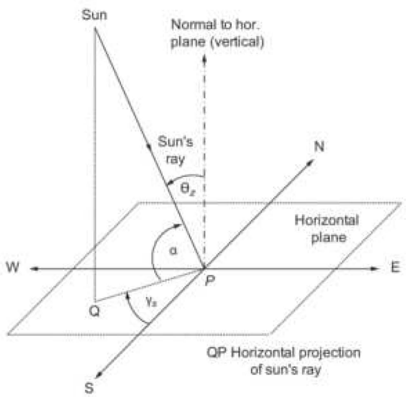

Fig. 4.16 *Solar altitude angle, solar azimuth angle and zenith angle*

(g) Slope (Tilt Angle), (β) It is the angle between the inclined plane surface (collector), under consideration and the horizontal. It is taken to be positive for the surface sloping towards south. (Ref. Fig. 4.17)

(h) Surface Azimuth Angle, (γ) It is the angle in the horizontal plane, between the line due south and the horizontal projection of the normal to the inclined plane surface (collector). It is taken as +ive when measured from south towards west. (Ref. Fig. 4.17)

(i) Angle of Incidence, (θ_i) It is the angle between the sun's ray incident on the plane surface (collector) and the normal to that surface. (Ref. Fig. 4.18)

These angles are shown in Fig. 4.17–19. In general, the angle of incidence can be expressed as

$$\cos\theta_i = (\cos\phi\cos\beta + \sin\phi\sin\beta\cos\gamma)\cos\delta\cos\omega + \cos\delta\sin\omega\sin\beta\sin\gamma$$
$$+ \sin\delta(\sin\phi\cos\beta - \cos\phi\sin\beta\cos\gamma) \tag{4.7}$$

Special Cases

(i) For a surface facing due south, $\gamma = 0$

$$\cos\theta_i = \cos(\phi - \beta)\cos\delta\cos\omega + \sin\delta\sin(\phi - \beta) \tag{4.8}$$

(ii) For a horizontal surface, $\beta = 0$, $\theta_i = \theta_z$ (zenith angle)

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\delta\sin\phi \tag{4.9}$$

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

$$\cos\theta_i = -\sin\delta\cos\phi + \cos\delta\cos\omega\sin\phi \tag{4.10}$$

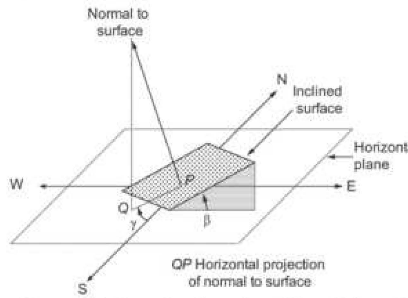

Fig. 4.17 *Surface azimuth angle and slope (tilt angle)*

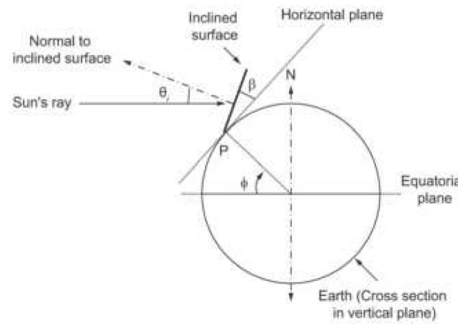

Fig. 4.18 *Angle of latitude, tilt angle, angle of incidence*

SOLAR DAY LENGTH

4.11 At sunrise, the sun's rays are parallel to the horizontal surface. Hence the angle of incidence, $\theta_i = \theta_z = 90^\circ$, the corresponding hour angle, ω_s, from Eq. (4.7):

$$\cos\theta_i = 0 = \cos\phi\cos\delta\cos\omega_s + \sin\delta\sin\phi$$

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \qquad (4.11)$$

The angle between sunrise and sunset is given by

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

Since 15° of hour angle is equivalent to one-hour duration, the duration of sunshine hours, t_d or daylight hours is given by

$$t_d = (2/15)\cos^{-1}(-\tan\phi\tan\delta) \qquad (4.12)$$

The variation of t_d with latitude (ϕ) for different days (n) of the year is shown in Fig. 4.19.

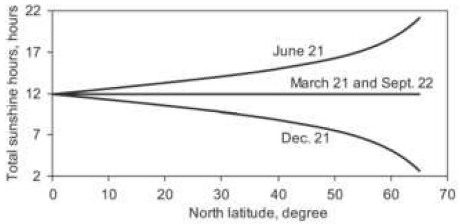

Fig. 4.19 *Variation of sunshine hours, t_d with latitude, on certain days of the year*

The hour angle, ω_s at sunrise (or sunset) for horizontal (collector) surface is given by Eq. 4.11., which yields positive and negative values for ω_s. The negative value corresponds to sunrise while the positive to sunset. The hour angle at sunrise as seen by the observer on an inclined surface facing south (i.e., $\gamma = 0$) will also be given by Eq. 4.11 if the day under consideration lies between September 22 and March 21, and the location is in the northern hemisphere. However, if the day under consideration lies between March 21 and September 22, the hour angle at sunrise or sunset would be smaller in magnitude than the value given by Eq. 4.11 and would be obtained by substituting $\theta_i = 90^\circ$ in Eq. 4.8. Thus,

$$\omega_{st} = \cos^{-1}[-\tan(\phi - \beta)\tan\delta] \qquad (4.13)$$

Example 4.1

Calculate the angle of incidence of beam radiation on a plane surface, tilted by 45° from the horizontal plane and pointing 30° west of south located at Mumbai at 1:30 P.M. (IST) on 15th November. The longitude and latitude of Mumbai are $72^\circ 49'$ E and $18^\circ 54'$ N respectively. The standard longitude for IST is $81^\circ 44'$ E.

