2

Solar Radiation and its Measurement

2.1. Introduction

In general, the energy produced and radiated by the sun, more specifically the term refers to the sun's energy that reaches the earth. Solar energy, received in the form of radiation, can be converted directly or indirectly into other forms of energy, such as heat and electricity, which can be utilized by man. Since the sun is expected to radiate at an essentially constant rate for a few billion years, it may be regarded as an in-exhaustible source of useful energy. The major drawbacks to the extensive application of solar energy are :

1. The intermittent and variable manner in which it arrives at the earth's surface and

2. The large area required to collect the energy at a useful rate.

Experiments are underway to use this energy for power production, house heating, air conditioning, cooking and high temperature melting of metals.

Energy is radiated by the sun as electromagnetic waves of which 99 per cent have wave lengths in the range of 0.2 to 4.0 micrometers (1 micrometer = 10^{-6} meter). Solar energy reaching the top of the earth's atmosphere consists of about 8 per cent ultraviolet radiation (short wave length, less than 0.39 micrometer), 46 per cent visible light (0.39 to 0.78 micrometer), and 46 per cent infrared radiation (long wave length more than 0.78 micrometer).

2.2. Solar Constant

The sun is a large sphere of very hot gases, the heat being generated by various kinds of fusion reactions. Its diameter is 1.39×10^6 km. while that of the earth is 1.27×10^4 km. The mean distance between the two is 1.50×10^8 km. Although the sun is large, it subtends an angle of only 32 minutes at the earth's surface. This is because it is also at a very large distance. Thus the beam radiation received from the sun on the earth is almost parallel. The brightness of the sun varies from its centre to its edge. However for engineering calculations, it is customary to assume that the brightness all over the solar disc is uniform. As viewed from the earth, the radiation coming from the sun appears to be essentially equivalent to that coming from a black surface at 5762°K.

The rate at which solar energy arrives at the top of the atmosphere is called the *solar constant* I_{sc}. *This is the amount of energy received in unit time on a unit area perpendicular to the sun's direction at the mean distance of the earth from the sun.* Because of the sun's distance and activity vary throughout the year, the rate of arrival of solar radiation varies accordingly. The so called solar constant is thus an average from which the actual values vary upto about 3 per cent in either direction. This variation is not important however, for most practical purposes. The National Aeronautics and Space Administration's (NASA) standard value for the solar constant, expressed in three common units, is as follows :

1.353 kilowatts per square metre or 1353 watt per square metre.

116.5 langleys (calories per sq. cm) per hour, or 1165 kcal per sq. m per hour (1 langley being equal to 1 cal/cm^2 of solar radiation received in one day).

429.2 Btu per sq. ft. per hour.

The distance between the earth and the sun varies a little through the year. Because of this variation, the extra-terrestrial (out side the earth's atmosphere) flux also varies. The earth is closest to the sun in the summer and farthest away in the winter. This variation in distance produces a nearly sinusoidal variation in the intensity of solar radiation I that reaches the earth. This can be approximated by the equation

$$\frac{I}{I_{sc}} = 1 + 0.033 \cos \frac{360(n-2)}{365} \quad \text{...(2.2.1)}$$

$$\simeq 1 + 0.033 \cos \frac{360 \times n}{365} \quad \text{...(2.2.2)}$$

where n is the day of the year. As the distance between earth and sun varies a little through the year, due to it extra- terrestrial radiation also varies.

It is also useful to know the spectral distribution of extraterrestrial solar radiation. Measurements of this distribution are made and recorded by M.P. Thekaekara. It will be noted from Fig. 2.2.1, which shows spectral distribution of solar radiation intensity at the outer limit of atmosphere, that the maximum value of 2074 W/m^2—μm occurs at a wavelength of 0.48 μm and that 99 per cent of the sun's radiation is obtained upto a wavelength of 4 μm. The percentage of

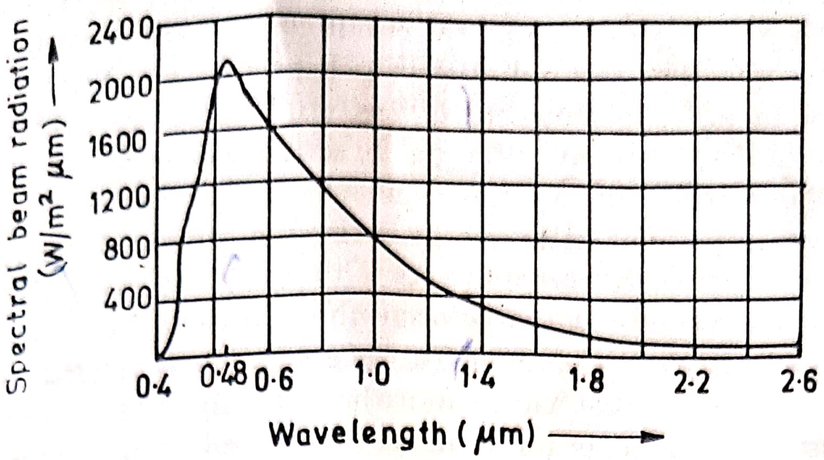


Fig. 2.2.1. Spectral distribution of solar radiation intensity.

radiation obtained upto a certain wavelength is also given in Table 2.2.1.

