Mechanical Engineering

Renewable Sources of Energy

Comprehensive Theory *with* Solved Examples

and **Practice Questions**

MADE EASY Publications

MADE EASY Publications

Corporate Office: 44-A/4, Kalu Sarai (Near Hauz Khas Metro Station), New Delhi-110016
E-mail: infomep@madeeasy.in
Contact: 011-45124660, 8860378007
Visit us at: www.madeeasypublications.org

Renewable Sources of Energy

First Edition: 2015
Second Edition: 2016
Third Edition: 2017
Fourth Edition: 2018
Fifth Edition: 2019
Sixth Edition: 2020

Contents

Renewable Sources of Energy

■■■■

CHAPTER 2

Solar Radiation

2.1 Solar Energy

Solar energy is one of the most promising source of renewable energy. Typically the power of the sun intercepted by the earth is approximately 1.8×10^{11} MW. This much power is sufficient enough to cater the need of world power consumption even if harnessed at an efficiency of 0.01%. Apart from a large source of energy, solar energy has two more factors in its favour. The first one is, it is clean/green energy and second one is its availability over all the parts of earth which are suitable for living.

Unlike any other source of energy, solar energy is also available in dilute form. Solar radiation flux rarely exceeds 1 kW/m^2 even in the hottest regions on earth. Total radiation over a day reaches to 7 kWh/m^2 at its best. As a consequence, large collector area is required to fulfil the need of industry or household applications. Which in turn raises its cost more than the cost incurred by conventional energy resources. Now a days because of the government policies, subsidies are given to setup solar energy harnessing units so that its cost can be brought comparable to the existing cost.

2.1.1 Methods used for utilisation of Solar Energy

Solar energy can be utilized directly or indirectly. Direct methods involve heating of water/air, drying of commodities and conversion into electricity using photovoltaic cells.

Indirect methods of solar energy drives ecology system. Hydropower is the most utilized indirect method of solar energy. In case of hydropower, water is evaporated from various sources and it falls back on earth in the form of rain. Dams are made in the pathways of river to generate electricity.

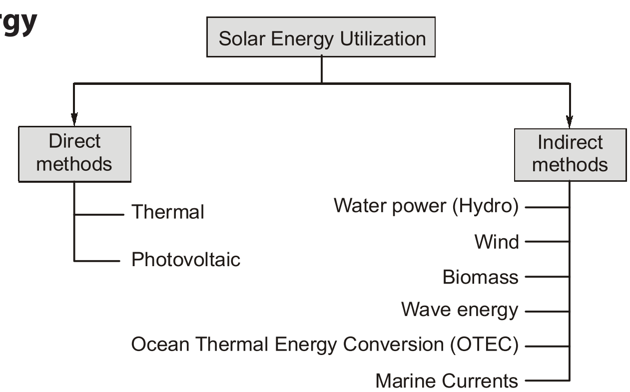


Fig: Utilization of Solar Energy

Other indirect ways are wind energy, biomass energy, wave energy, etc. These methods are shown graphically in the given figure:

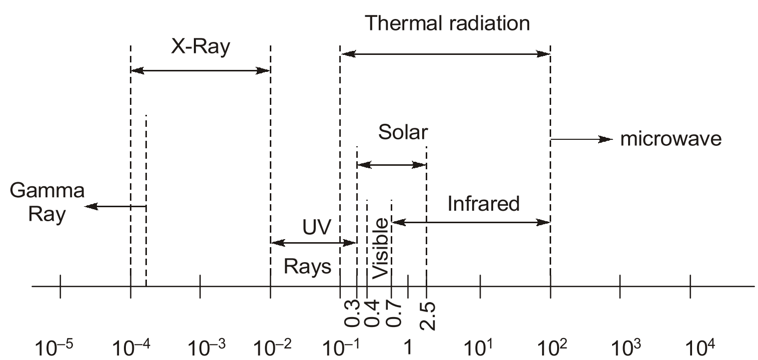
Before proceeding to the utilities of solar energy, one has to understand how solar energy is received on earth and how atmosphere of Earth interacts with this energy.

2.2 Solar Radiation

The sun is a large sphere of diameter $D_s = 1.39 \times 10^6$ km. Because of nuclear fusion, temperature at the core of the sun is around 10^7 K. The temperature at the outer passive layer of the sun reaches to 5880 K so it becomes a source of radiation. Since the fluctuation at the surface temperature is not relatively high hence it emits radiation with a relatively continuous spectral distribution.

