UNIT 1 SOLAR RADIATION AND RADIATION CHARACTERISTICS OF MATERIALS

Structure

1.1 INTRODUCTION

All the solar energy devices depend upon the electromagnetic radiation continuously being emitted from the sun and striking the Earth surface. These are short wave radiations. When solar radiation strikes the Earth's surface, it gets absorbed and is re-emitted as long wavelength thermal radiation. Thus, thermal radiations are a form of energy emission and depend solely on the temperature and the characteristics of the emitting surface. The various forms of radiations differ only in wavelength. If you study the spectrum of electromagnetic waves, the range of wavelength of thermal radiation is, theoretically, from zero meter to infinity. A large part of thermal radiation has wavelength in the range from about 0.1 μm to 100 μm (1 μm = 10^{-6} meter). The visible portion of thermal radiation ranges from approximately 0.4 μm to 0.7 μm.

As solar radiation passes through the atmosphere, some of it is absorbed, some is scattered, and the rest is reflected by the following :

- Air molecules
- Water vapor

- Clouds
- Dust
- Pollutants
- Forest fires
- Volcanoes

The radiation reaching the Earth's surface is called diffused solar radiation or simply diffused radiation. The solar radiation which reaches the Earth's surface without being diffused is called direct solar radiation or simply direct insolation. The sum of the diffused and direct insolation is called global insolation. Atmospheric conditions can reduce direct insolation by about 10% on clear, dry days and by 100% on thick, cloudy days.

> The surface of the sun has an effective temperature of approximately 5760ºK and emits most of its energy between 0.1 μm and 3 μm.

Objectives

After studying this unit, you will be able to

- understand solar radiation,
- understand how to estimate solar radiation on a horizontal surface, and
- understand how to estimate solar radiation on a tilted surface.

1.2 HEAT TRANSFER CHARACTERISTICS OF SURFACES

Thermal radiations are electromagnetic radiations and travel at the speed of light, which is equal to about 3×10^8 m/s in vacuum. This speed of thermal radiations is related to the wavelength and frequency by the following equation :

$$c = \lambda \nu \qquad \ldots (1.1)$$

where c = speed of light, m/s,

λ = wavelength of radiation, m, and

ν = frequency of radiation, s^{-1}.

The electromagnetic radiations have dual nature, behaving like waves and also like particles. As particles electromagnetic waves are discrete quanta, called photons of energy E given by

$$E = h \nu \qquad \ldots (1.2)$$

where E = energy of a photon in Joules,

h = Planck constant = 6.6×10^{-34} J.s, and

ν = frequency of radiation, s^{-1}.

When a beam of thermal radiation is incident on the surface of a body, the following could happen :

(a) some of it may gets reflected away from the surface,

(b) some of it may get absorbed by the body, and

(c) some of it may get transmitted through the body.

This is shown in Figure 1.1. The radiation characteristics of a surface are its ability to reflect (reflectivity), its ability to absorb (absorptivity) and its ability to transmit (transmissivity). These are defined as follows:

α = reflectivity = fraction of radiation reflected by the surface,

ρ = absorptivity = fraction of radiation absorbed by the surface, and

τ = transmissivity = fraction of radiation transmitted through the surface.

Thus, $$\alpha + \rho + \tau = 1 \qquad \text{. . . (1.3)}$$

Most of the solid objects are opaque and hence $\tau = 0$. If a body absorbs all the incoming radiation (such a body is called black body), we have $\tau = 0$, $\rho = 1$and hence $\alpha = 0$.

> The radiation characteristics of a surface depend not only on the surface properties but also on the wavelength and direction of the radiation.

The emissive power, E_b, of a black body is expressed by Stefan-Boltzman law defined as follows :

$$E_b = \sigma\, T^4 \qquad \text{. . . (1.4)}$$

Whereσ = Stefan-Boltzmann constant = 5.67×10^{-8} W/m^2.K^4 and T is the temperature in degree Kelvin.