Table 2.2.1

Wavelength (μ)	0—0.38	0.38—0.78	0.78—4.0
Approximate energy (W/m^2)	95	640	618
Approximate percentage of total energy	7%	47.3%	45.7%

2.3. Solar Radiation at the Earth's Surface

From the point of view of utilisation of solar energy we are more interested in the energy received at the earth's surface than in the extra-terrestial energy. Solar radiation received at the surface of the earth is entirely different due to the various reasons. Before studying this it is important to know the following terms :

Beam and Diffuse Solar Radiation. The solar radiation that penetrates the earth's atmosphere and reaches the surface differs in both amount and character from the radiation at the top of the atmosphere. In the first place, part of the radiation is reflected back into the space, especially by clouds. Further more, the radiation entering the atmosphere is partly absorbed by molecules in the air. Oxygen and ozone (O_3), formed from oxygen, absorb nearly all the ultraviolet radiation, and water vapour and carbon dioxide absorb some of the energy in the infrared range. In addition, part of the solar radiation is scattered (*i.e.*, its direction has been changed) by droplets in clouds by atmospheric molecules, and by dust particles.

Solar radiation that has not been absorbed or scattered and reaches the ground directly from the sun is called "*direct radiation*" or *Beam radiation*. It is the radiation which produces a shadow when interrupted by an opaque object. *Diffuse radiation* is that solar radiation received from the sun after its direction has been changed by reflection and scattering by the atmosphere. Because of the solar radiation is scattered in all directions in the atmosphere, diffuse radiation comes to the earth from all parts of the sky Fig. 2.3.1. The total solar radiation received at any point on the earth's surface is the sum of the direct and diffuse radiation. This is referred to in a general sense as the *insolation* at that point. More specifically, the insolation is defined as the total solar radiation energy received on a horizontal surface of unit area (*e.g.*, 1 sq. m) on the ground in unit time (*e.g.*, 1 day).

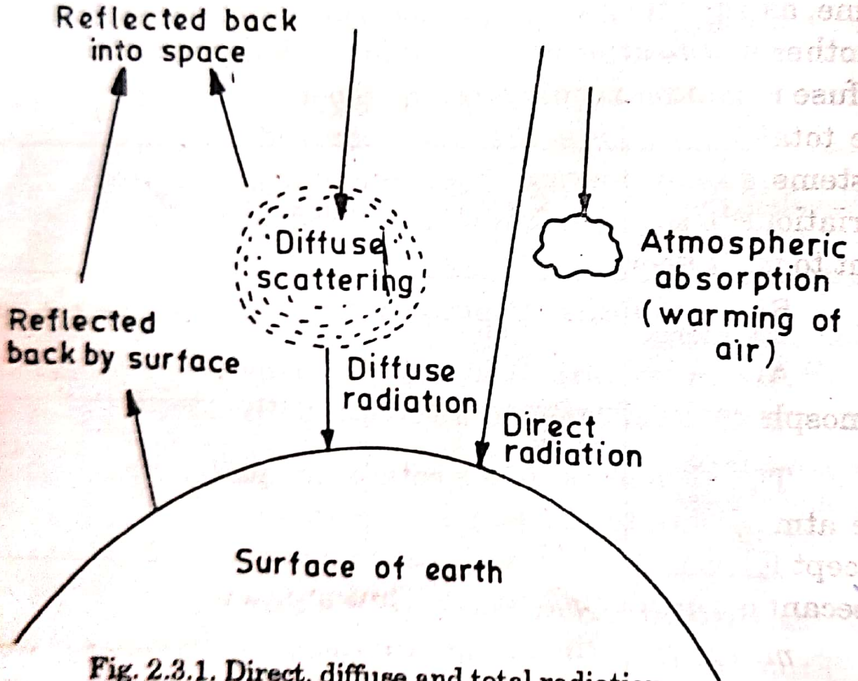


Fig. 2.3.1. Direct, diffuse and total radiation.

The insolation at a given location on the earth's surface depends, among other factors, on the altitude of the sun in the sky. (The altitude is the angle between the sun's direction and the horizontal). Since the sun's altitude changes with the date and time of the day and with the geographic latitude at which the observations are made, the rate of arrival of solar radiation on the ground is a variable quantity even in the time.

There are, nevertheless, some general points that can be made. The smaller the sun's altitude, the greater the thickness of atmosphere through which the solar radiation must pass the reach the ground Fig. 2.3.1. As a result of absorption and scattering, the insolation is less when the sun is low in the sky than when it is higher. However, when scattering occurs, diffuse radiation constitutes a larger fraction of the

total received. On a clear, cloudless day, about 10 to 20 per cent of the insolation is from diffuse radiation, the proportion increases upto 100 per cent when the sun is completely obscured by clouds. When the humidity is high, the insolation on a cloudy day, consisting entirely of diffuse radiation, may be as high as 50 per cent of the insolation on a clear day at the same time and place.

The intensity of the diffuse radiation seen by an observer on a clear day is not isotropic, but varies as a function of latitude time of the year, time of the day, atmospheric content, and other factors. This is discussed by a number of authors. The relationship is so complex that it is seldom considered theoretically. Most, often for solar system design purposes the diffuse radiation is assumed to be isotropic over the sky dome, as any other assumption is simply unwieldy for designers to use. Another justification often used for making this assumption is that the diffuse radiation is only a relatively small fraction (5 to 15 per cent) of the total when the sun is not obscured clouds, and that most solar systems do not operate when the sun is obscured by clouds. Hence variations in the distribution of the diffuse radiation are not too important to most users.

Sun at Zenith. Position of the sun directly over head.

Air mass (m). It is the path length of radiation through the atmosphere, considering the vertical path at sea level as unity.