Solar flux reaches Earth's surface at a maximum flux density of 1.0 kW/m^2 in the wavelength band of 0.3 and 2.5 μm. This range is known as short wave radiation.

Solar radiation is the energy emitted by sun in the form of electromagnetic waves and hence solar radiation belongs to a particular region of electromagnetic waves. Electromagnetic wave spectrum is shown below to describe the wavelength of various waves of practical importance.



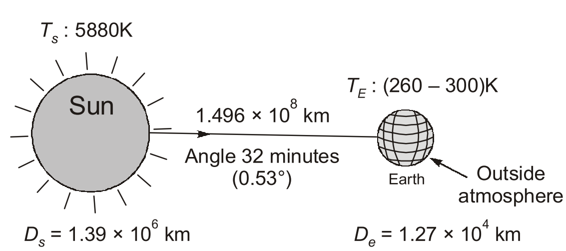
Wavelength (λ) in μm

Spectrum of Electromagnetic waves

It can be seen from the spectrum of electromagnetic waves that the solar radiation covers entire range of visible radiation and some part of ultraviolet (UV) and infrared radiation (IR). The proportion of solar radiation received on Earth's surface for an incidence angle of 45° is shown in Table given below :

S.No.	Region	Wavelength (μm)	% Irradiance
1.	UV rays	(0.3 to 0.4)	~ 6.4%
2.	Visible	(0.4 to 0.7)	~ 48%
3.	Infrared	(0.7 to 2.3)	~ 45.6%

2.3 Solar Radiation Quantification



Sun being at higher temperature (5880 K) emits radiation in all possible directions. Temperature of earth is around (260 - 300) K and it receives solar radiations. Because of very large size of Sun (Diameter $D_s \simeq 1.39 \times 10^6$ km) compared to earth (Diameter $D_e \simeq 1.27 \times 10^4$ km) it substends an angle 32 minutes i.e. 0.53° as the mean distance of Sun and Earth is 1.496×10^8 km.

Experimental studies showed that the energy flux received from the sun outside the atmosphere is constant. This energy flux is expressed in the form of Solar constant (I_{SC}). The Solar constant (I_{SC}) is the rate at which energy is received from the sun on a unit area perpendicular to the rays of the sun, at the mean distance of Earth from Sun.

A standard value of Solar constant I_{SC} = 1353 W/m^2 was adopted in 1971 but based on subsequent measurement, a revised value of I_{SC} = 1367 W/m^2 is adopted.

i.e. $$I_{SC} = 1367 \text{ W/m}^2$$

The orbit of earth on which it revolves around the Sun is elliptical and hence mean distance between earth and sun varies so does Solar constant. This variation is accounted by the equation given below :

$$I'_{SC} = I_{SC}\left[1+0.033\cos\frac{360n}{365}\right] \quad \text{. . . (2.1)}$$

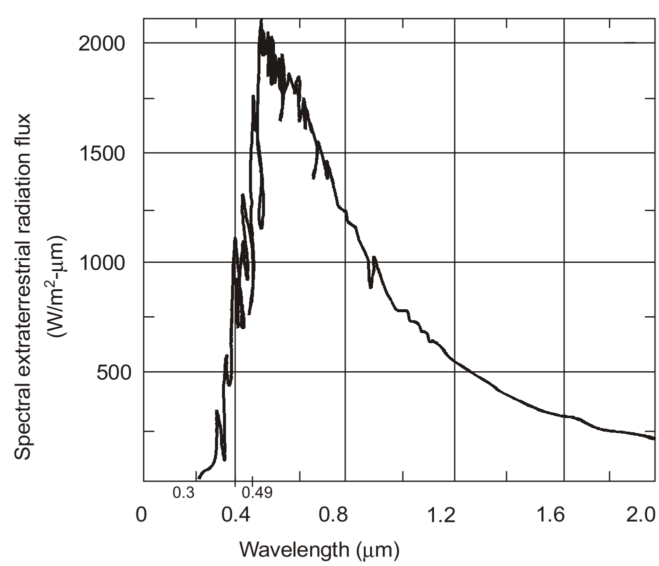
Here 'n' is number of the day on which solar constant is calculated.

n = 1 on 1st January & I_{SC} = 1367 W/m^2

The Solar constant I'_{SC} is also known as extraterrestrial flux. It can be observed from equation (2.1), I'_{SC} is function of cosine which can vary from – 1 to 1. The variation causes ±3.3 % variation in I'_{SC} over a year.