Solution From the given data,

$n = 319$

From Eq. (4.5) $\delta = -19.148^\circ$

From Eq. (4.4) $E = 14.74$ min.

Standard Time = 1:30 p.m. = 13:30 h.

From Eq. (4.3), Solar Time $= 13\text{ h } 30\text{ min} - 4\,(81.733^\circ - 72.816^\circ)\text{ min} + 14.74\text{ min}$

$= 13\text{ h } 9.072\text{ min}$

From Eq. 4.6 hour angle, $\omega = 17.27^\circ$

$\gamma = 30^\circ$, $\beta = 45^\circ$, $\phi = +18.9^\circ$

Now the angle of incidence can be calculated using Eq. 4.7

$\cos\theta_i = [\cos(+18.9^\circ)\cos(45^\circ) + \sin(+18.9^\circ)\sin(45^\circ)\cos(30^\circ)] + \sin(-19.148^\circ)[\sin(+18.9^\circ)\cos(45^\circ) - \cos(+18.9^\circ)\sin(45^\circ)\cos(30^\circ)]$

$\theta_i = \cos^{-1}(0.99686) = 4.54^\circ$

Example 4.2

Calculate the number of daylight hours (sunshine hours) in Srinagar on January 1 and July 1. The latitude of Srinagar is $34^\circ 05'$ N..

Solution From the given data,

$n = 1$ and 182 respectively for January 1 and July 1.

From Eq. 4.5, $\delta = -23.01^\circ$ and 23.12° respectively for January 1 and July 1.

From Eq. 4.12,

on January 1, $t_d = (2/15)\cos^{-1}[-\tan(34.083^\circ)\tan(-23.01^\circ)]$
$= 9.77$ h

on July 1, $t_d = (2/15)\cos^{-1}[-\tan(34.083^\circ)\tan(23.12^\circ)]$
$= 14.24$ h

4.12 EMPIRICAL EQUATIONS FOR ESTIMATING SOLAR RADIATION AVAILABILITY ON HORIZONTAL SURFACE FOR CLOUDY SKIES

Since measurements of solar radiation are often not available at every location of the earth, attempts have been made by many researchers to establish relationships linking the values of radiation (global or diffuse) with meteorological parameters like number of sunshine hours, cloud cover and precipitation, etc. Some of these equations will be given in the following sections. These equations are generally valid for cloudy skies.

4.12.1 Monthly Average, Daily Global Radiation

The correlation for estimating the monthly average daily total (global) radiation on a horizontal surface can be given as

$$\frac{\overline{H}_g}{\overline{H}_o} = a + b\left(\frac{\overline{n}}{\overline{N}}\right) \tag{4.14}$$

where $\overline{H}_g$ = monthly average, daily total radiation on a horizontal surface at a location

$\overline{H}_o$ = monthly average, daily extraterrestrial radiation that would fall at the location on a horizontal surface (in the absence of an atmosphere)

$\overline{n}$ = monthly average, daily hours of bright sunshine obtained from actual records at the location (i.e., bright sunshine hours)

$\overline{N}$ = monthly average of maximum possible daily hours of sunshine (i.e., the day length of the average day of the month)

$\frac{\overline{n}}{\overline{N}}$ = p.u. possible bright sunshine

a,b = regression parameters are constants for a particular location and obtained by fitting data

Values of a and b have been obtained for many cities of the world. These values are given for some Indian cities in Table 4.1.

Table 4.1 *Constants a and b for some Indian cities* [43]

S.N.	Name of the city	a	b	Mean error (percent)
1.	Ahmedabad	0.28	0.48	3.0
2.	Bengaloore	0.18	0.64	3.9
3.	Bhavnagar	0.28	0.47	2.8
4.	Chennai	0.30	0.44	3.5
5.	Goa	0.30	0.48	2.1
6.	Jodhpur	0.33	0.46	2.0
7.	Kodaikanal	0.32	0.55	2.9
8.	Kolkata	0.28	0.42	1.3
9.	Mangalore	0.27	0.43	4.2
10.	Minicoy	0.26	0.39	1.4
11.	Nagpur	0.27	0.50	1.6
12.	New Delhi	0.25	0.57	3.0
13.	Pune	0.31	0.43	1.9
14.	Shilong	0.22	0.57	3.0
15.	Srinagar	0.35	0.40	4.7
16.	Thiruvanan-thapuraam	0.37	0.39	2.5
17.	Vishakhapatnam	0.28	0.47	1.2

In Eq. 4.14, $\overline{H}_o$ is the mean or average of H_o for each day of the month, which can be calculated as follows:

From Eq. 4.2, the extraterrestrial radiation in kW/m² may be given as

$$I_{ext} = I_{sc}\left[1.0 + 0.033\cos\left(\frac{360n}{365}\right)\right]$$

On a horizontal surface, this would become, $I_{ext}\cos\theta_Z$

Using Eq. 4.9, the extraterrestrial radiation that would fall on a horizontal surface at the location may be written as

$$I_{sc}\left[1.0 + 0.033\cos\left(\frac{360n}{365}\right)\right] (\cos\phi\cos\delta\cos\omega + \sin\delta\sin\phi)\ (\text{kW/m}^2)$$