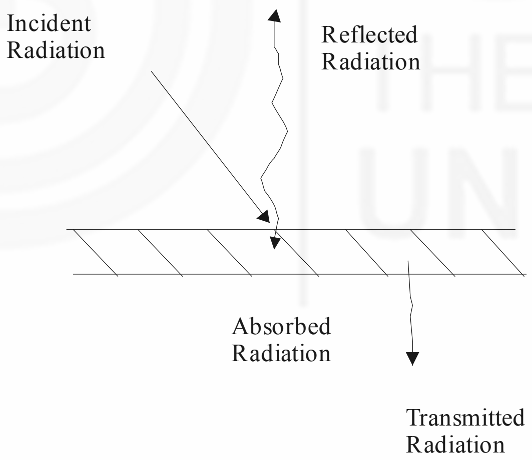

Figure 1.1 : Solar Radiation Striking a Surface

1.3 RADIATIVE PROPERTIES OF REAL SURFACES

An ideal black body is a perfect absorber as well as perfect emitter of thermal radiations. All real surfaces emit less energy than corresponding blackbodies.

1.3.1 Emmissivity of a Surface

The ratio of the total emissive power E of a real surface to the total emissive power, E_b, of a blackbody is called the emissivity, ε, of the real surface.

Thus, $$\varepsilon = \frac{E}{E_b} \qquad \text{. . . (1.5)}$$

The emissivity of a surface is a function of following parameters :

(1) surface temperature,

(2) wavelength of the incident radiation, and

(3) direction of the incident radiation.

The emissivity defined by Eq. (1.5) is the average value over the entire wavelength range in all directions. It is called total emissivity.

1.3.2 Kirchoff's Law

The Krichhoff's law of radiation states that the monochromatic (single wavelength) emissivity is equal to the monochromatic absorptivity for any surface when in thermal equilibrium with its surroundings. This may be expressed as follows :

$$\varepsilon_{\lambda}(T) = \alpha_{\lambda}(T) \quad \ldots (1.6)$$

where $\varepsilon_{\lambda}(T)$ is the monochromatic emissivity at wavelength λ and temperature T and $\alpha_{\lambda}(T)$ is the monochromatic absorptivity at wavelength λ and temperature T.

You will learn later in this course that the solar energy absorbed by a solar collector is always in the process of losing the absorbed radiation to the environment by radiation, conduction and convection.

1.3.3 Advantages of Selective Surfaces

The radiation losses from a solar absorber can be reduced significantly when the receiving surface has selective radiation properties. Table 1.1 gives the properties of some selective surfaces.

Table 1.1 : Properties of a Some Selected Surfaces

Material	Short-wave Absorptivity	Long-wave Emissivity
Black nickel on nickel-plated steel	0.95	0.07
Black chrome on nickel-plated steel	0.95	0.09
Black chrome on galvanized steel	0.95	0.16
Black chrome on copper	0.95	0.14
Black copper on copper	0.88	0.15
CuO on nickel	0.81	0.17
CuO on aluminum	0.93	0.11
PbS crystals on aluminum	0.89	0.20

You can see the following properties of selective surfaces :

- high absorptivity for radiation in the solar range of wavelengths, and
- low emissivity for long wave thermal radiation.

To be Remembered

It is highly desirable to make use of selective surfaces in solar collector absorbers to attain high solar energy absorption, and at the same time to reduce radiation losses to surroundings.

1.4 SOLAR RADIATION ON A SURFACE

1.4.1 Basic Principles

Each location on Earth receives sunlight at least for a part of the year. The amount of solar radiation that reaches a particular "spot" on the Earth's surface depends on a number of factors. These factors are :

- Geographic location
- Time of day
- Season
- Local landscape
- Local weather

The Sun strikes the surface at different angles ranging from 0° (just above the horizon) to 90° (directly overhead) due to nearly round shape of the earth. When the Sun's rays are vertical, the Earth's surface gets maximum energy possible. The more slanted the Sun's rays are, the longer they travel through the atmosphere, becoming more scattered and diffused reducing the amount of energy reaching Earth's surface.

Earth revolves around the Sun in an elliptical orbit and is closer to the Sun during a part of the year. When the Sun is nearer the Earth, the Earth's surface receives a little more solar energy. The Earth is nearer the Sun when it's summer in the southern hemisphere and winter in the northern hemisphere. The 23.5° tilt in the Earth's axis of rotation is also a significant factor in determining the amount of sunlight striking the Earth at a particular location.

The rotation of the Earth around its own axis is responsible for hourly variations in sunlight. In the early morning and late afternoon, the Sun is low in the sky. Its rays travel longer through the atmosphere than at noon when the sun is at its highest point. On a clear day, the maximum amount of solar energy reaches a solar collector around solar noon.

SAQ 1

What are the factors which affect the amount of solar radiation reaching a surface?

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SAQ 2

What causes the hourly variations of the solar radiation reaching the earth?