The air mass m is the ratio of the path of the sun's rays through the atmosphere to the length of path when the sun is at the zenith. Except for very low solar altitude angles, the air mass is equal to the cosecant of the altitude angle. Thus at sea level $m = 1$.

$m = 1$ when the sun is at zenith, *i.e.*, directly over head.

$m = 2$ when zenith angle is 60° (θ_z, the angle subtended by the zenith and the line of sight to the sun).

$m = \sec \theta_z$ when $m > 3$.

$m = 0$ just above the earth's atmosphere.

Attenuation of Beam Radiation. The variation in solar radiation reaching the earth than received at the outside of the atmosphere is due to absorption and scattering in atmosphere.

(*i*) **Absorption.** As solar radiation passes through the earth's atmosphere the short-wave ultraviolet rays are absorbed by the ozone in the atmosphere and the long wave infra-red waves are absorbed by the carbon dioxide and moisture in the atmosphere. This results in narrowing of the band width. In fact most of the terrestrial solar energy (*i.e.*, energy received by the earth) lies within the range of 0.29 μ to 2.5 μ.

(*ii*) **Scattering.** As solar radiation passes through the earth's atmosphere the components of the atmosphere, such as water vapour and dust, scatter a portion of the radiation. A portion of this scattered radiation always reaches the earth's surface as diffuse radiation. Thus the radiation finally received at the earth's surface consists partly of beam radiation and partly of diffuse radiation.

It must be realized that scattering attenuates the radiation. The exact amount of scattering and consequential attenuation depends on the atmospheric conditions which vary from place to place and at a given place depend on the time of the day, the month of the year and the local weather.

Ozone absorbs mainly in the ultraviolet band. It absorbs almost completely the short wave radiation below 0.29 μm, and its transmittance is almost unity above wavelengths of 0.35 μm. Water vapour absorbs mainly in the infrared bands. At wavelength lower than 2.3 μm, the extra terrestrial solar radiation by H_2O and CO_2 in atmosphere, is strong. Hence for terrestrial application of solar energy, only wavelengths between 0.29 and 2.5 μm need be considered.

Fig. 2.3.2 shows spectral distribution curves. Under favourable atmospheric conditions, the maximum intensity observed at noon on an oriented surface at sea level is 1 kW/m^2. At an altitude of 1000 metres,

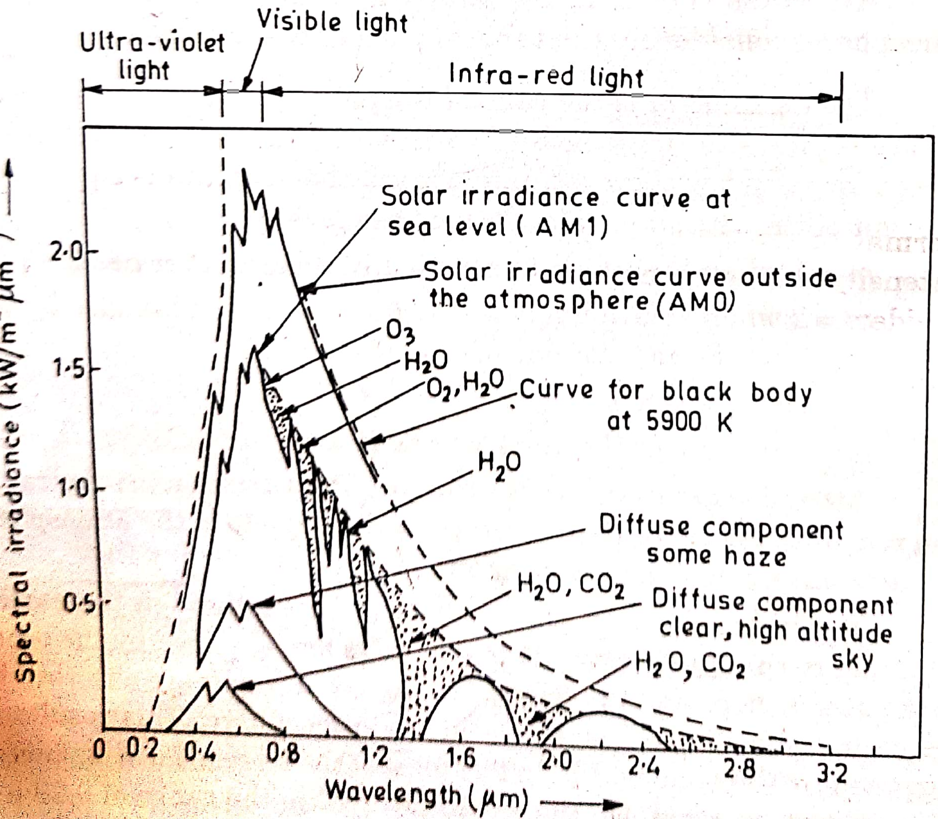


Fig. 2.3.2. The solar spectrum outside the atmosphere at a ground level.

the value rises to about 1.05 kW/m^2, and in higher mountains values slightly above 1.1 kW/m^2 are obtained, compared with 1.353 kW/m^2 (the solar constant) in outer space. The latter value is sometimes called *air mass* 0 (AM0), whereas at sea level, the maximum possible intensity is called AM1. The upper curve applies at the outer limit of the atmosphere (AM0). The other lower curve applies to the earth's surface during clear days for a sea level location, for AM1. Dotted curve shows curve for a black body at 5900°K. The lower two curves are for diffuse components for some haze and clear sky conditions respectively. Considering the solar irradiation curve or lower and upper curve case, the *atmospheric transmission factor* is given as the area under lower curve divided by the area under the upper curve (solar constant). For m = 1.0, the, transmission factor is 0.633, and for m = 5.0, at the earth surface sea level, the transmission factor is 0.276. For different values of m, the transmission factor can be determined. Thus the length of the sun's rays through the atmosphere is of extreme importance in affecting reduction of solar intensity.