To get hourly radiated energy per square metre (i.e. in kJ/m²h), the above term is to be multiplied by a factor of 3600:

$$3600 \times I_{sc}\left[1.0 + 0.033\cos\left(\frac{360n}{365}\right)\right] (\cos\phi\cos\delta\cos\omega + \sin\delta\sin\phi)\ (\text{kJ/m}^2\,\text{h})$$

One day radiation, H_o (in kJ/m² day) can be obtained by integrating the above expression over the day length where time is expressed in hours.

$$H_o = 3600 \times I_{sc}\left[1.0 + 0.033\cos\left(\frac{360n}{365}\right)\right] \int (\cos\varphi\cos\delta\cos\omega + \sin\delta\sin\delta\sin i\ dt \tag{4.15}$$

As explained in Section 4.10, since an hour of 15° is equivalent to 1 hour duration of sunshine, we have,

$$t = \frac{\omega}{15} \times \frac{180}{\pi}$$

where t is hours and ω is in radians.

Hence, $dt = \frac{180}{15\pi}\, d\omega$

From Eq. 4.14, we have

$$H_o = 3600 \times \frac{12}{\pi}\, I_{sc} \left[1.0 + 0.033 \left(\frac{360n}{365}\right)\right] \int_{-\omega_s}^{+\omega_s} (\cos\phi \cos\delta \cos\omega + \sin\delta \operatorname{in}\delta\phi)\, d\omega$$

$$= 3600 \times \frac{24}{\pi}\, I_{sc} \left[1.0 + 0.033 \cos \left(\frac{360n}{365}\right)\right] (\cos\phi \cos\delta \sin\omega_s + \omega_s \sin\phi \sin\delta) \qquad (4.16)$$

The calculation of H_o can be simplified from the fact that in each month, there is a particular day on which H_o is nearly equal to the monthly mean value $\overline{H}_o$. The dates on which the value of H_o is equal to $\overline{H}_o$ are January 17, February 16, Mach 16, April 15, May 15, June 11, July 17, August 16, September 15, October 15, November 14 and December 10. As expected, these dates are close to the middle of the month. The values of sunshine hours for these dates are used as $\overline{N}$ for that month.

Equation 4.16 can be used to determine the monthly average of daily global radiation on a horizontal surface at a location for known sunshine hours and where the values of a and b are known for a nearby location.

Other meteorological parameters have also been used for predicting the availability of solar radiation. These include cloud cover and precipitation. However, in general, the sunshine ratio parameter $\frac{\overline{n}}{\overline{N}}$ has been found to be the most reliable predictor.

Example 4.3

Estimate the monthly average of the daily global radiation on a horizontal surface at Agra (27° 10' N, 78° 05' E) during the month of January, if the average sunshine hour per day is 7 h.

Solution Here, we shall use the values of a and b available for New Delhi as this is the closest town of known data. Therefore,

$$a = 0.25,\ b = 0.57$$

For Agra, $\phi = 27.166°$

For the month of January we shall use the 17th day of the month as the day for which H_o is equal to $\overline{H}_o$.

Thus, the day of the year, $n = 17$

Also it is given that average sunshine hours, $\overline{n} = 7$ h

Using Eq. 4.5, $\delta = 23.45 \times \sin\left[\frac{360}{365}(284 + 17)\right]$ degrees

$$= {}^{-}20.96°$$

The hour angle at sunrise may be calculated from Eq. 4.11

$\omega_s = \cos^{-1}[{}^{-}\tan(27.166)\ \tan(-29.96)]$

$\omega_s = 78.66°$ or 1.7328 radians

Using Eq. 4.12, day length, $\overline{N} = \frac{2}{15} \times 78.66 = 10.488$ h

From Eq. 4.16,

$$\overline{H}_o = 3600 \times \frac{24}{\pi} \times 1.367 \times [1.0 + 0.033 \cos\left(\frac{360 \times 17}{365}\right)]$$

$\times$[cos (27.166) × cos (−20.96) × sin (78.66) + 1.3728 × sin (27.166) × sin (−20.96)]

= 37540.195 × [1.031597] × [0.81459–0.2242]

= 22863.3 kJ/m²-day

Now, from Eq. 4.13,

$$\frac{\overline{H}_g}{\overline{H}_o} = a + b\left(\frac{\overline{n}}{\overline{N}}\right)$$

$$\frac{\overline{H}_g}{\overline{H}_o} = 22863.3 \times [0.25 + 0.57 \times \frac{7}{10.488}]$$

$\overline{H}_g$= 14413.82 kJ/m²-day

4.12.2 Monthly Average, Daily Diffused Radiation

Based on a study of data for a few countries, it has been found that the correlation is not same throughout the globe. A number of correlations have been developed. For Indian conditions where the diffuse component is relatively larger, the following correlation is found to predict diffused radiation with an accuracy of about 10 per cent.

$$\frac{\overline{H}_d}{\overline{H}_g} = 1.354 - 1.570\, \overline{K}_T \qquad (4.17)$$

where $\overline{H}_d$ = monthly average, daily diffused radiation on a horizontal surface at a location.

$\overline{K}_T = \frac{\overline{H}_g}{\overline{H}_o}$, known as monthly average daily clearness index

The correlation is valid in the range $0.3 < \overline{K}_T < 0.7$.