2.4 Spectral Distribution of Extraterrestrial Radiation

As discussed earlier, solar radiation covers entire range of visible rays and some part of UV and infrared rays. Solar flux or extraterrestrial radiation is distributed non-uniformly over this range (0.3 to 2.5 μm). The distribution of extraterrestrial radiation with wavelength is shown below :



The analysis of spectral distribution shows that spectral extraterrestrial radiation flux reaches at peak for wavelength ≈ 0.49 μm. Extraterrestrial radiation flux increases rapidly with increase in wavelength from 0.3 to 0.49 μm and then decreases asymptotically to zero. 99% of sun's radiations are obtained upto a wavelength of 4 μm, and 96% at wavelength of 2.5 μm. The area under the curve gives average extraterrestrial radiation flux which is approximately 1.0 kW/m^2.

A close analysis of spectral distribution of radiation flux revealed that the solar radiation flux follows the distribution of black body radiation. Hence all the laws of black body radiation are applicable on solar radiation.

A black body has following characteristics :

1. A black body absorbs all the incident radiations, regardless of wavelength and direction.
2. For a prescribed temperature and wavelength, no surface can emit more energy than a black body.
3. Although the radiation emitted by a black body is a function of wavelength and temperature, it is independent of direction. It means black body is a diffuse emitter.

Since solar radiations are similar to black body radiations and hence spectral intensity can be calculated by Planck's law.

$$I_{\lambda,sc}(\lambda, T) = \frac{2hc_0^2}{\lambda^5\left[\exp\left(\frac{hc_o}{\lambda kT}-1\right)\right]} \quad \text{... (2.2)}$$

where,

$I_{\lambda,sc}$ = Solar intensity

h = Universal Planck's constant, $h = 6.626 \times 10^{-34}$ J.s

k = Universal Boltzman constant, $k = 1.381 \times 10^{-23}$ J/K

C_0 = Speed of light in vacuum, $C_0 = 2.998 \times 10^8$ m/s

λ = Wavelength

T = Absolute temperature

Spectral emissive power of a blackbody is given by :

$$E_{\lambda,sc} = \pi I_{\lambda,sc}$$

Upon substituting value of $I_{\lambda,sc}$ from Eq. (2.2)

$$E_{\lambda,sc} = \frac{2\pi hC_o^2}{\lambda^5\left[\exp\left(\frac{hco}{\lambda kt}-1\right)\right]} = \frac{C_1}{\lambda^5\left[\exp\left(\frac{c_2}{\lambda T}-1\right)\right]} \quad \text{... (2.3)}$$

Where

$$C_1 = 2\pi hC_o^2 = 3.742 \times 10^8 \text{ W.}\mu\text{m}^4/\text{m}^2$$

$$C_2 = \left(\frac{hc_0}{k}\right) = 1.439 \times 10^4 \mu\text{.m.K}$$

Equation (2.3) is also known as Planck's distribution. The salient points which can be inferred from equation (2.3) are :

1. The emitted radiation varies continuously with wavelength.
2. At any wavelength the magnitude of emitted radiations increases with increase in temperature.
3. As the temperature increases more radiations appear at shorter wavelength.

Solar radiation follows all these observations. Moreover, the peak value of spectral emissivity can be obtained by differentiating equation (2.3). It is found that a maximum value in spectral distribution appears at

$$\lambda_{max.} T = \text{constant} = C_3 \quad \text{... (2.4)}$$

Here λ_{max} is the wavelength corresponding to maximum value of spectral emissive power.

T is absolute temperature

C_3 is third radiation constant, $C_3 = 2898$ μm.K

In case of solar radiation T = 5880 K

$\therefore$ λ_{max} = 0.49 μm

Which was observed in spectral distribution of solar radiation.

Equation (2.4) is also known as Wien's Displacement law. This equation can be expressed as

$$\lambda_{max} \propto \frac{1}{T_{source}} \qquad \text{. . . (2.5)}$$

It means if temperature of the source is high, maximum spectral emissive power will be obtained at lower value of wavelength. In other words, with increase in temperature of the source, the peak value shifts towards shorter wavelengths.

The total emissive power of a blackbody can be obtained by integrating Planck's equation i.e. equation (2.3) all over the wavelength. Integration of equation (2.3) gives Stefan-Boltzmann law

i.e. $$E_b = \sigma T^4 \qquad \text{. . . (2.6)}$$

where σ is Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ W/m^2-K^4

T is absolute temperature in kelvin

Emissive power of real surfaces is obtained by multiplying it with emissivity of the surface i.e.

$$E_{real} = \varepsilon(\sigma T^4) \qquad \text{. . .(2.7)}$$

where ε is emissivity of the surface.