2.4. Solar Radiation Geometry

In solar radiation analysis, the following angles are useful :

ϕ_l = latitude of location

δ = declination

ω = hour angle

γ_s = solar Azimuth angle

s = slope

α = altitude angle

θ_z = zenith angle.

If θ is the angle between an incident beam radiation I and the normal to the plane surface, then the equivalent flux or radiation intensity falling normal to the surface is given by I cos θ. θ is called incident angle.

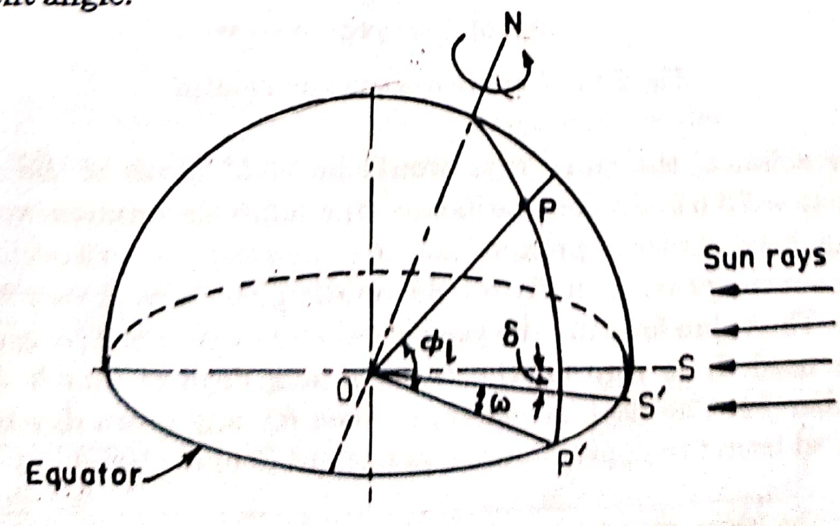


Fig. 2.4.1. Latitude ϕ_l, hour angle ω, and sun's declination δ.

Let us first define the above angles. The *altitude* ϕ_l of a point or location is the angle made by the radial line joining the location to the centre of the earth with the projection of the line on the equatorial plane. It is the angular distance north or south of the equator measured from centre of earth. As shown in Fig. 2.4.1, it is the angle between the line $\overline{OP}$ and the projection of $\overline{OP}$ on the equatorial plane. Point P represents the location on the earth surface and O represents the centre of the earth. By convention the latitude will be measured as positive for the northern hemisphere.

The *declination* δ is the angular distance of the sun's rays north (or south) of the equator. It is the angle between a line extending from the centre of the sun to the centre of the earth and the projection of this line upon the earth's equatorial plane.

This is the direct consequence of the tilt and it would vary between 23.5° on June 22 to 23.5° on December 22. At the time of winter solstice. (It is the latin world, meaning sun standing still. For minimum or maximum declination the sun appears to stand still) the sun rays would be 23.5° south of the earth's equator ($\delta = -23.5°$). At the time of

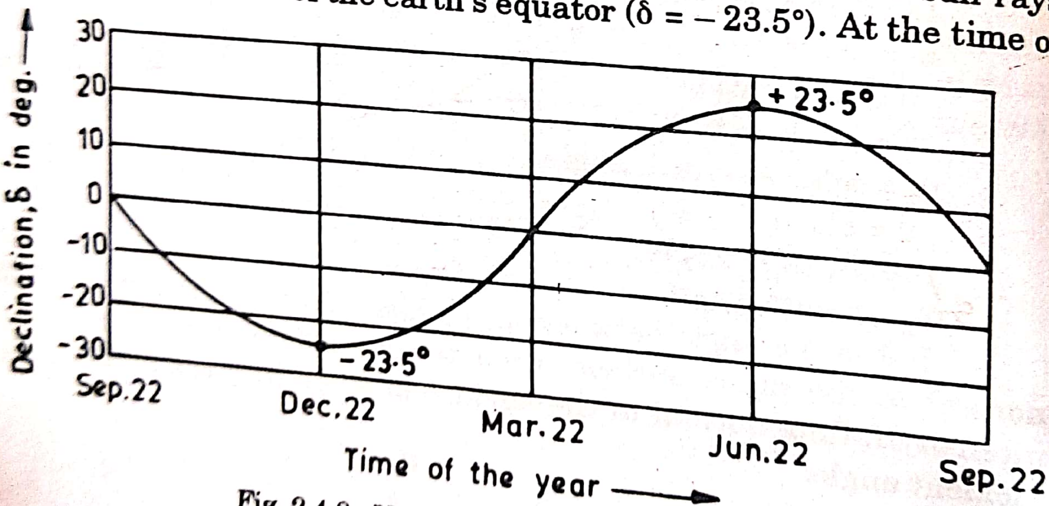


Fig. 2.4.2. Variation of sun's declination.

summer solstice, the sun's rays would be 23.5° north of the earth's equator ($\delta = 23.5°$). At the equinoxes* the sun's declination would be zero. Fig. 2.4.2 shows approximately the variation of sun's declination throughout the year. Actually the declination varies from year to year, slightly. The value for a middle year between two consecutive leap year may be used. It is zero on the two equinox days of March 22 and September 22. The declination in degrees for any given day may be calculated from the approximate equation of Cooper (1969).

