Solar Energy

Solar energy is the energy force that sustains life on earth for all plant, animals and people. It provides a compelling solution for all societies to meet their needs for clean, abundant sources of energy in the future. The source of solar energy is the nuclear interaction at the core of the sun, where the energy comes from the conversion of hydrogen into helium. Sunlight is readily available, secure from geopolitical tensions, and poses no threat to our environment and our global climate systems from pollution emissions.

Solar energy is primarily transmitted to the earth by electromagnetic waves, which can also be represented by particles (photons). The earth is essentially a huge solar energy collector receiving large quantities of solar energy that manifest in various forms, such as direct sunlight used for plant photosynthesis, heated air masses causing wind, and evaporation of the oceans resulting as rain, which forms rivers and provides hydropower.

Solar energy can be tapped directly (e.g, PV); indirectly as with wind, biomass, hydropower; or as fossil biomass fuels such as coal, natural gas, and oil. Sunlight is by far the largest carbon-free energy source on the planet. More energy from sunlight strikes the earth in 1 hour (4.3 x 10^{20}J) than all the energy consumed in the planet in a year (4.1 x 10^{20}J). Although, the earth receives about 10 times as much energy from sunlight each year as that contained in all the known reserves of coal, oil, natural gas and uranium combined, renewable energy (solar) has been given a dismally low priority by most political, business leaders and agricultural processors.

STRUCTURE OF THE SUN

The sun's structure and characteristics determine the nature of the energy it radiates into space.

In general, it is not practical to start from knowledge of extraterrestrial radiation and predict the intensity and spectral distribution to be expected on the ground. Adequate meteorological data for such calculations are seldom available, and recourse usually is made to measurements. However, an understanding of the nature of extraterrestrial radiation, atmospheric attenuation, and the effects of orienting a receiving surface is important in understanding and using solar radiation data. The sun is a typical middle-aged star with a diameter of 1.39 x 10^6km, a mass 2 x 10^{30}kg, and a luminosity of 4 x 10^{26}W. The sun is a plasma primarily composed of 70% hydrogen and 28% helium. This changes over time as hydrogen is converted into helium. The sun is composed of the core, the radiation and the convention zones, and its atmosphere. The conditions of the sun vary greatly along its radius. The core with a radius of 0.2 R, is the source of all the sun’s energy and it contains half of the sun’s mass. The temperature and pressure in this zone are extreme: 1.5 x 10^7K and 250 x 10^9kg atm, with a density of 150g/cm^3 – 13 times greater than that of solid lead. The combination of high temperature and high density creates the correct environment for the thermonuclear reaction to take place; two atoms of hydrogen come together to produce one heavier atom of helium, releasing a great amount of energy.

Once energy is produced in the core, it travels from the centre to the outer regions. The region immediate to the core is identified as the radiation zone because energy is transported by radiation and it extends to 0.7R. It takes thousands of years for the energy released by the core to exit this zone. The temperature in the radiation zone is about 5 x 10^6K. Once the energy has left this zone and its temperature has dropped down to 2 x 10^6K, rolling turbulent motion of gases arise; this is known as the convection zone. It takes around a week for the hot material to bring its energy to the top of the convection zone. It takes around a week for the hot material to bring its energy to the top of the convention zone. This layer extends from 0.7R to R. The solar atmosphere, the exterior of the sun, is composed of the photosphere, chromospheres, and the corona. The photosphere corresponds to the lowest and densest part of the atmosphere; in the interior of the sun, the gas becomes much denser so that is not possible to see through it. Because the sum is completely made of gas and there is no hard surface, the photosphere is usually referred to as the sun's surface. The photosphere's temperature is about 5 x 10^3K. Above the photosphere is a layer of gas, approximately 2 x 10^3km thick, known as the chromosphere. In this layer, energy continues to be transported by radiation but it also presents convection patterns with the presence of reddish flames extending several thousands of kilometers and then falling again. The outermost layer is called the corona. The shape of this is mostly determined by the magnetic field of the sun, forming dynamic loops and arches. The corona emits energy of many different wavelengths that emerge from the interior of the sun from long wave-length radio waves to short wavelength x-rays.

The outermost layer of the sun exhibit different rotation – that is, each latitude rotates at slightly different speeds due to the fact that the sun is not a solid body like the earth. The surface rotates faster at the equator that at the areas by the poles. It rotates once every 25 days at the equator and 36 days near the poles.

The amount and the intensity of solar radiation reaching the earth's surface depend on the geometric relationship of the earth with respect to the sun.