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Before we discuss solar radiation on a surface (horizontal or tilted), let us talk about the nature of the solar radiation. The earth receives two types of solar radiation called beam and diffuse radiation. These are defined in the following sections.

1.4.2 Beam Radiation or Direct Radiation

The radiation received by the Earth without any change in the direction is referred to as beam radiation or direct radiation as shown in Figure 1.2.

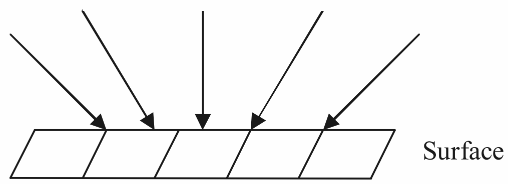

Figure 1.2 : Beam Radiation

1.4.3 Diffused Radiation

The diffused radiation is received by the Earth from all directions. The radiations may change their direction due to scattering from dust particles, clouds etc. while passing through atmosphere. Diffused radiations do not have a unique direction. The diffused radiation is shown in Figure 1.3. The concept of how beam and diffused radiations are received by the surface is shown in Figure 1.4. Diffused component of solar radiation (B) is that portion which is reflected from clouds, the ground, and nearby objects, and direct component of solar radiation (A) is that portion which falls onto flat-plate solar panels.

Some of the other terms used to discuss solar radiation are described below;

1.4.4 Global Radiation (Solar Insolation)

The total radiation is the sum of direct radiation and diffused radiation and is called ***global radiation*** or simply ***insolation***.

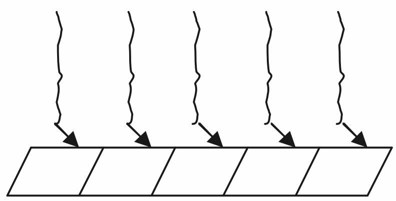

Figure 1.3 : Diffused Radiation

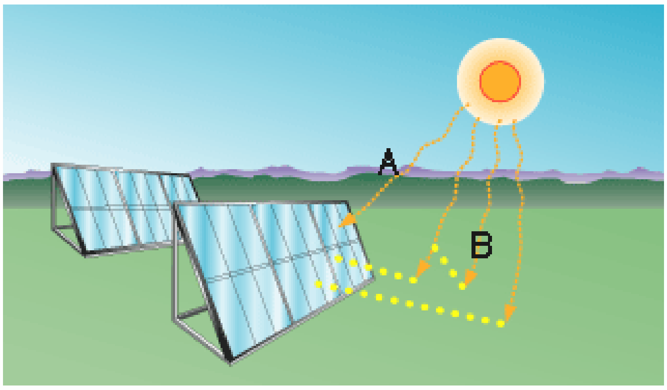

Figure 1.4 : Beam and Diffuse Radiation (Us Dept. of Energy)

Insolation : Total amount of solar radiation per unit area per day reaching a part of the Earth is called the 'insolation', a short form of "incident solar radiation".

Solar insolation is defined as the amount of sunshine incident on the surface of the Earth per unit area per day. You can determine the size of solar collectors provided the value of solar insolation is known. If the value of solar insolation is less, the area of the collector will be large as compared to the case where solar insolation is high.

Solar insolation is expressed in KWh/m^2/day. It is the amount of solar energy which falls on a square meter of Earth's surface in a single day.

To be Remembered
1 KWh/m^2/day = 3.6 MJ/m^2/day = 317.1 Btu/ft^2/day
1 KWh = 3.6 MJ = 859.8 KCal = 3412 BTu

1.4.5 Irradiance

The rate at which radiations fall on a surface per unit area is called irradiance (W/m^2).

In solar energy engineering, we come across the term extraterrestrial solar radiation and terrestrial solar radiation. In order to understand these terms, let us consider terrestrial and extraterrestrial regions as shown in Figure 1.5.