*The Latin word "equinox" means *equal nights*. The nights are equal when the declination of the sun is zero.

$$\delta \text{ (in degrees)} = 23.45 \sin\left[\frac{360}{365}(284 + n)\right] \qquad \text{...(2.4.1)}$$

where n is the day of the year, [*e.g.* June 21, 1988 is the 173th (31 + 29 + 31 + 30 + 31 + 21) day of 1988 *i.e.*, n = 173].

The hour angle ω is the angle through which the earth must turn to bring the meridian of a point directly in line with the sun's rays. The hour angle ω is equivalent to 15° per hour. It is measured from noon based on the local solar time (LST) or local apparent time, being positive in the morning and negative in the afternoon. (The term LST will be defined a little later). It is the angle measured in the earth's equatorial plane, between the projection of $\overline{OP}$ and the projection of a line from the centre of the sun to the centre of the earth.

Altitude angle α (solar altitude). It is a vertical angle between the projection of the sun's rays on the horizontal plane and the direction of sun's rays (passing through the point). (Refer Fig. 2.4.3).

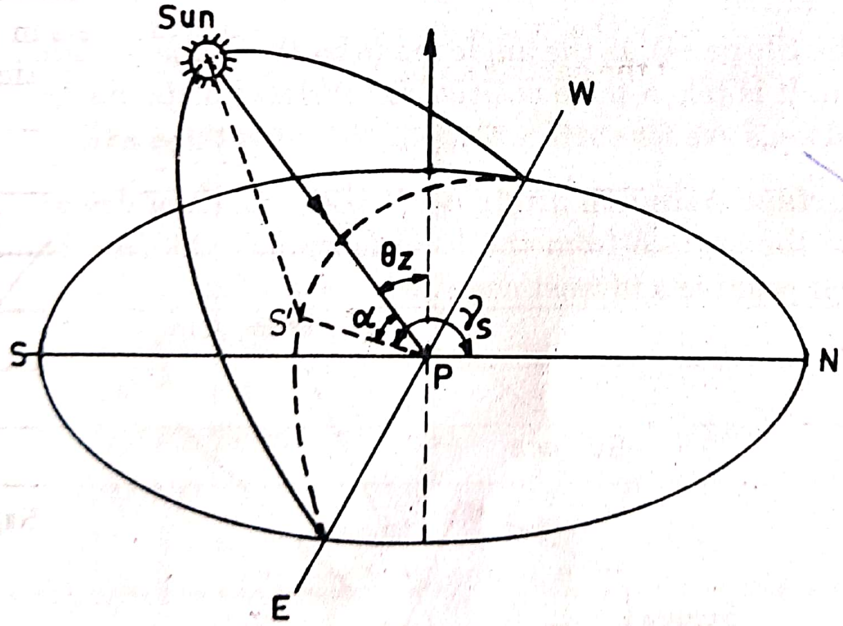


Fig. 2.4.3. Sun's zenith, altitude and azimuth angles.

Zenith angle θ_z. It is complimentary angle of sun's altitude angle. It is a vertical angle between the sun's rays and a line perpendicular to the horizontal plane through the point *i.e.* the angle between the beam from the sun and the vertical

$$\theta_z = \frac{\pi}{2} - \alpha.$$

Solar Azimuth angle γ_s. It is the solar angle in degrees along the horizon east or west of north or it is a horizontal angle measured from north to the horizontal projection of the sun's rays. This angle is positive when measured west wise.

...nce

$$\cos\theta_T = \cos(28.58° - 38.58°)\cos(-22.11°)\cos 45° + \sin(-22.11°)\sin(28.58° - 38.58°)$$
$$= \cos 10° \cos 22.11° \cos 45° + \sin 22.11° \sin 10°$$
$$= 0.6451 + 0.0653$$
$$= 0.7104$$

or $\theta_T = 44.72°$. **Ans.**

2.5. Solar Radiation Measurements

Measurements of solar radiation are important because of the increasing number of solar heating and cooling applications, and the need for accurate solar irradiation data to predict performance. Experimental determination of the energy transferred to a surface by solar radiation required instruments which will measure the heating effect of direct solar radiation and diffuse solar radiation. Measurements are also made of beam radiation, which respond to solar radiation received from a very small portion of the circum solar sky. A total radiation type of instrument may be used for measuring diffuse radiation alone by shading the sensing element from the sun's direct rays.

Two basic types of instruments are employed for solar radiation measurement:

(1) a *pyrheliometer*, which collimates the radiation to determine the beam intensity as a function of incident angle, and

(2) a *pyranometer*, which measures the total hemispherical solar radiation. The pyranometer measurements are the most common.

The total solar radiation arriving at the outer edge of the atmosphere is called the solar constant as already mentioned.

(A) Pyrheliometers. A pyrheliometer is an instrument which measures beam radiation. In contrast to a pyranometer, the sensor disc is located at the base of a tube whose axis is aligned with the direction of the sun's rays. Thus diffuse radiation is essentially blocked from the sensor surface.