Example 4.4 *From the data given in Example 4.3 for Agra, estimate the monthly average of the daily diffused and beam radiations on a horizontal surface.*

Solution As per calculation of Example 4.3,

$\overline{H}_o = 22863.3$ kJ/m²-day and $\overline{H}_g = 14413.82$ kJ/m²-day

$$\text{Therefore, } \overline{K}_T = \frac{\overline{H}_g}{\overline{H}_o} = \frac{14413.82}{22863.3} = 0.63$$

From Eq. 4.17,

$$\frac{\overline{H}_d}{\overline{H}_g} = 1.354 - 1.570\,\overline{K}_T$$

$$\overline{H}_d = 14413.82 \times (1.354 - 1.570 \times 0.63) = 5259.6 \text{ kJ/m}^2\text{- day}$$

Beam component, can be calculated as,

$H_b = H_g - H_d = 14413.82 - 5259.6 = 9154.22$ kJ/m²-day

4.12.3 Monthly Average, Hourly Global Radiation

On the lines similar to prediction of daily radiation discussed in the previous section, correlations are suggested for estimating monthly average, hourly radiation. One such correlation is given below:

$$\frac{\bar{I}_g}{\overline{H}_g} = (a + b\cos\omega)\frac{\bar{I}_o}{\overline{H}_o} \tag{4.18}$$

where $\bar{I}_o$ and $\overline{H}_o$ are monthly average, hourly and daily extraterrestrial radiation, respectively that would fall at the location on a horizontal surface (in the absence of atmosphere).

$\bar{I}_g$ = monthly average, hourly radiation, on a horizontal surface

The values of a and b may be obtained as follows:

$a = 0.409 + 0.5016 \sin(\omega_s - 60^o)$

$b = 0.6609 - 0.4767 \sin(\omega_s - 60^o)$

ω = hour angle at a particular time

It should be noted that $\bar{I}_o$ is expressed in kJ/m²-h, which can be calculated by obtaining the instantaneous value (in kW/m²) at the midpoint of the hour under consideration and multiplying by 3600.

4.12.4 Monthly Average, Hourly Diffused Radiation

There is a close correlation between the values of ratios $\left(\bar{I}_d / \overline{H}_d\right)$ and $\left(\bar{I}_o / \overline{H}_o\right)$. The following correlation is suggested between the two.

$$\frac{\bar{I}_d}{\overline{H}_d} = (a' + b'\cos\omega)\frac{\bar{I}_o}{\overline{H}_o} \tag{4.19}$$

$$\text{where} \quad a' = 0.4922 + \left(\frac{0.27}{\overline{H}_d / \overline{H}_g}\right) \quad \text{for } 0.1 \le (\overline{H}_d / \overline{H}_g) \le 0.7$$

$$= 0.76 + \left(\frac{0.113}{\overline{H}_d / \overline{H}_g}\right) \quad \text{for } 0.7 \le (\overline{H}_d / \overline{H}_g) \le 0.9$$

and $b' = 2(1 - a')(\sin\omega_s - \omega_s\cos\omega_s)/(\omega_s - 0.5\sin 2\omega_s)$

Example 4.5 *From the data given in Example 4.3 for Agra, calculate the monthly average of the hourly global and hourly diffuse radiations on a horizontal surface during 1100 to 1200 h (LAT).*

Solution Given data:

For Agra, $\phi = 27.166^o$

For the month of January, we shall use the 17th day of the month as the day for which H_0 is equal to $\overline{H}_o$.

Thus, the day of the year, $n = 17$

For the above data, the values calculated in Example 4.3 are

$\delta = -20.96^o$

$\omega_s = 78.66^o$ or 1.7328 radians

$\overline{H}_o = 22863.3$ kJ/m²-day

$\overline{H}_g = 14413.82$ kJ/m²-day

The hourly extraterrestrial radiation, I_o on a horizontal surface at the location at a particular hour may be obtained in kJ/m²-h by multiplying the instantaneous radiation (in kW/m²) by 3600. Thus,

$$I_o = 3600 \times I_{sc}\left[1.0 + 0.033\cos\left(\frac{360n}{365}\right)\right](\cos\phi\cos\delta\cos\omega + \sin\delta\sin\phi)$$

The value of ω is calculated from Eq. 4.6 at the middle of the hour, i.e., at 11:30.

ω = [Solar Time–1200] (in H) ϕ 15 degrees

= $-$ 7.5° or $-$0.1309 radian

Now,

$$I_o = 3600 \times 1.367 \times \left[1.0 + 0.033 \cos\left(\frac{360 \times 17}{365}\right)\right] (\cos 27.166^\circ \cos(-20.96) \cos(-7.5^\circ) + \sin(-20.96) \sin 27.166^\circ)$$

$= 4921.2 \times [1.031597] \times 0.6604$

$I_o = 3352.58$ kJ/m²-h

I_o may be taken as $\bar{I}_o$ on January 17.