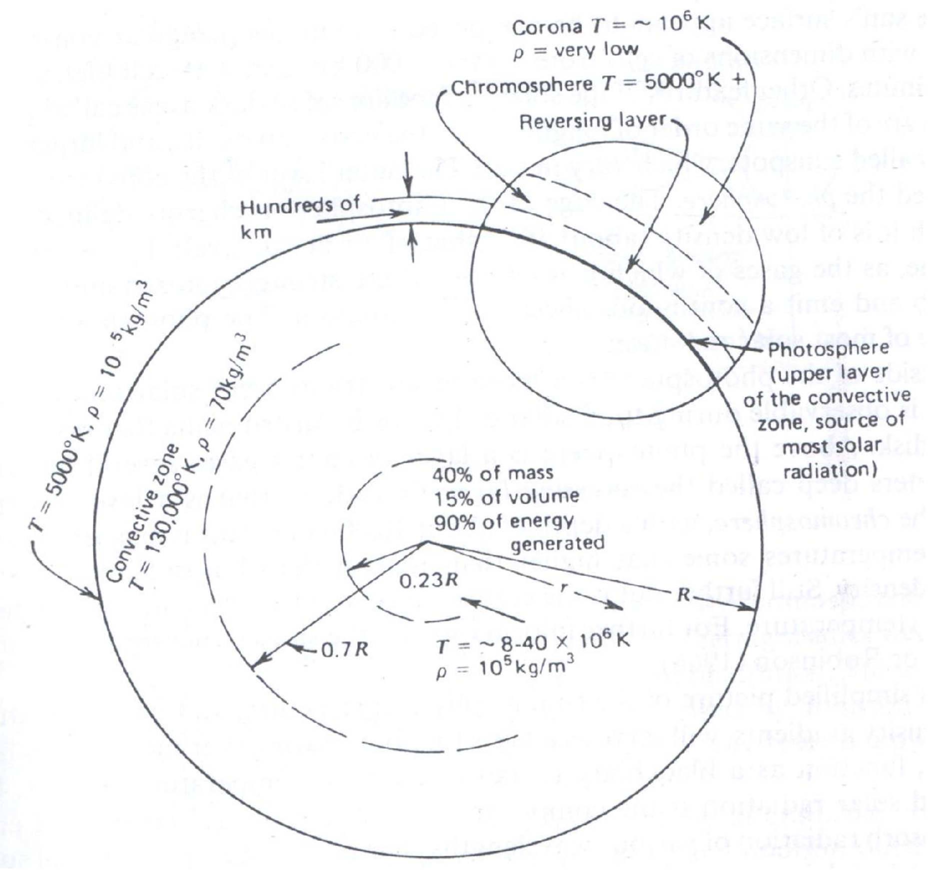


Fig.8 The structure of the sun

The sun is a sphere of intensely hot gaseous matter with a diameter of 1.39 x 10^9m and is on the average, 1.5 x 10^{11} m from the earth. As seen from the earth, the sun rotates on its axis about once every four weeks. However, it does not rotate as a solid body; the equator takes about 27 days and the polar regions take about 30 days for each rotation.

The sun has an effective blackbody temperature of 5762K. The temperature in the central interior regions is variously estimated at 8 x 10^6 to 40 x 10^6 K and the density at about 100 times that of water. The sun is, in effect, a continuous fusion reactor with its constituent gases as the "containing vessel" retained by gravitational forces. Several fusion reactions have been suggested to supply the energy radiated by the sun; the one considered the most important is a process in which hydrogen (i.e; four protons); combines to form helium (i.e. one helium nucleus); the mass of the helium nucleus is less than that of the four protons, mass having been lost in the reaction and converted to energy.

This energy is produced in the interior of the solar sphere, at temperatures of many millions of degrees. It must be transferred out to the surface and then be radiated into space. A succession of radiative and convective processes must occur, with successive emission, absorption, and reradiation; the radiation in the sun's core must be in the x-ray and gamma-ray parts of the spectrum with the wavelengths of the radiation increasing as the temperature drops at larger radial distances.

A schematic of the structure of the sun is shown in Figure 9. It is estimated that 90% of the energy is generated in the region of 0 to 0.23R (where *R* is the radius of the sun), which contains 40 % of the mass of the sun. At a distance 0.7R from the center, the* temperature has dropped to about 130,000 K and the density has dropped to 70 kg/m^3; here convection processes begin to become important and the zone from 0.7 to l.0R is known as the *convective zone.* Within this zone, the temperature drops to about 5000 K and the density to about 10^{-5} kg/m^3.

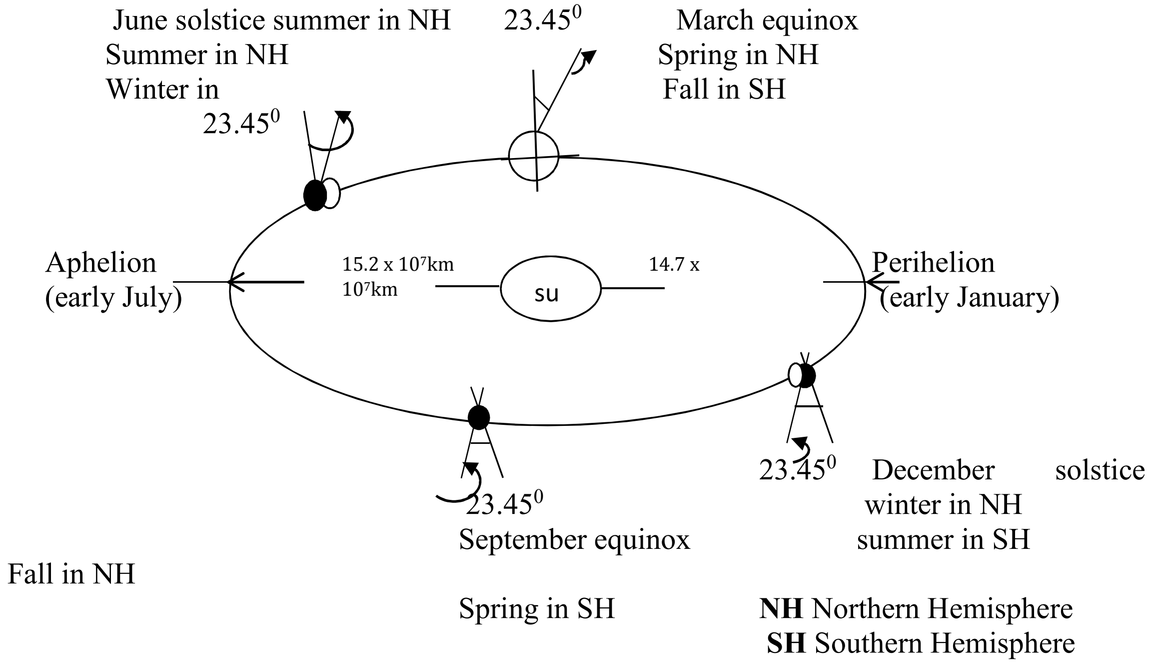


Fig.9.