Most pyrheliometers used for routine measurements operate on the thermopile effect and are similar to pyranometer in this respect. They differ in that mechanically they must follow the sun to measure only direct sunlight and avoid the diffuse component. In practice, direct solar radiation is measured by attaching the instrument to an electrically driven equatorial mount for tracking the sun. The diffuse component is avoided by installing a collimator tube over the sensor with a circular cone angle of about 5°.

Problems with pyrheliometer measurements are several fold; the aperture angle, the circum solar contributions and imprecision in the tracking mechanism. The first two problems are almost impossible to eliminate because of the inability to define the solar disk precisely and the finite dimensions of the instrument components. The practical matter of precise taking and sensor orientation are simply great. The use of correction factors in not only involved but somewhat unreliable.

The direct solar component on a horizontal surface may also be obtained using a shading ring, this is done by subtracting the shaded (diffuse) from the unshaded (global) reading.

Current practice in solar radiometry relies primarily on thermoelectric transducers. However, relatively low cost photovoltaic transducers are becoming more popular. To measure the direct solar radiation, the receiving surface must be normal to direct solar rays, *i.e.* a line joining the sun and receiver. Three pyrheliometers have been in wide-spread use to measure normal incident beam radiation :

(*i*) the Angstrom pyrheliometer

(*ii*) the Abbot silver disc pyrheliometer

(*iii*) Eppley pyrheliometer.

The instruments provide primary and secondary standard of solar radiation measurements.

(*i*) **Angstrom compensation Pyrheliometer.** In this pyrheliometer, a thin blackened shaded manganin strip (Size 20 × 2 × 0.1 mm) is heated electrically until it is at the same temperature as a similar strip which is exposed to solar radiation. It is shown schematically in Fig. 2.5.1. Under steady state conditions (both strips at identical

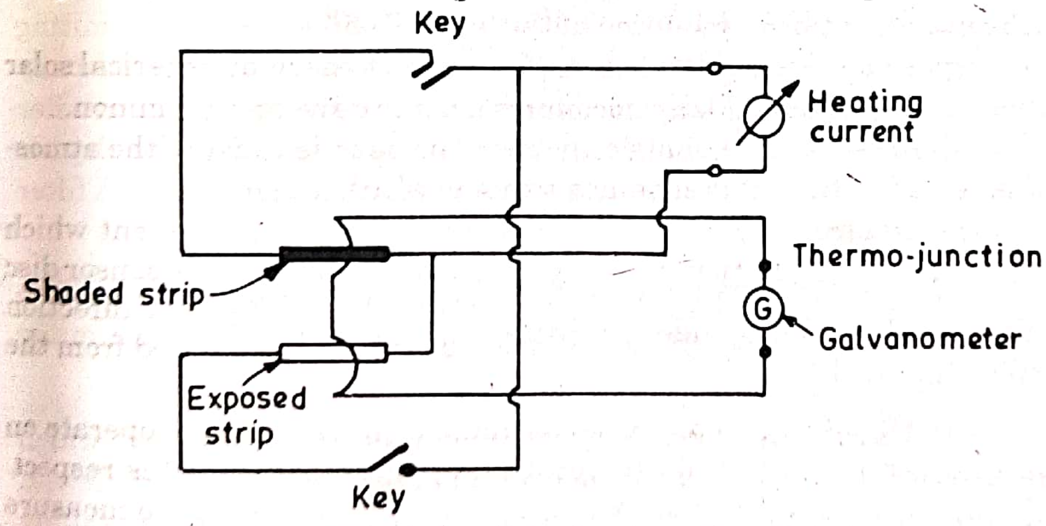


Fig. 2.5.1. Electric circuit for Angstrom Pyrheliometer.

temperature) the energy used for heating is equal to the absorbed solar energy. The thermocouples on the back of each strip, connected in opposition through a sensitive galvanometer (or other null detector), are used to test for the equality of temperature. The energy H of direct radiation is calculated by means of the formula,

$$H_{DN} = Ki^2$$

where H_{DN} = Direct radiation incident on an area normal to sun's rays

2.7. Estimation of Average Solar Radiation

One of the earliest expressions, for monthly average horizontal solar radiation H_{av} was given by Angstrom (1924), which is

$$H_{av} = H_o' \left(a' + b' \frac{\bar{n}}{N} \right) \quad ...(2.7.1)$$

where a' and b' are arbitrary constants. (Freitz 1951, suggested that $a' = 0.35$ and $b' = 0.61$),

H_o = the monthly average horizontal solar radiation for a clear day.

$\bar{n}$ = average daily hours of bright sunshine for same period.

N = maximum daily hours of bright sunshine for the same period.

Values H_0' for use in equation 2.7.1 can be obtained from charts of Fig. 2.7.1. The day length can be obtained from a nomogram developed by Whillier (Fig. 2.7.2) or can be calculated from the equation