Now, $\bar{I}_g$ can be calculated using Eq. 4.18:

$$\frac{\bar{I}_g}{\bar{H}_g} = (a + b \cos \omega)\frac{\bar{I}_o}{\bar{H}_o}$$

The values of a and b may be obtained as follows:

$a = 0.409 + 0.5016 \sin(\omega_s - 60^\circ) = 0.409 + 0.5016 \sin(78.66^\circ - 60^\circ)$

$= 0.5695$

$b = 0.6609 - 0.4767 \sin(\omega_s - 60^\circ) = 0.6609 - 0.4767 \sin(78.66^\circ - 60^\circ)$

$= 0.2093$

Substituting these values in Eq. 4.18,

$$\bar{I}_g = 14413.82 \times (0.5695 + 0.2093 \times \cos(-7.5^\circ)) \times \frac{3352.58}{22863.3}$$

$= 1642.27$ kJ/m²-h

Thus the monthly average of the hourly global radiation on a horizontal surface during 1100 to 12:00 hours (LAT) at Agra = 1642.27 kJ/m²-h

The monthly average of the hourly diffused radiation can be calculated from Eq. 4.19

$$\frac{\bar{I}_d}{\bar{H}_d} = (a' + b' \cos \omega)\frac{\bar{I}_o}{\bar{H}_o}$$

As calculated in Example 4.4, $\bar{H}_d = 5259.6 \text{ kJ/m}^2\text{-day}$

$\bar{H}_d / \bar{H}_g = 5259.6/14413.82 = 0.3649$

$$a' = 0.4922 + \left(\frac{0.27}{\bar{H}_d / \bar{H}_g}\right) = 1.2321$$

$b' = 2(1 - a')(\sin \omega_s - \omega_s \cos \omega_s)/(\omega_s - 0.5 \sin 2\omega_s)$

$= 2 \times (1 - 1.2321) \times (\sin 78.66^\circ - 1.7328 \times \cos 78.66^\circ)/(1.7328 - 0.5 \times \sin(2 \times 78.66^\circ))$

$= 2 \times (-0.2321) \times 1.3212/1.54 = -0.3983$

Now, from Eq. 4.19,

$$\bar{I}_d = 5259.6 \times (1.2321 - 0.3983 \times \cos(-7.5^\circ)) \times \frac{3352.58}{22863.3}$$

$= 645.695$ kJ/m²-h

Thus, the monthly average of the hourly diffused radiation on a horizontal surface during 11:00 to 12:00 hours (LAT) at Agra = 645.695 kJ/m²-h

4.12.5 Daily and Hourly Diffused Radiation on an Individual Day

Normally, global radiation is recorded at many locations whereas diffused radiation is not. Therefore, correlations have been suggested to predict daily and hourly diffused radiation from measured daily and hourly global-radiation data respectively.

Correlation for Daily Diffused Radiation

$$\frac{H_d}{H_g} = 0.99 \quad \text{for } K_T \le 0.17$$

$$= 1.188 - 2.272\, K_T + 9.437\, K_T^2 - 21.856\, K_T^3 + 14.648\, K_T^4 \quad \text{for } 0.17 < K_T \le 0.8 \qquad (4.20)$$

where $K_T = H_g/H_o$, is the daily clearness index for an individual day.

On the same lines, correlations have also been developed for estimating hourly diffused radiation I_d from measured value of hourly global radiation.

$$\frac{I_d}{I_g} = a - b\, k_T \qquad (4.21)$$

where $k_T = I_g/I_o$, is the hourly clearness index at an hour of an individual day.

$a = 0.949 + 0.0118\, |\phi|$

$b = 1.185 + 0.0135\, |\phi|$

and ϕ = latitude in degrees

Equations 4.20 and 4.21 are valid for $0.35 \le k_T \le 0.75$.

4.13 HOURLY GLOBAL, DIFFUSE AND BEAM RADIATIONS ON HORIZONTAL SURFACE UNDER CLOUDLESS SKIES

The hourly global radiation I_g on a horizontal surface is the sum of the hourly beam radiation, I_b and the hourly diffuse radiation I_d. Thus:

$$I_g = I_b + I_d$$

Now, if I_{bn} is the beam radiation on a surface normal to the direction of sun rays, the beam radiation received on a horizontal surface may be given as

$$I_b = I_{bn} \cos \theta_Z \tag{4.22}$$

Thus, $$I_g = I_{bn} \cos \theta_Z + I_d \tag{4.23}$$

I_{bn} and I_d are estimated as follows:

$$I_{bn} = A \exp(-B/\cos \theta_Z) \tag{4.24}$$

$$I_d = C\, I_{bn} \tag{4.25}$$

where A, B and C are constants whose values have been determined monthwise on the basis of measurements carried out in USA. These constants change during the year because of seasonal changes in dust and moisture contents of the atmosphere and also because of change in the sun–earth distance. The values are tabulated in Table 4.2.

Table 4.2 *Constants A, B and C for predicting hourly solar radiation on clear days* [43].

Month	A (W/m²)	B	C
January 21	1202	0.141	0.103
February 21	1187	0.142	0.104
March 21	1164	0.149	0.109
April 21	1130	0.164	0.120
May 21	1106	0.177	0.130
June 21	1092	0.185	0.137
July 21	1093	0.186	0.138
August 21	1107	0.182	0.134
September 21	1136	0.165	0.121
October 21	1136	0.152	0.111
November 21	1190	0.144	0.106
December 21	1204	0.141	0.103

Example 4.6

Estimate the hourly global, beam and diffused radiations at New Delhi (28° 35′ N, 77° 12′ E) between 1300 to 1400 hours (LAT) on May 15 and compare these data with measured values given in Tables C1 and C2 in Appendix C.