Electromagnetic Spectrum

Electromagnetic radiation is self-propagated in wave form through space with electric and magnetic components as shown below. These components oscillate at right angles to each other and to the direction of propagation and area in phase with each other. An electromagnetic wave is characterized by its wavelength (λ) and (f). Because a wave consists of successive troughs or crests, the wavelength is the distance between two identical adjacent points in the repeating cycles of the propagating wave, and the frequency is defined as the number of cycles per unit of time. The electromagnetic wave spectrum covers energy having wavelengths from thousands of meters, such as the very long radio waves, to fractions of the size of an atom, such as the very short gamma ray waves.

Frequency is inversely proportional to wavelength:

$F = \frac{v}{\lambda}$ or $v = f\lambda$

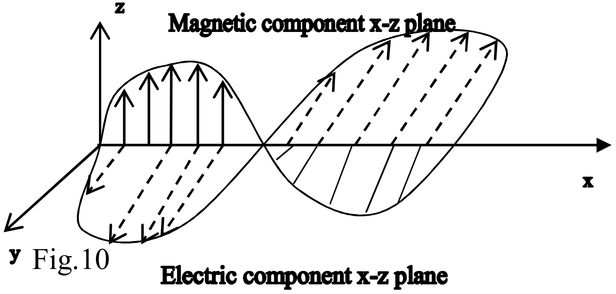
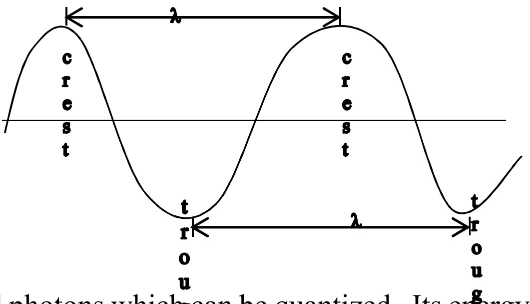


Fig.10



A wave consists of discrete pockets of energy called photons which can be quantized. Its energy (E) depends on the frequency (f) of the electromagnetic radiation according to Planck's equation:

$$E = hf = \frac{hv}{\lambda} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; (14)$$

Where h = constant of Planck (h $\simeq$ 6.626069 x 10^{-34} J-s or 4.13527μeV/GH$_3$).

Blackbody

A blackbody is an ideal concept and refers to a perfect absorbing body of thermal radiation, with no reflection and transmission involved. Because no light is reflected or transmitted, the object appears black when it is cold. If the blackbody is hot, these properties make it also an ideal source of thermal radiation. For a blackbody, the spectral absorption factor (α_λ) is equal to the emissivity (ε_λ); this relation is known as a Kirchhoff's law of thermal radiation.

$$\alpha_\lambda = \varepsilon_\lambda = 1 \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; (15)$$

The emissivity of a material, other than a blackbody, is the ratio of the energy radiated by the materials to the energy radiated by a blackbody at the same temperature. The spectral radiation intensity emitted by a blackbody at all wavelengths (I^b_λ) at a temperature T is given by Planck's law.

$$I^b_\lambda = \frac{c_1}{\lambda^s}\,\frac{1}{\exp(c_2/\lambda T)-1} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; (16)$$

Where c_1 = 3.746 x 10^{-16}Wm^2 and C_2 = 0.014384mk (Plank's first & second radiation constants)

T = absolute temperature in Kelvin.

The integration of Planck's law over the whole electromagnetic spectrum gives the total energy radiated per unit surface area of a blackbody per unit time-also called irradiance.

The Stefan-Boltzmann law states that the irradiance is directly proportional to the fourth power of the blackbody absolute temperature.

$$I^b = \int_0^\infty I^b_\lambda \, d\lambda = \int_0^\infty \frac{c_1}{\lambda^s}\,\frac{1}{\exp(c_2/\lambda T)-1}\, d\lambda = \sigma T^4 \;\ldots\ldots\ldots\ldots\; (17)$$

Where σ is the constant of Stefan-Boltzmann [σ = 5.67 x 10^{-8} W/(m^{2}k^4)].

The hotter an object is, the shorter is the wavelength range at which it will emit most of its radiation and the higher is the frequency for maximal radiation power. Wien's displacement Law states that there is an inverse relationship between the peak wavelength of the blackbody's emission and its temperature.

$$\lambda_{max}T = 2.897768 \times 10^6 nmk \text{ ………………….. } (18)$$

where λ_{max} is the wavelength in nanometers at which the maximum radiation emission occurs and T is the blackbody temperature in Kelvin.

Example 1

What is the irradiance of a material with absolute temperature of 6,000k?

Solution (According to Stefan-Boltzmann law,)

$$I^b = \int_o^\infty I_\lambda^b \, d\lambda = \sigma T^4$$

$$I^b = 5.67 \times 10^{-8} W/(m^2k^4) \times (6{,}000k)^4$$

$$I^b = 11.4124 \quad w/m^2$$

Example 2

What is the wavelength at which the maximum monochromatic emission occurs for a star behaving as a blackbody at 8,000k?