$$N = t_d = \frac{2}{15} \cos^{-1} (-\tan \phi \tan \delta).$$

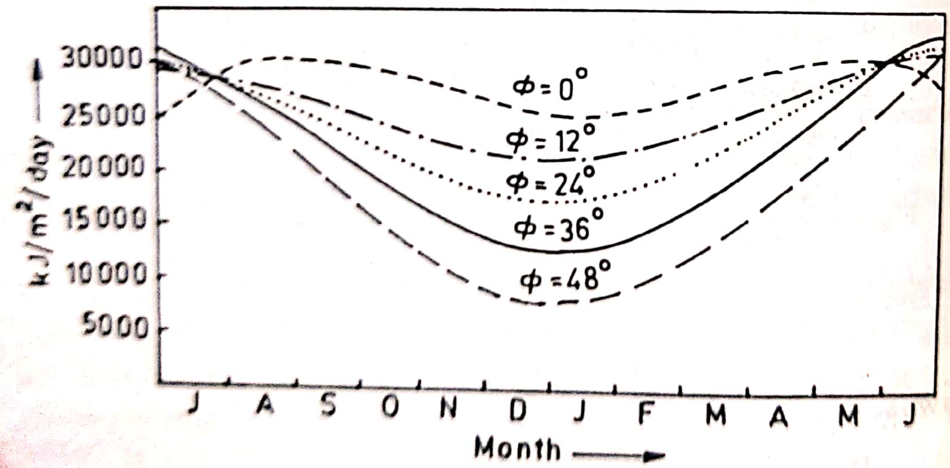


Fig. 2.7.1. Solar radiation on a horizontal plane for a clear day at various latitudes.

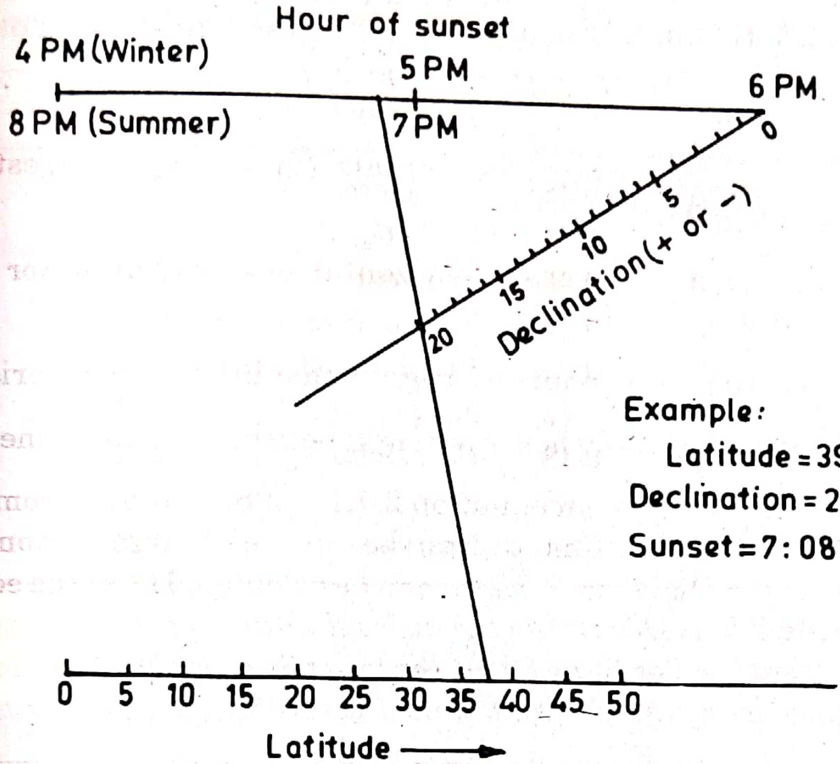
A better form of equation 2.7.1 is suggested by Page (1964).

$$H_{av} = H_o \left(a + b \frac{\bar{n}}{N} \right) \quad ...(2.7.2)$$

where H_o = the average monthly insolation at the top of the atmosphere.

a and b are the modified constants depending upon the location.

Constant a and b for various locations and climate conditions can be obtained from standard tables.



Example Latitude = 37° N

Declination = 20°

Sunset = 7.08 P.M.

Fig. 2.7.2. Nomograph to determine δ and hour of sunrise/sunset in solar time (Whillier 1965).

Table 2.7.1 gives the values of constants a and b for some Indian towns.

H_o can be obtained from charts or it can be calculated by following empirical relation

$$H_o = \frac{24}{\pi} I_{sc} \left[\left\{ 1 + 0.033 \cos \left(\frac{360\, n}{365} \right) \right\} \left(\cos\phi \cos\delta \sin\omega_s + \frac{2\pi\omega_s}{360} \sin\phi \sin\delta \right) \right] \quad \text{...(2.7.3)}$$

where

I_{sc} = solar constant per hour

n = day of the year

ω_s = sunrise hour angle.

$$= \frac{24}{3.14} I_{sc} [1 - 0.033, 0.9816)(0.9848 - 0.9171 \times 0.9970 + 1.65 \times 0.1765 \times 0.3987)]$$

$$= \frac{24}{3.14} I_{sc} [(0.9675)(1.0143)]$$

$$= \frac{24}{3.14} I_{sc}\, 0.9816 \qquad ...(i)$$

The value of I_{sc} in S.I. units is 1353 W/m^2 or 4871 kJ/m^2 hr and MKS units is = 1165 kcal/hr m^2.

SI units

$$H_0 = \frac{24}{3.14} \times 1353 \times 0.9816 = 10143 \text{ W/m}^2 \text{ day}$$

$$\therefore \quad H_{ac} = 10143 \times (0.3 + 0.51 \times 0.55)$$

$$= 10143 \times 0.58 = \mathbf{5884\ W/m^2\ day.} \quad \textbf{Ans.}$$

MKS units

$$H_0 = \frac{24}{3.14} \times 1165 \times 0.9816 = \mathbf{8740\ kcal/m^2\ day.}$$

$$\therefore \quad H_{av} = 8740 \times 0.58 = \mathbf{5070\ kcal/m^2\ day.} \quad \textbf{Ans.}$$

2.8. Solar Radiation on Tilted Surfaces

The rate of receipt of solar energy on a given surface on the ground depends on the orientation of the surface with reference to the sun. A fully sun-tracking surface that always faces the sun receives the maximum possible solar energy at the particular location. A surface of the same area oriented in any other direction will receive a smaller amount of solar radiation. Because solar radiation is such a 'dilute' form of energy, it is desirable to capture as much as possible on a given area. We have seen in the preceding sections that the measuring instruments give the values of solar radiation falling on a horizontal surface. Because most of the solar collectors or solar radiation collecting devices are tilted at an angle to horizontal, it is therefore necessary to convert data for a hourly radiation (measured or estimated) on a horizontal surface of radiation on a tilted surface.