Example 2.1 **Consider the average temperature of Earth $\simeq$ 300 K. Calculate the wavelength at which maximum spectral emissive power is obtained. Compose it with that of sun and comment on the results.**

Solution:

By Wien's Displacement law

$$\lambda_{max} T = 2898 \, \mu\text{mK}$$

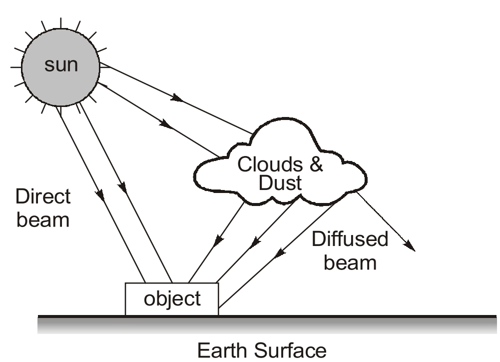
$$\lambda_{max} = \frac{2898}{300} = 9.66 \, \mu\text{m}$$

Peak radiation emitted by the surface of earth appears in far infrared region whereas solar radiation is short wave radiation.

Based on the results, it can be said, spectral distribution of earth's radiation is not intercepted by solar radiation.

2.5 Effect of Environment on Solar Radiation

Solar radiations received on the surface of the earth are attenuated primarily because of the absorption in ozone layer and water vapour. Apart from absorption, scattering occurs because of the presence of gaseous molecules and dust particles.



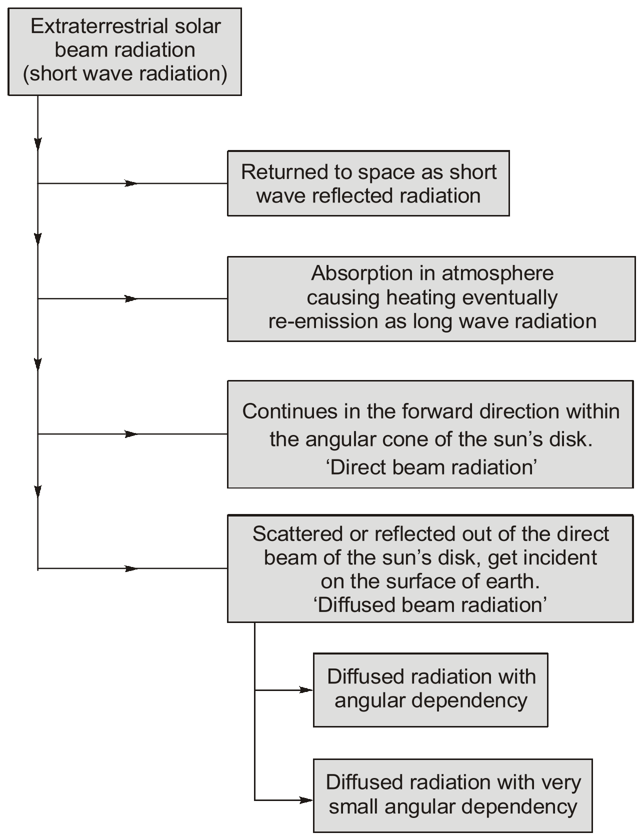
The atmosphere at any location on the earth's surface is often classified into two broad types

(i) Atmosphere without clouds

(ii) Atmosphere with clouds

The maximum radiation received at Earth's surface is for cloudless sky. Sometime cloudless sky conditions are taken as standard for comparing solar fluxes but it is always difficult to distinguish cloudless and cloudful sky.

Extraterrestrial solar radiation flow diagram shows how solar radiation reaches to the earth surface. The flow diagram is shown below :



2.5.1 Terminology Used in Solar Radiation

(i) Direct Radiation : Solar radiation received at the surface of Earth in line with the Sun is known as direct radiation. This is also known as beam radiations and denoted by (I_b).

(ii) Diffused Radiation : Solar radiation received on earth after getting scattered because of the atmosphere of the Earth is known as diffused radiation. This is denoted by I_d. Even on a clear sky day some part of the solar radiation is diffused radiation.

(iii) Global Radiation : The sum of the beam and the diffused component of the solar radiation is called total solar radiation or global solar radiation. This is denoted by (I_G)

$$\therefore \quad I_G = I_b + I_d$$

(iv) Irradiance : The solar irradiance (I) is the rate at which the radiant energy is incident on a unit area of a surface. Its unit is W/m^2.