According to Wien's displacement law

$$\lambda_{max}T = 2.897768 \times 10^6 nmk$$

$$\lambda = \frac{2.897768 \times 10^6 nmk}{8{,}000k} = 362nm$$

Visible Spectrum

The range of the spectrum that we can see, visible (sometimes referred to as light), is small with red light (800nm or 8×10^{-7}m) having a longer wavelength than blue light (400nm or 4×10^{-7}m). A rainbow is a familiar example of the colour that we can see. White light is just a superposition (combination of the colours). All the different colours we can see and generate are just absorption and reflections of different parts of the visible spectrum. There are some animals that see in the ultraviolet (bees) and infrared (snakes) ranges.

Example 3

What is the fraction of the power emitted by the sun in the visible region of the electromagnetic spectrum solar?

Solution

The visible ranges from 400 to 800nm

Fraction of power = $F(\lambda_2 - \lambda_1)$

= $F(800 - 400) = 0.54963 - 0.07858 = 0.47105$

Variation of Extraterrestrial Radiation

There are two sources of variation in the extraterrestrial radiation. The first is the variation in the radiation emitted by the sun. There are conflicting reports in the literature on periodic variations of intrinsic solar radiation. It has been suggested that there are small variation (less than ±1.5 percent) with different periodicities and variation related to sunspot activities. Others consider the measurements to be inconclusive or not indicative of regular variability. For engineering purposes, in view of the uncertainties and variability of atmospheric transmission, the energy emitted by the sun can be considered to be fixed.

Variation of the earth-sun distance, however, does lead to variation of extraterrestrial radiation flux in the range of ±3%. The dependence of extraterrestrial radiation on time of year is given by:

$$G_{on} = G_{sc}\left(1 + 0.033 \cos \frac{360n}{365}\right) \text{ ……………………… } (19)$$

Where G_{on} = extraterrestrial radiation, measured on the plane normal to the radiation

n = number of days of the year

G_{sc} = solar constant (1353 w/m^2)

SOLAR TIME

Definitions

(i) *Zenith Angle, θ_2:* The angle subtended by as vertical line to the zenith (i.e. the point directly overhead) and the line of sight to the sun.

(ii) *Air mass, M:* The ratio of the optical thickness of the atmosphere through which beam radiation passes to the optical thickness if the sun were at the zenith. Thus at sea level, m = 1 when the sun is at the zenith, and m = 2 for a zenith angle θ_2, of 60^0, for zenith angles from 0^0 to 70^0 at the sea level, m = $(\cos \theta_3)^{-1}$.

(iii) *Beam Radiation:* The solar radiation received from the sun without having been scattered by the atmosphere (this is often referred to as direct solar radiation.

(iv) *Diffusion Radiation:* The solar radiation received from the sun after its direction has been changed by scattered by the atmosphere (also referred to as sky radiation or solar sky radiation).

(v) *Total solar radiation:* The sum of the beam and the diffuse radiation on a surface. (often referred to as global radiation).

(vi) *Irradiance, w/m^2:* The rate at which radiation energy is incident on a surface per unit area of surface.

(vii) *Irradiation or Radiant Exposure. J/m^2:* The incident energy per unit area on a surface, found by integration of irradiance over a specified time, usually an hour or a day (Insolation is a term applying specifically to solar energy irradiation).

(viii) *Radiosity or Radiant Exitance, w/m^2*: The rate at which radiant energy leaves a surface, per unit area, by combined emission, reflection, and transmission.

(ix) *Emission Power or Radiant Self Exitance, w/m^2*: The rate at which radiant energy leaves a surface per unit area, by emission only.

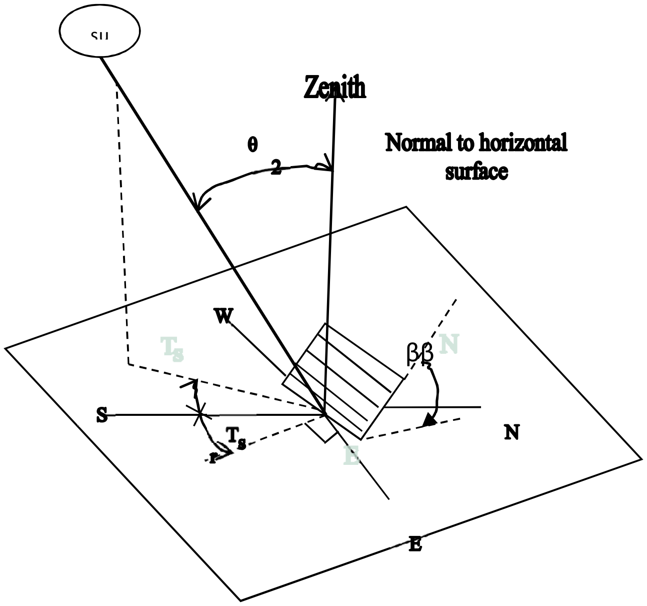


Fig.11

(x) **Solar Time:** Time based on the apparent angular motion of the sun across the sky, with solar noon, the time the sun crosses the meridian of the observer is called the solar time.