Beam Radiation. In most cases ; the tilted surface faces due south *i.e.*, $\gamma = 0$, for this case,

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

For horizontal surface ($\theta = \theta_z$)

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

It follows that the ratio of the beam radiation falling on the tilted surface to that falling on a horizontal (Fig. 2.8.1) surface is given by

$$R_b = \frac{H_T}{H}$$

$$= \frac{H_n \cos\theta_T}{H_n \cos\theta_z} = \frac{\cos\theta_T}{\cos\theta_z}$$

$$= \frac{\sin(\phi - s)\sin\delta + \cos(\phi - s)\cos\delta\cos\omega}{\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega} \quad ...(2.8.1)$$

This ratio is called the *tilt factor* for beam radiation.

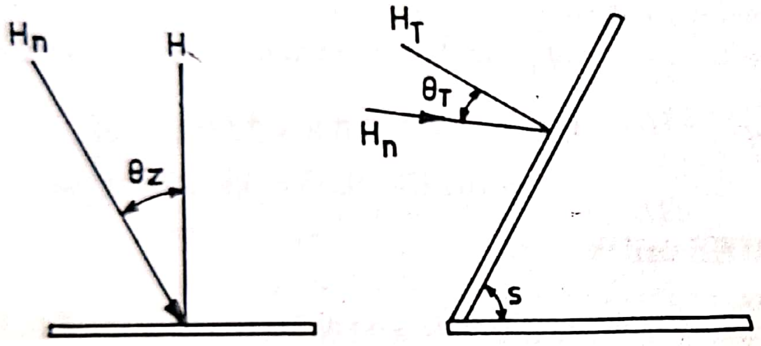


Fig. 2.8.1. Radiation on horizontal and tilted surface.

Total Radiation. Beam and diffuse component of solar radiation are absorbed in flat plate type collector. The angular correction factor has been determined for beam radiation as given by equation 2.8.1. Correction for diffuse radiation can be applied for clear days, for that it can be assumed that their origin is near the sun, that is, the scattering of solar radiation is mostly forward scattering. For such a case R may be assumed equal to R_b, where R is the correction factor for both direct and diffuse radiation.

$$R = \frac{H_T}{H}$$

or

$$H_T = R(H_b + H_d) \quad ...(2.8.2)$$

For cloudy or hazy days diffuse radiation can be assumed as uniformly distributed over the sky. The effective ratio of solar energy on the tilted surface to that on the horizontal surface is then

$$R = \frac{H_T}{H} = \frac{H_b}{H} R_b + \frac{H_d}{H} \quad ...(2.8.3)$$

Conversion factor for diffuse radiation (R_d) is given by equation

$$R_d = \frac{(1 + \cos s)}{2}$$

A surface tilted at slope s from the horizontal sees $\frac{(1 + \cos s)}{2}$ of the sky dome.

The tilted surface also sees ground or other surroundings and if those surroundings have a diffuse reflectance of ρ for solar radiation, the reflected radiation from the surrounding on the surface from total solar radiation is

$$(H_b + H_d)(1 - \cos s)\frac{\rho}{2}.$$

Hence three components ; the beam radiation, diffuse solar radiation and solar radiation reflected from the ground which the tilted surface sees, are considered above. This was first considered by Liu and Jordon. Hence combining the three terms.

$$H_T = H_b R_b + H_d \frac{(1 + \cos s)}{2} + (H_b + H_d)\frac{(1 - \cos s)}{2}\rho \quad ...(2.8.4)$$

and

$$R = \frac{H_b}{H} R_b + \frac{H_b}{H}\frac{(1 + \cos s)}{2} + \frac{(1 - \cos s)}{2}\rho \quad ...(2.8.5)$$

The values of diffuse reflectance as suggested by Liu and Jordon are as follows

$\rho = 0.2$ when there is no snow

$= 0.7$ when there is a snow cover.

Therefore for Indian conditions, a value around 0.2 is generally expected with surfaces of concrete or glass and can be used. Fortunately the reflected radiation term does not contribute much to the total because in India the value of the angle s would rarely exceed 30°

Questions

2.1. (*i*) Define solar constant.

(*ii*) What are the reasons for variation in solar radiation reaching the earth than received at the outside of the atmosphere ?

2.2. Write notes on Beam and Diffuse radiation.

2.3. Define the terms :

(*i*) Altitude angle (*ii*) Incident angle,

(*iii*) Zenith angle. (*iv*) Solar azimuth angle,

(*v*) Latitude angle, (*vi*) Declination angle,

(*vii*) Hour angle.

2.4. Calculate the angle made by the beam radiation with the normal to a flat-plate collector, pointing due south located in New Delhi (28° 38′ N, 77° 17′ E) at 9 : 00 hour, solar time on December 1. The collector is tilted at angle of 36° with the horizontal. **[Ans. 45.8°]**