Solution Given data:

$\phi = 28.58°$

For May 15, $n = 135$

$$\delta = 23.45 \times \sin\left[\frac{360}{365}(284 + 135)\right]$$
$$= 18.79°$$

We shall consider hour angle ω for the middle of the hour, i.e., 1330 hours.

ω = [Solar Time–1200] (in hours) × 15 degrees = 22.5°

From Eq. 4.9,

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

$= \cos 28.58° \cos 18.79° \cos 22.5° + \sin 18.79° \sin 28.58°$

$= 0.768 + 0.154$

$= 0.922$

From Table 4.2, the values of A, B and C are obtained as

$A = 1106 \text{ W/m}^2 = 3.6 \times 1106 \text{ kJ/m}^2\text{-h} = 3981.6 \text{ kJ/m}^2\text{-h}$

$B = 0.177$

$C = 0.130$

From Eq. 4.24,

$I_{bn} = A \exp(-B/\cos \theta_Z) = 3981.6 \times \exp(-0.177/0.922)$

$= 3285.63 \text{ kJ/m}^2\text{-h}$

From Eq. 4.25, the diffused radiation,

$I_d = C\, I_{bn} = 0.130 \times 3285.63 = 427.13 \text{ kJ/m}^2\text{-h}$

From Eq. (4.22), the beam radiation,

$I_b = I_{bn} \cos \theta_z = 3285.63 \times 0.922 = 3029.35 \text{ kJ/m}^2\text{-h}$

The global radiation $I_g = I_b + I_d = 3456.48 \text{ kJ/m}^2\text{-h}$

Comparison

	Estimated	Measured
Diffused radiation	427.13 kJ/m²-h	1108.4 kJ/m²-h
Beam radiation	3029.35 kJ/m²-h	1930 kJ/m²-0068
Global radiation	3456.48 kJ/m²-h	3038.4 kJ/m²-h

It is seen that the values of A, B and C obtained on the basis of US data, predict high values of beam radiation and low values for diffused radiation, when used under Indian conditions. However, the two effects tend to balance each other to some extent and therefore, the values for global radiations are predicted to a reasonable degree of accuracy.

4.14 SOLAR RADIATION ON AN INCLINED PLANE SURFACE

Total radiation incident on an inclined surface consists of three components: (i) beam radiation, (ii) diffused radiation and (iii) radiation reflected from the ground and surroundings. It may be mentioned here that both beam and diffused components of radiation undergo reflection from the ground and surroundings. The total radiation on a surface of arbitrary orientation may be evaluated as:

$$I_T = I_b r_b + I_d r_d + (I_b + I_d) r_r \tag{4.26}$$

where r_b, r_d and r_r are known as tilt factors for beam, diffuse and reflected components respectively. The expressions for these factors are given below:

r_b It is defined as the ratio of flux of beam radiation incident on an inclined surface (I_b') to that on a horizontal surface (I_b).

$$I_b' = I_{bn} \cos \theta_i$$

$$I_b = I_{bn} \cos \theta_z$$

where I_{bn} is the beam radiation on a surface normal to the direction of sun rays

$$r_b = \frac{I_b'}{I_b} = \frac{\cos \theta_i}{\cos \theta_z} \tag{4.27}$$

For a tilted surface facing south, $\gamma = 0°$, the expression for r_b may be written as

$$r_b = \frac{\sin \delta \sin (\phi - \beta) + \cos \delta \cos \omega \cos (\phi - \beta)}{\sin \delta \sin \phi + \cos \delta \cos \omega \cos \phi} \tag{4.28}$$

r_d It is defined as the ratio of flux of diffused radiation falling on an inclined surface to that on the horizontal surface. The value of this tilt factor depends upon the distribution of diffused radiation over the sky and on the portion of the sky dome seen by the tilted surface. Assume that the sky is an isotropic source of diffused radiation; we have for a tilted surface with slope β,

$$r_d = \frac{1 + \cos \beta}{2} \tag{4.29}$$

r_r The reflected component comes mainly from the ground and surrounding objects. Since $(1 + \cos \beta)/2$ is the radiation shape factor for a tilted surface with respect to the sky, it follows that $(1 - \cos \beta)/2$ is the radiation shape factor for the surface with respect to the surrounding ground. Assume that the reflection of the beam and diffused radiation falling on the ground is diffused and isotropic and the reflectivity is ρ. The tilt factor for reflected radiation may be written as

$$r_r = \rho\left(\frac{1 - \cos \beta}{2}\right) \tag{4.30}$$

where ρ is the reflection coefficient of the ground (equal to 0.2 for ordinary grass or concrete and 0.6 for snow-covered ground respectively)

For a vertical surface, $\beta = 90°$, $r_d = 0.5$ and $r_r = 0.5\rho$. This indicates tShat half of the diffused and half of the total reflected radiation is received by a vertical surface. For a horizontal plane, $r_d = 1$ and $r_r = 0$, which indicates that maximum diffuse radiation is received by the horizontal surface and that a horizontal surface receives no ground reflected radiation. The ratio r' of total solar energy incident on an inclined surface to that on a horizontal surface is given as

$$r' = \frac{I_T}{I_b + I_d} = \frac{I_T}{I_g} = \left(1 - \frac{I_d}{I_g}\right) r_b + \frac{I_d}{I_g} r_d + r_r \tag{4.31}$$

Equation 4.31 can be used for calculating hourly radiation falling on a tilted surface if the hour angle ω is considered at the midpoint of the hour concerned.