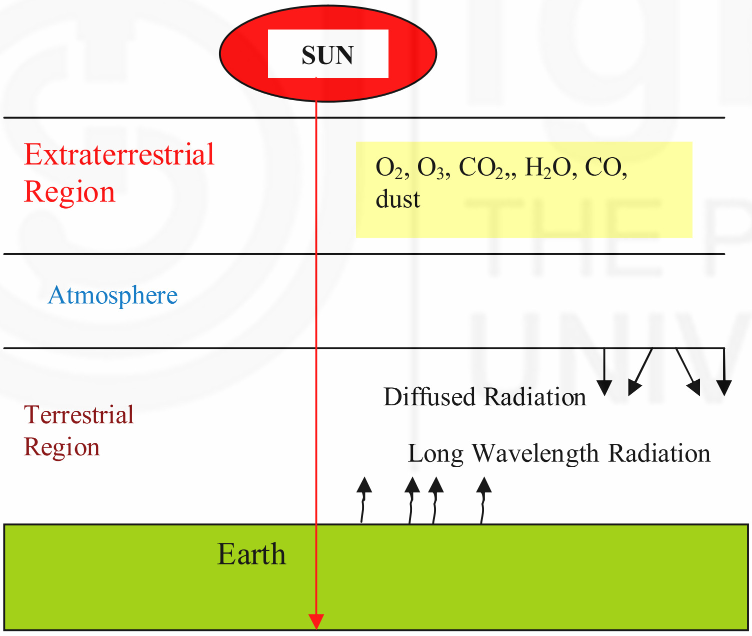

Figure 1.5 : Terrestrial and Extraterrestrial Regions

1.4.6 Extraterrestrial Solar Radiation

You know that Earth is inclined at an angle and revolves around the Sun in an elliptic orbit. The orientation of the Earth's orbit around the Sun is such that the Earth-Sun distance varies only by about 1.7 %. The solar radiation outside Earth's atmosphere is almost constant and is called solar constant.

Solar Constant

The radiation received per second by a surface of unit area held normal to the sun's rays at the mean earth-sun distance outside the atmosphere is constant throughout the year. It is called Solar Constant and is equal to 1367 W/m^2.

> Solar Constant is defined as the radiation received per second by a surface of unit area held normal to the sun's rays at the mean earth-sun distance outside the atmosphere. The value of solar constant is equal to 1367 W/m^2.

The intensity of extraterrestrial radiation measured at a plane normal to the radiation is given by (Duffie and Beckman 1991).

$$I_{ext} = I_{sc}[1 + 0.033\cos(360n/365)] \quad \ldots (1.7)$$

where I_{ext} = extraterrestrial radiation,

I_{sc} = solar constant, and

n = day of the year (n = 1 for January 1, n = 365 for December 31).

> **SAQ 3**
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> Define solar constant.
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Example 1.1

Evaluate the extraterrestrial solar radiation on January 1, June 22 and December 1.

Solution

For January 1, n = 1

For June 22, n = 174

For December 21, n = 355

Using Eq. (1.7), we get

For January 1 :

$$I_{ext} = 1367\ [1 + 0.033 \cos (360 \times 1/365)] = 1412\ \text{W/m}^2$$

For June 22 :

$$I_{ext} = 1367\ [1 + 0.033 \cos (360 \times 174/365)] = 1322\ \text{W/m}^2$$

For December 21 :

$$I_{ext} = 1367\ [1 + 0.033 \cos (360 \times 355/365)] = 1411\ \text{W/m}^2$$

1.4.7 Main Features of Solar Radiation

Sun is continuously radiating energy in the form of electromagnetic radiations. These radiations while passing through earth's atmosphere are subject to absorption (by ozone O_3, oxygen O_2, nitrogen N_2, carbon dioxide CO_2, carbon monoxide CO and water vapour H_2O) and scattering (by dust particles, air molecules and water droplets etc) in the atmosphere. A fraction of the radiation striking the earth's surface is reflected back into the atmosphere where it is again absorbed and scattered. The remaining radiations are absorbed by the Earth's surface.

To be Remembered

(1) x-rays and extreme ultra-violet radiations are absorbed by the nitrogen, oxygen and other atmospheric gases.

(2) ozone absorbs ultraviolet radiations (wavelengths less than 0.4 μm.

(3) water vapours absorbs infrared radiations (wavelengths greater than 2.3 μm.

The main components of solar radiation falling on the earth are the following :

- Short wavelength (optical wavelengths) radiation from the Sun reaches the top of the atmosphere.
- Clouds reflect 17% back into space. If the Earth gets more cloudy, as some climate models predict, more radiation will be reflected back and less will reach the surface.
- 8% is scattered backwards by air molecules.
- 6% is actually directly reflected off the surface back into the space.
- So the total reflectivity of the earth is 31% which is technically known as **Albedo**.

During Ice Ages, the Albedo of the Earth increases as more of its surface is reflective.