Solar time is the time specified in all by the sun angle relationships; it does not coincide with local clock time. It is necessary to convert standard time to solar time by applying two corrections. First, there is a constant correction for the difference in longitude between the observer's meridian location and the meridian on which the local standard time is based; the sun takes four minutes to transverse 1^0 of longitude. The second correction is from the equation of time, which takes into account the per urbations in the earth's rate of rotation, which affect the time the sun crosses the observer's meridian.

Solar time = Standard time + $4(L_{st} – L_{loc})$ + E ………………. (20)

Where E = Equation of time = 9.87 sin 2B – 7.53 cos B – 1.5 sin B.

L_{st} = Standard meridian for the local time zone.

L_{loc} = Longitude of the location is question in degrees west.

$B = \frac{360\ (n-81)}{364}$

n = day of the year, $1 \leq n \leq 365$

Example 4

At Madison, WI, what is the solar time corresponding to 10.30 A.M. Central standard time on February 2?

Solution

Solar time = Standard time + $4(L_{st} – L_{loc})$ + E ……. (i)

E = 9.87 sin 2B – 7.53 cos B – 1.5 sin B ……. (ii)

$$\text{But } B = \frac{360\ (n-81)}{364}$$

$$= \frac{360\ (33-81)}{364}$$

$$B = -47.5$$

From equation (ii)

E = {9.87 sin -47.5(2)} – {7.53 cos -47.5} – {1.5 sin -47.5}

= {9.87 x 0.996} – {7.53 x 0.676} – {1.5 x -0.737}

= - 9.87 – 5.09 + 1.1100

= -13.81

Therefore, equation (i)

Solar time = Standard time + 4 (90 – 89.4) + (-13.8)

Where Medison's $L_{st} = 90^0$w, $L_{loc} = 89.4^0$

Solar time = Standard time + 2.48 – 13.8

Solar time = Standard time – 11.32 mins.

Solar time = 10.30 AM – 11mins.

Solar time = 10.19 AM.

Direction of Beam Radiation

The geometric relationships between a plane of any particular orientation relative to the earth at any time (whether that plane is fixed or moving relative to the earth) and the incoming beam solar radiation, that is, the position of the sun relative to that plane, can be described in terms of several angles. These as follows:

(i) ϕ Latitude, that is the angular location North or south of the equator, North positive, $-90^0 \leq \phi \leq 90^0$

(ii) δ Declination, that is, the angular position of the sun at solar noon with respect to the plane of the equator, north positive, $-23.45^0 \leq \delta \leq 23.45^0$

(iii) β Slope, that is, the angle between the plane surface in question and the horizontal $0 \leq \beta \leq 180^0$. ($\beta > 90^0$ means that the surface has downward facing component).

(iv) γ Surface azimuth angle, that is the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative, west positive, $-180^0 \le \boldsymbol{\gamma} \le 180^0$.

(v) **ω** Hour angle, that is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15^0 per hour, morning negative, afternoon positive.

(vi) **Θ** Angle of incidence, that is the angle between the beam radiation on a surface and the normal to that surface.

The declination, δ is given as:

$\delta = 23.45 \sin (360 \frac{284+n}{365})$ …………………………… (21)

The equation relating the angle of incidence of beam radiation, θ, and the others angles is:

$\cos\theta = \sin\delta \sin\phi \cos\beta - \sin\delta \cos\phi \sin\beta \cos\boldsymbol{\gamma}$
$+ \cos\delta \cos\phi \cos\beta \cos\omega$
$+ \cos\delta \sin\phi \sin\beta \cos\ c\,\boldsymbol{\gamma}\ os\ \omega$
$+ \cos\delta \sin\beta \sin\boldsymbol{\gamma} \sin\omega$ ………………………….. (22)

Example 5

Calculate the angle of incidence of beam radiation on a surface located at Medison, WI at 10.30 (solar time) on February 13, if the surface is tilled 45^0 from the horizontal and is pointed 15^0 west of south.

Solution

Given: $\cos\theta = \sin\delta \sin\phi \cos\beta - \sin\delta \cos\phi \sin\beta \cos\boldsymbol{\gamma}$
$+ \cos\delta \cos\phi \cos\beta \cos\omega$
$+ \cos\delta \sin\phi \sin\beta\ coscos\ \boldsymbol{\gamma}\ \omega$
$+ \cos\delta \sin\beta\ sins\ \boldsymbol{\gamma}\ in\ \omega$

$\boldsymbol{\gamma} = 15^0$
$\delta = 45^0$
Madison's $\phi = 43^0$N

But $\delta = 23.45 \sin (360 \frac{284+n}{365})$
$= 23.45 \sin (360 \frac{284+44}{365})$
$= 23.45 (\sin 323.5)$
$= 23.45 (-0.5948)$
$= -13.94$
$\simeq -14^0$

ω at 10.30 am solar time
⇒ $1^1/_2$ hour before noon
90 mins before noon
$\frac{90}{4} = 22.5$
$\therefore \omega = -22.5^0$

Angle of incidence θ

$\cos\theta = \sin(-14^0) \sin 43^0 \cos 45^0 - \sin(-14^0) \cos 43^0 \sin 45^0 \cos 15^0$
$+ \cos(-14^0) \cos 43^0 \cos 45^0 \cos(-22.5^0)$
$+ \cos(-14^0) \sin 43^0 \sin 45^0 \cos 15^0 \cos(-22.5^0)$
$+ \cos(-14^0) \sin 45^0 \sin 15^0 \sin(-22.5^0)$

$\cos\theta = -0.117 + 0.121 + 0.464 + 0.418 + 0.068$
$= 0.817$
$\theta = \cos^{-1} 0.817$
$= 35.2^0$
$\simeq 35^0$

The solar azimuth angle ɤs, is the angular displacement from south of the projection of the beam radiation on the horizontal plane for fixed surfaces sloped toward the south or north, Zenith angle of the sun is:

$$\cos\theta_z = \cos\delta\cos\phi\cos\omega + \sin\delta\sin\phi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (23)$$

Example 6

Calculate the solar zenith angle as in example 5.