The monthly average, hourly value $\overline{I_T}$ can be obtained by considering the representative day of the month for calculation of I_T. Eq. 4.32 will then be modified as

$$\frac{\bar{I}_T}{\bar{I}_g} = \left(1 - \frac{\bar{I}_d}{\bar{I}_g}\right)\bar{r}_b + \frac{\bar{I}_d}{\bar{I}_g}\bar{r}_d + \bar{r}_r \tag{4.32}$$

where $\bar{r}_b = r_b$ on representative day of the month,

$$\bar{r}_d = r_d$$

$$\bar{r}_r = r_r$$

On similar lines, the ratio of the daily total radiation on tilted surface H_T to the daily global radiation on a horizontal surface may be written as

$$\frac{H_T}{H_g} = \left(1 - \frac{H_d}{H_g}\right) R_b + \frac{H_d}{H_g} R_d + R_r \tag{4.33}$$

For a south-facing surface, $\gamma = 0°$,

$$R_b = \frac{\omega_{st} \sin \delta \sin (\phi - \beta) + \cos \delta \sin \omega_{st} \cos (\phi - \beta)}{\omega_s \sin \delta \sin \phi + \cos \delta \sin \omega_s \cos \phi} \tag{4.35}$$

where ω_{sr} = sunrise hour angle expressed in radians on a tilted surface

ω_s = sunrise hour angle expressed in radians on a horizontal surface

And $$R_d = r_d = \frac{1+\cos\beta}{2} \quad (4.36)$$

$$R_r = r_r = \rho\left(\frac{1-\cos\beta}{2}\right) \quad (4.37)$$

Eq. 4.33 can also be used for calculating monthly average of daily radiation falling on an inclined surface if the required values are calculated for a representative day of the month. Eq. 4.33 may then be written in its revised form,

$$\frac{\overline{H}_T}{\overline{H}_g} = \left(1 - \frac{\overline{H}_d}{\overline{H}_g}\right)\overline{R}_b + \frac{\overline{H}_d}{\overline{H}_g}\overline{R}_d + \overline{R}_r \quad (4.38)$$

where $\overline{R}_b = R_b$ on the representative day of the month

$$\overline{R}_d = R_d = \frac{1+\cos\beta}{2} \quad (4.39)$$

$$\overline{R}_r = R_r = \rho\left(\frac{1-\cos\beta}{2}\right) \quad (4.40)$$

Example 4.7

Calculate the monthly average, total daily radiation falling on a flat-plate collector facing south ($\gamma = 0^\circ$) and tilted by 30° from the ground, at New Delhi (28° 35′ N, 77° 12′ E) for the month of November. Assume ground reflectivity as 0.2.

Solution Given data:

$\phi = 28.58^\circ$

$B = 30^\circ$

The representative day for the month of November is 14th.

Therefore, for the day of the year on November 14, $n = 318$

Monthly average of the daily global radiation for the month of November in New Delhi (from Table C1 in Appendix C),

$$\overline{H}_g = 16282.8 \text{ kJ/m}^2\text{-day}$$

Monthly average of the daily diffused radiation for the month of November in New Delhi (from Table C2 in Appendix C),

$$\overline{H}_d = 4107.6 \text{ kJ/m}^2\text{-day}$$

Using Eq. 4.5, $\delta = -18.91^\circ$

Using Eq. 4.11, $\omega_s = 79.245^\circ$, or 1.383 radians

As the day under consideration lies between September 22 and March 21, the hour angle at sunrise will be same as that obtained for a horizontal surface. Thus,

$\omega_{sr} = \omega_s = 79.245^\circ$, or 1.383 radians

Using Eq. 4.35,

$$R_b = \frac{1.383 \times \sin(-18.91)\sin(28.58-30) + \cos(-18.91)\sin 79.245\cos(28.58-30)}{1.383 \times \sin 28.58 \sin(-18.91) + \cos(-18.91)\sin 79.24 \cos 28.58}$$

$= 1.56$

Using Eq. 4.39,

$$\overline{R}_d = \frac{1+\cos 30^\circ}{2} = 0.933$$

Using Eq. (4.40),

$$\overline{R}_r = 0.2 \times \left(\frac{1-\cos 30^\circ}{2}\right) = 0.0134$$

Now, monthly average total daily radiation, $\overline{H}_T$ on a tilted surface may be calculated using Eq. 4.38,

$$\frac{\overline{H}_T}{\overline{H}_g} = \left(1 - \frac{\overline{H}_d}{\overline{H}_g}\right)\overline{R}_b + \frac{\overline{H}_d}{\overline{H}_g}\overline{R}_d + \overline{R}_r$$

$$\overline{H}_T = 16282.8 \times \left[\left(1 - \frac{4107.6}{16282.8}\right) \times 1.56 + \frac{4107.6}{16282.8} \times 0.933 + 0.0134\right]$$

$= 23043.89$ kJ/m²-day

Review Questions

1. What are the disadvantages of solar energy?
2. What are the indirect forms of solar energy?
3. How is the energy continuously being produced in the sun?
4. What do you understand by the earth's albedo?
5. At what wavelengths are the radiation emitted from the sun and that reflected from the earth centered?
6. Define solar irradiance, solar constant, extraterrestrial and terrestrial radiations. What is the standard value of solar constant?
7. Describe the percentage-wise distribution of various components in extraterrestrial radiation.
8. Explain the depletion process of solar radiation as it passes through the atmosphere to reach the surface of the earth.
9. What is solar time and why it is different from the standard clock time of a country?