You may be wondering what happens to the remaining 69% of the incoming radiation that doesn't get reflected back. Here is the approximate break up :

- 19% gets absorbed directly by dust, ozone and water vapour in the upper atmosphere. This region is also known as stratosphere and is heated by this absorbed radiation.
- 4% gets absorbed by the clouds located in the troposphere. This is lower part of the Earth's atmosphere.
- The remaining 46% of the sunlight that is incident on top of the earth's atmosphere reaches the surface.

Example 1.2

Estimate the average energy from the Sun that reaches the surface of the Earth.

Solution

Incident solar energy on the ground :

- Average over the entire Earth = 170 W/m^2 over a 24 hour day
- 8 hour summer day, 40 degree latitude = 600 W/m^2

So this 8 hour will receive

- 8 hours* 600 W/m^2 = 4800 Whr/m^2 which equals 4.8 KWh /m^2.

To be Remembered

Classes of solar radiation :

- Ultraviolet (UV): < 0.38 μm wavelength, approximately 7% of solar radiation
- Visible: 0.38-78 μm, 47% of solar radiation
- Infrared (IR): > 0.78 μm, 46% of solar radiation

SAQ 5

What is Albedo?

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1.5 SOLAR RADIATION ON A TILTED SURFACE

Let us consider the solar radiation falling on a surface. The amount of solar radiation on a terrestrial surface at a given location for a given time depends on the orientation and slope of the surface. A surface which is always normal to the sun's rays would receive maximum amount of solar radiation. The solar energy collectors may be tilted at a suitable angle so that it is roughly normal to the sun's rays so that maximum energy collection is obtained.

If you wish to design any solar energy device, you need to know the data of solar radiation on such tilted surfaces. However, measured or estimated radiation data are available mostly either for normal incidence or for horizontal surfaces. It is necessary to convert these data to radiation on tilted surfaces.

Let us consider beam radiation falling on horizontal and tilted surfaces as shown in Figure 1.6.

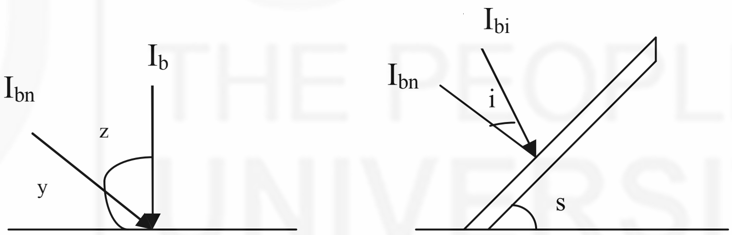

Figure 1.6 : Beam Radiation on Horizontal and Tilted Surfaces

Let I_{bn} = beam radiation at normal incidence,

I_s = beam radiation at horizontal surface, and

I_{bi} = beam radiation at tilted surface.

From Figure 1.6, we have

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

$$I_{bi} = I_{bn} \cos i$$

The beam radiation tilt factor, R_b, is then given by

$$R_b = I_{bi}/I_b = \cos i/\cos z$$

A tilted surface receives diffused radiation as well as reflected radiation form the ground and surroundings in addition to the beam radiation.

The diffused sky radiation on the tilted surface at an angle s is given by

$$I_d\,(1+ \cos s)/2$$

where I_d is the diffuse sky radiation on a horizontal surface.

If the ground and other surfaces seen by the tilted surface have a diffuse reflectivity τ_g for both beam and diffuse sky radiation, the amount of ground-reflected solar radiation on the tilted surface is equal to τ_g (1 – cos s)/2, of the total radiation ($I_b + I_d$) on the horizontal surface.

The beam, diffuse, and reflected components, can be added to give the total incident radiation, I_t, on a tilted surface. The total solar radiation on a horizontal surface, I, is the sum of horizontal beam and diffuse radiation.

1.6 MONTHLY AVERAGE OF DAILY TOTAL SOLAR RADIATION ON HORIZONTAL SURFACE

The computation of solar radiation on a horizontal or tilted surface is not an easy task and requires a complete knowledge of solar geometry and earth sun relationships. However, there are correlations available for estimation of solar radiations at horizontal surfaces. Ultimately we need the values of monthly average of daily solar radiation on a horizontal surface.

The correlation for determining monthly average of daily solar radiation on a horizontal surface is given by the following relation :

$$\frac{H}{H_o} = a + b\left(\frac{n}{N}\right) \qquad \ldots (1.8)$$

where H = monthly average daily total radiation on a horizontal surface,

H_o = monthly average daily extraterrestrial radiation on a horizontal surface,

n = monthly average daily hours of bright sunshine hours, and

N = monthly average of the maximum possible daily hours of bright sunshine hours.