(v) **Insolation :** The incident solar energy radiation if measured for specific period then it is called insolation. If it is measured for the whole day then it is expressed in W-hr/m^2/day and denoted by '*H*'.

(vi) **Air mass :** Air mass (AM) is a measure of path length of radiation through the atmosphere. For the sake of comparison, vertical path of solar radiation is considered unity. Air mass is thus expressed in terms of air mass ratio (AMR).

AMR is defined as the mass of the atmosphere through which the beam radiation passes to the mass it would pass through if the sun is directly overhead.

Mathematically,
$$AMR = \frac{1}{\cos\theta_z} \quad \text{. . . (2.8)}$$

where θ_z is the zenith angle which is defined in the subsequent section. Equation (2.8) is valid for zenith angle θ_z between 0° to 70° at sea level.

If sun is directly overhead i.e. $\theta_z = 0°$

$$AMR = \frac{1}{\cos 0°} = 1$$

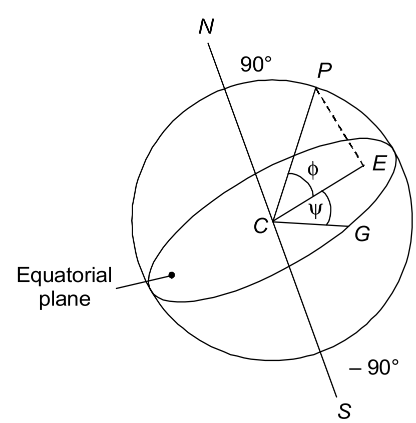
Similarly for $\theta_z = 60°$

$$AMR = \frac{1}{\cos 60} = 2$$

For higher value of θ_z (Which indicates low value of incident angle) curvature of earth plays an important role and hence equation (2.8) is not valid.

2.6 Definition of Important Angles in Solar Radiation Effect of Geometry of Earth & Sun

Any location on the surface of earth is identified in terms of longitude (ψ) and latitude (ϕ). For the calculation of solar radiation, latitude of the location is sought.



The axis N-S is the axis along which Earth rotates in 24 hours. '*N*' represent point on North Pole and '*S*' represent point on South Pole. This axis is perpendicular to the equatorial plane.

(i) **Latitude Angle (ϕ) :** The latitude of a location (*P*) is the angle made by radial line joining the location to the center of the earth with the projection of the line on the equatorial plane.

Sign convention :

+ve for northern hemisphere

–ve for southern hemisphere

Variation :

–90° to 90° (from *S* to *N*)

(ii) **Longitude (ψ) :** Longitude is measured positive eastward from Greenwich, England which is accepted as standard by International communities. Longitude is the angle between the projection line of any point on equatorial plane to the projection of line having same latitude as that of 'Greenwich'.

D. Angle through which earth has rotated since solar noon.

List-II
1. Latitude angle
2. Declination angle
3. Incidence angle
4. Aximuth angle
5. Hour angle
6. Slope

Codes :

	A	B	C	D
(a)	3	1	5	2
(b)	6	5	3	4
(c)	3	1	2	5
(d)	5	6	3	4

16. Declination angle on 21st March is
(a) 0 (b) +23.45°
(c) –23.45° (d) 1°

17. The unit of solar radiation flux is
(a) Watt (b) Samul
(c) Hertz (d) Langley

18. The instrument used to measure direct solar radiation is
(a) Pyranometer (b) Pyrheliometer
(c) Albedometer (d) Sun shine recorder

19. Match the Following

List-I
A. Pyranometer
B. Pyrheliometer
C. Albedometer
D. Sunshine recorder

List-II
1. Diffuse radiation
2. Global radiation
3. Global and reflected radiation
4. Global and diffuse radiation
5. Direct and diffuse radiation
6. Direct radiation
7. Sunshine hour

Codes :

	A	B	C	D
(a)	4	6	3	7
(b)	5	2	4	1
(c)	3	4	2	7
(d)	1	6	3	7

20. For a horizontal surface which statements are true
1. $\theta = \theta_z$ 2. $\beta = 90°$
3. $\beta = 0°$ 4. $\phi = \theta$
(a) 1 and 2 (b) 1 and 3
(c) 1, 2 and 4 (d) 3 and 4

ANSWERS

1. (d)	2. (c)	3. (a)	4. (b)	5. (c)
6. (b)	7. (b)	8. (c)	9. (d)	10. (c)
11. (b)	12. (d)	13. (c)	14. (b)	15. (c)
16. (a)	17. (d)	18. (b)	19. (a)	20. (b)