Given $\gamma = 15^0$

$B = 45^0$

$\phi = 43^0N$

But $\delta = 23.45\sin(360\frac{284+n}{365})$

$= 23.45\sin(360\frac{284+44}{365})$

$= 23.45(\sin 323.5)$

$= 23.45(-0.5948)$

$= -13.94$

$\simeq -14^0$

ω at 10.30 am solar time

$\Rightarrow 1^1/_2$ hour before noon

90 mins before noon

$\frac{90}{4} = 22.5$

$\therefore \omega = -22.5^0$

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

$\cos\theta_z = \cos -14\cos 43\cos -22.5 + \sin -14\sin 43$

$\cos\theta_z = 0.656 - 0.165 = 0.491.$

$= 60.6°$

Extraterrestrial Radiation on Horizontal Surface

Solar radiation outside the atmosphere incident on a horizontal plane is G_o in w/m^2 (watts per square meter)

$$G_o = G_{sc}[1+0.033\cos(\frac{360n}{365})]\,Cos\theta_z \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (24)$$

Where, G_{sc} = solar constant

N = day of the year

Θ_z = zenith angle

Solar radiation (G_o) for a horizontal surface at any time between sunrise and sunset is given by

$$G_o = G_{sc}[1+0.033\cos(\frac{360n}{365})]\,(\sin\phi\sin\delta + \cos\phi\cos\delta\cos\boldsymbol{\gamma}) \quad \ldots\ldots\ldots\ldots\ldots (25)$$

Daily extraterrestrial radiation (H_o) on horizontal surface over the period from sunrise to sunset (joules per square meter)

$$H_o = \frac{24\times3600G_{sc}}{\pi}\left[1+\ 0.033\cos\left(\frac{360n}{365}\right)\right]\times[\cos\phi\cos\delta\sin\omega_s + \frac{2\pi\omega_s}{360}\ \sin\phi\sin\delta]$$

Where w_s = sunset hour angle, in degrees.

NOTE H_o = Daily total extraterrestrial radiation.

$\bar{H}_o$ = Monthly mean of daily extraterrestrial radiation.

Example 7

W hat is the day's solar radiation on a horizontal surface in the absence of the atmosphere, Ho, at latitude 43^0N, on April 15?

Solution

Given $\emptyset = 43^0$

$n = 105$

$G_{sc} = 1353$

$\delta = 23.45 \sin (360 \frac{284+n}{365})$

$\delta = 23.45 \sin (360 \frac{284+105}{365})$

$23.45 \sin 383.7$

$= 9.43^0 \approx 9.4^0$

$\text{Cos } w_s = -\tan\emptyset \tan\delta$

$= -\tan43\tan9.4$

$= -0.154$

$w_s = \cos^{-1} - 0.154$

$98.85^0 \approx 98.9^0.$

From

$$H_o = \frac{24\times3600}{\pi} \text{ x } G_{sc}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right] \times \left[cos\phi cos\delta sin\omega_s + \frac{2\pi\omega_s}{360}\ sin\phi sin\delta\right]$$

$$H_o = \frac{24\times3600}{\pi} \times 1353\ \left[1 + 0.033\cos\left(\frac{360\times105}{365}\right)\right] \times \left[cos43cos9.4sin98.9 + \frac{2\pi\times98.9}{360}\ sin43sin9.4\right]$$

$= 372 \text{ x } 10^5[0.9922] \text{ x } [1.713 + 0.192]$

$372\text{x } 10^5(0.9922) \text{ x } 0.905$

$334\text{x } 105 \text{ J/m}^2 = 33.4 \text{ MJ/m}^2$

Extraterrestrial Radiation on Horizontal Surface for an Hour Period (I_o)

$$I_o = \frac{12\times3600G_{sc}}{\pi}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right] \times \left[cos\phi cos\delta(sin\omega_2 - sin\omega_1) + \frac{2\pi(\omega_2-\omega_1)}{360}\ sin\phi sin\delta\right].$$

Example 8

What is the solar radiation on a horizontal surface in the absence of the atmosphere at latitude 43^0N on April 15, between the hour of 10.00 and 11.00?

Solution

10.00 = 2hrs before noon = 120mins. 1^0 = 4mins

$w_1 = -30^0$

11.00 = 1hr before noon = 60mins. = -15^0

$W_2 = -15^0$

$\Phi = 43^0$

An hour solar radiation

$$I_o = \frac{12\times3600G_{sc}}{\pi}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right] \times \left[cos\phi cos\delta(sin\omega_2 - sin\omega_1) + \frac{2\pi(\omega_2-\omega_1)}{360}\ sin\phi sin\delta\right]$$

$\delta = 23.45 \sin (360 \frac{284+n}{365})$

$\delta = 23.45 \sin (360 \frac{284+105}{365})$

$23.45 \sin 383.7$

$= 9.43^0 \approx 9.4^0$

$$I_o = \frac{12\times3600}{\pi}(1353)\left[1 + 0.033\cos\left(\frac{360\times105}{365}\right)\right] \times \left[cos43cos9.4(\sin(-15) - \sin(-30)) + \frac{2\pi(-15-(-30))}{360}\ sin43sin9.4\right]$$

$= 3.75\text{MJ/M}^2$

Terrestrial Solar Radiation

In space, solar radiation is practically constant; on Earth, it varies with the day of the year, time of the day, the latitude, and state of the atmosphere. In solar engineering the surface that capture or redirect solar radiation are known as solar collectors. The amount of solar radiation striking solar collectors depends also on the position of the surface and on the local landscape.