The a and b are the regression parameters and are given by :

$$a = -0.309 + 0.539 \cos\phi - 0.0693 E_0 + 0.290 (n/N) \qquad \ldots (1.9)$$

$$b = 1.527 - 1.027 \cos\phi + 0.0926 E_0 - 0.359 (n/N) \qquad \ldots (1.10)$$

where φ = latitude, and

E_0 = elevation of the location above sea level in kilometers.

The values of φ (latitude) and E_0 (elevation of the location above sea level in kilometers) are given in Table 1.2 for few locations.

Table 1.2 : Latitude and Elevation of Some Places in India

Place	Latitude, ϕ	Elevation, E_0
Bangalore	12º58′ N	921 m
Mumbai	18º54′ N	11 m
Jodhpur	26º18′ N	224 m
New Delhi	28º35′ N	216 m
Shimla	31º06′ N	2202 m
Kolkata	22º32′ N	6 m
Chennai	13º00′ N	16 m

1.7 LET US SUM UP

The major portion of the energy of thermal radiation lies in the range from approximately 0.1 μm. to 100 μm. The visible portion of thermal radiation ranges from approximately 0.4 to 0.7 μm.

The electromagnetic radiations behave like wave as well as particles. The electromagnetic waves are made of small discrete quanta, called photons which travel with the speed of light.

The emissive power of a black body is expressed by Stefan-Boltzman law $E_b = \sigma T^4$.

The ratio of the total emissive power E of a real surface to the total emissive power E_b of a blackbody is called the emissivity of the real surface.

The monochromatic (single wavelength) emissivity is equal to the monochromatic absorptivity for any surface when in thermal equilibrium. This is called the Krichhoff's law of radiation. Some surfaces have high absorptivity for radiation in the solar range of wavelengths and low emissivity for long wave thermal radiation.

The radiation received by the earth without any change in the direction is referred to as beam radiation or direct radiation. The diffused radiation is received by the earth from all directions. The radiations may change their direction after scattering from dust particles, clouds, etc. while passing through atmosphere.

The total radiation is the sum of direct radiation and diffuse radiation and is called as global radiation or simply insolation. Solar insolation is defined as the amount of sunshine incident on the surface of the Earth.

You can determine the size of solar collectors, if the value of solar insolation is known. For low values of solar insolation, the area of the collector will be large as compared to the case of higher insolation.

1.8 KEY WORDS

Absorptivity

A property of a material; fraction of solar radiation falling on a material gets absorbed by the material, its value is less than unity

Absorptance

The ratio of the radiation absorbed by a surface to the total solar energy falling on that surface; given in percentage

Albedo

The total reflectivity of the earth, which is 31%

Angle of Incidence

The angle that the sun's rays make with a line perpendicular to a surface.

Direct Radiation

A portion of solar radiation that has traveled a straight path from the sun

Diffuse Radiation

A portion of solar radiation, scattered by water vapor, dust and other particles as it passes through the atmosphere; higher on hazy or overcast days than on clear days

Insolation

The total amount of solar radiation (direct, diffuse, and reflected) striking a surface exposed to the sky; expressed in W/m^2

Irradiance

The rate at which radiations fall on a surface per unit area.

Kirchoff's Law

The monochromatic emissivity is equal to the monochromatic absorptivity for any surface when in thermal equilibrium.

1.9 ANSWERS TO THE SAQs

SAQ 1

These factors are :

- Geographic location
- Time of day
- Season
- Local landscape
- Local weather

SAQ 2

The rotation of the Earth is responsible for hourly variations in sunlight. In the early morning and late afternoon, the Sun is low in the sky. Its rays travel longer through the atmosphere than at noon when the sun is at its highest point.

SAQ 3

Solar Constant is defined as the radiation received per second by a surface of unit area held normal to the sun's rays at the mean earth-sun distance outside the atmosphere. The value of solar constant is equal to 1367 W/m^2.

SAQ 4

The total reflectivity of the earth, which is 31%, is known as Albedo.

REFERENCES

1. G. N. Tiwari and M. K. Ghosh, Renewable Energy Resources : Basic Principles and Applications, Narora Publishing House, New Delhi, 2005.

2. J. A. Duffiie and W. A. Beckman, Solar Engineering of Thermal Processes, John Wiley and Sons, New York, 1991.