10. Define declination angle, hour angle, zenith angle, solar azimuth angle and angle of incidence:
11. Derive an expression for solar day length.
12. Define beam, diffused and global radiation. Derive an expression for total radiation on an inclined surface. Show that a horizontal surface receives no ground-reflected radiation.
13. Explain the construction and principle of operation of a sunshine recorder.
14. How does the collection of solar energy get affected by tilting a flat-plate collector with respect to the ground?
15. How does sun tracking help in energy collection by a flat-plate solar collector?
16. What are the basic features required in an ideal pyranometer?

Problems

1. Calculate the number of daylight hours (daylength) at Bangalore on 21 June and 21 December in a leap year. The latitude of Bangalore is 12° 58′ N.

(**Ans.** 12:056 h, 11:944 h)

2. Calculate the angle made by beam radiation with the normal to a flat-plate collector, tilted by 30° from the horizontal, pointing due south, located at New Delhi, at 11:00 h (IST), on 1 June. The latitude and longitude of New Delhi are 28° 35′ N and 77° 12′ E respectively. The standard IST longitude is 81° 44′ E.

(**Ans.** 29.88°)

3. Calculate the angle of incidence on a horizontal plane surface at Kolkata, at 14:00 h (IST) on 21 March in a leap year. The longitude and latitude of Kolkata are 88° 20′ E and 22° 32′ N respectively. The standard longitude of IST is 81° 44′ E.

(**Ans.** 40.6°)

4. An inclined surface, facing due south, tilted at 60° with the horizontal, is location at Aligarh (latitude 27° 54′ N, longitude 78° 05′ E) on 22 March at 1 p.m. (IST). The reflection coefficient ρ of the ground is 0.2. Calculate the total radiation received at the surface. Also, calculate the values of R_b, R_r, R_d and R'.

(**Ans.** 929.72W/sq. m, 0.964, 0.75, 0.05, 0.9877)

5. Calculate the monthly average of the daily global radiation on the horizontal surface at Gulmarg (34.05° N, 74.38° E), during the month of October if the average sunshine hour per day is 5 hours.

(**Ans.** 13562.859 kJ/m²-day)

6. From the data given in Problem 5 for Gulmarg, estimate the monthly average of the daily diffused and beam radiations on a horizontal surface.

(**Ans.** 7083.35 kJ/m²-day, 6479.5 kJ/m²-day)

7. From the data given in Problem 5 above for Gulmarg, calculate the monthly average of the hourly global and hourly diffused radiations on a horizontal surface during 13:00 to 14:00 hours (LAT).

(**Ans.** 1151.284 kJ/m²-h, 800 kJ/m²-h)

8. The following hourly values are measured between 11:00 to 12:00 hours on a clear day on 20 March at Mumbai (19° 07′N, 72° 51′ E).
Global radiation = 3196.8 kJ/m²-h
Diffuse radiation = 745.2 kJ/m²-h
Using empirical relations, estimate the values of global and diffused radiations and compare with the measured data.

(**Ans.** I_g = 3608 kJ/m²-h, I_d = 387.48 kJ/m²-h)

9. Calculate the monthly average, total daily radiation falling on a flat-plate collector facing south (γ = 0°) and tilted by an angle equal to latitude from ground, at Mumbai (19° 07′ N, 72° 51′ E) for the month of September. Assume ground reflectivity as 0.15. For the month of September at Mumbai, the daily average data are given as H_g = 17560.8 kJ/m²-h and H_d = 10296 kJ/m²-h.

(**Ans.** 17202.8 kJ/m²-h)

10. Calculate the hour angles at sunrise on 21 June and also on 21 December for a flat-plate solar collector inclined due south (i.e., γ = 0°) at an angle equal to the latitude of the place. The collector is located at Nagpur (21° 06′ N, 79° 03′ E)

(**Ans.** 90°, 83.36°)

Objective-type Questions

1. Which process is responsible for production of energy in the sun?
(a) Nuclear fission reaction (b) Nuclear fusion reaction
(c) Exothermal chemical reaction (d) All of the above

2. Which one of the following statements is not true for solar energy?
(a) It is a dilute form of energy.
(b) Its availability is diurnal.
(c) Availability at any instant of time is uncertain.
(d) Its harnessing at large scale is easy.

3. Diffused radiation
(a) has no unique direction
(b) has a unique direction
(c) has short wavelength as compared to beam radiation
(d) has larger magnitude as compared to beam radiation

4. In extraterrestrial radiation, what is the approximate percentage content of infra-red component?
(a) 45.5% (b) 55.5% (c) 20% (d) 80%

5. Terrestrial radiation has a wavelength in the range of
(a) 0.2 μm to 4 μm (b) 0.2 μm to 0.5 μm
(c) 0.380 μm to 0.760 μm (d) 0.29 μm to 2.3 μm

6. What is the standard value of solar constant?
(a) 1 kW m² (b) 1.367 kW m² (c) 1.5 kW m² (d) 5 kW m²

7. When incoming solar radiation passes through the atmosphere of the earth
(a) radiation of all wavelengths is absorbed uniformly by different types of molecules
(b) different molecules selectively absorb the radiation of different wavelengths