Solar radiation can be converted into useful forms of energy such as heat and electricity using a variety of thermal and photovoltaic (PV) technologies, respectively. The thermal systems are used to generate heat for hot water, cooking, drying, melting, and steam engines, among others. Photovoltaics are used to generate electricity foe grid-tied or stand-alone off-grid systems. There are also applications where ultraviolet solar energy is used in chemical reactions.

When electromagnetic waves are absorbed by an object, the energy of the wave is typically converted to heat. This is a very familiar effect because sunlight warms surfaces that it irradiates. Often, this phenomenon is associated particularly with infrared radiation, but any kind of electromagnetic radiation will warm an object that absorbs it. Electromagnetic waves can be reflected or scattered, in which case their energy is redirected or redistributed as well.

The *total solar radiation* incident on either a horizontal H or tilted plane I consists of three components: beam, diffuse, and reflected radiation. As sunlight passes through the atmosphere, some of it absorbed, scattered, and reflected by air molecules, water vapour, clouds, dust and pollutants. The *diffuse solar radiation* is the portion scattering downward from the atmosphere that arrives at the Earth's surface and the energy reflected on the surface from the surroundings. For a horizontal surface, this is expressed as H_d and for a tilted one as I_d. The solar radiation that reaches the Earth's surface without being modified in the atmosphere is called *direct beam solar* radiation. H_b for a horizontal and I_b for a tilted surface. Measurements of solar energy are typically expressed as total solar radiation on horizontal or tilted surface and calculated from the relationship.

In designing and sizing solar energy systems, the quantification of the amount of solar energy incoming to solar collectors can be represented as irradiance and insolation. *Irradiance* is the instantaneous radiant power incident on a surface, per unit area. Usually, it is expressed in Watts per square meter. The integration of the irradiance over a specified period of time corresponds to the insolation.

Measurement of Terrestrial Solar Radiation

Solar radiation data are required for resource assessment, model development, system design, and collector testing- among other activities in solar engineering and research.

The most commonly used instruments to measure solar radiation today are based on either thermoelectric or the photoelectric effects. The thermoelectric effect is achieved using a thermopile that comprises collections of thermocouples, which consist of dissimilar metals mechanically jointed together. They produce a small current proportional to their temperature. When they are appropriately arranged and coated with a dull dark finish, they serve as nearly perfect blackbody detectors that absorb energy across the entire range of the solar spectrum. The hot junction is attached to one side of a thin metallic plate. The other side of the plate is blackened to be highly absorptive when exposed to the sun's radiation. The cold junction is exposed to a cold cavity within the instrument. The output is compensated electrically for the cavity temperature. The amount of insulation is related to the elevated temperature achieved by the hot junction and the electromagnetic force generated. The response is linearized and calibrated so that the output voltage can be readily converted to the radiative flux. The PV sensors are simpler and have instantaneous response and good overall stability. The PV effect occurs when solar radiation strikes a light-sensitive detector; atoms in the detector absorb some of the photons' energy. In this excited state, which may be produced only by light in a specific range of wavelengths, the atoms release electrons, which can flow through a conductor to produce an electrical current. The current is proportional to the intensity of the radiation striking the detector. The major disadvantage of these sensors is that the spectral response is not uniform in the solar band.

Instruments used to measure the transmission of sunlight through Earth's atmosphere fall into two general categories: instruments that measure radiation from the entire sky and instruments that measure only direct solar radiation. Within each of these categories, instruments can be further subdivided into those that measure radiation over a broad range of wavelengths and those that measure only specific wavelengths. The full-sky instruments need an unobstructed 360° view of the horizon, without significant obstacles. Full-sky instruments are called radiometers or, in the case of solar monitors, pyranometers (Figure 12). Good quality ones are typically about 15 cm in diameter. The sensor is under one or two hemispherical glass domes. The glass is specially formulated to transimit solar radiation over a wide range of wavelengths and is isolated thermally from the sensor. The pyranometer is intended for use in the permanently mounted horizontal position for which it is calibrated.

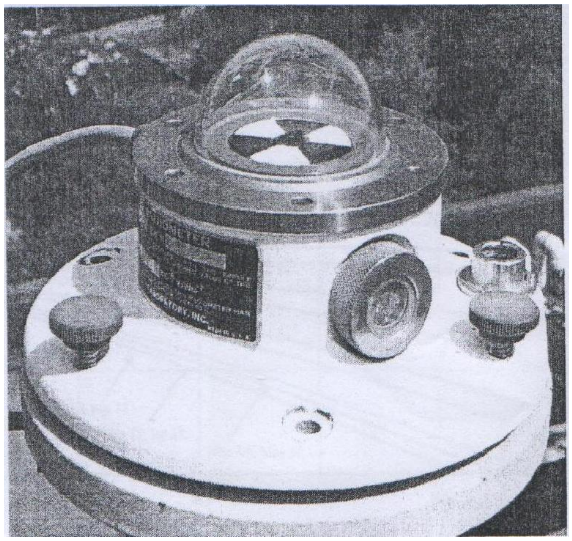


Fig.12. Pyranometer Eppley Model PSP

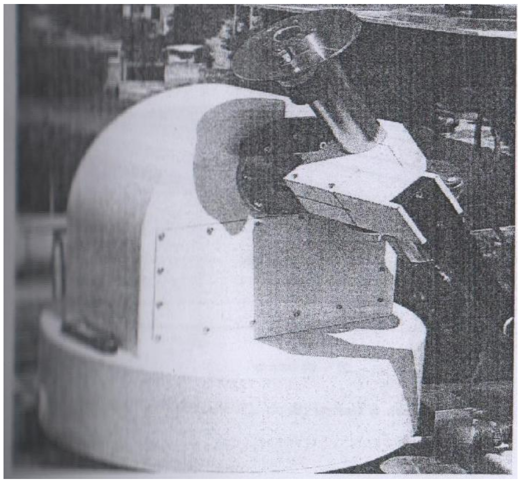


Fig.13 Pyrheliometer

The direct sunlight radiation is measured with pyrheliometers (Fig. 13). These are designed to view only light coming directly from the sun. The radiation incident on the detector is restricted to a narrow cone of the sky to avoid scattered light. The sensor is located at the base of a tube fitted with annular diaphragms where only nearly normal incident radiation reaches. The tubes housing the detector at the bottom are about 50cm long. This instrument automatically tracks the sun under computer control; the solar disk subtends about 0.5^0.

Terrestrial Insolation on Tilted Collectors

When designing solar energy systems or conducting performance monitoring, it is necessary to account for the availability of solar radiation data in order to calculate the amount of solar radiation striking on tilted collectors. Average hourly, daily, and monthly local insolation data are usually used; the most common insolation measurements are local horizontal global or beam.

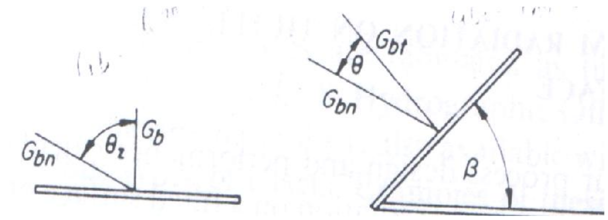
The global insolation is the most important input to estimate accurately insolation over tilted surfaces. Many mathematical models have been proposed to estimate hourly and daily global solar radiation on tilted surfaces from that measured on horizontal surfaces that include information such as level of cloudiness, pollution, temperature, and humidity, among other variables. Although these methods work well at local levels, there is not yet a general highly accurate method for predicting insolation. At any time, the ratio of beam radiation on a tilted surface to that on horizontal surface is related by the geometric factor R_h.

Ratio of Beam Radiation on Tilted Surface to that on Horizontal Surface

For the purpose of solar process design and performance calculations, it is often necessary to calculate the hourly radiation on a tilted surface of a collector from measurements or estimates of solar radiation on a horizontal surface. The most commonly available data are total radiation for hours or days on the horizontal.

Geometric factor (R_b) is the ratio of beam radiation on the tilted surface to that on a horizontal surface at any time.

$$R_b = \frac{G_{bt}}{G_b} = \frac{G_{bn} COS\theta}{G_{bn} COS\theta_Z} = \frac{COS\theta}{COS\theta_Z} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (26)$$



Example 9

What is the ratio of beam radiation for the surface and time specified in example 5 to that on a horizontal surface?

Solution

From example 5, $\cos\Theta = 0.817$

$$\cos\Theta_z = \cos\delta\cos\phi\cos\omega + \sin\delta\sin\phi$$
$$= 0.650 - 0.165$$
$$= 0.491$$

$$R_b = \frac{Cos\theta}{Cos\theta_z}$$

$$R_b = \frac{0.817}{0.491} = \mathbf{1.6}$$

The optimum azimuth angle for Flat plate collector is usually 0^0 in the northern hemisphere (or 180^0 in the southern).

$$R_b = \frac{\cos(\emptyset-\beta)\cos\delta\ \cos\omega + \sin(\emptyset-\beta)\sin\delta}{\cos\emptyset\cos\delta\cos\omega + \sin\emptyset\sin\delta} \quad \text{\}Northern hemisphere} \ldots\ldots\ldots\ldots\ldots\ldots.. (27)$$

$$R_b = \frac{\cos(\emptyset+\beta)\cos\delta\ \cos\omega + \sin(\emptyset+\beta)\sin\delta}{\cos\emptyset\cos\delta\cos\omega + \sin\emptyset\sin\delta} \quad \text{\}Southern hemisphere} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (28)$$

Example 10

Calculate R_b for a surface at latitude 40^0N at a tilt 30^0 toward the south, for the hour 9 to 10 , solar time, 0n February 16.

Solution

$R_b = \frac{\cos(\emptyset-\beta)cos\delta\ cos\omega+\sin(\emptyset-\beta)sin\delta}{cos\emptyset cos\delta cos\omega+sin\emptyset sin\delta}$ }Northern hemisphere

For hours 9 - 10 solar time = $2^1/_2$ before noon

But 1^0 = 4mins

: . w = -37.5

$\Phi = 40^0$

$\beta = 30^0$

$\boldsymbol{\gamma} = 180^0$

$\delta = 23.45 \sin (360\ \frac{284+47}{365})$

23.45 sin 326.5

$= -12.9^0 \approx -13^0$

Also, $\text{Cos}\Theta = \sin\delta \sin\boldsymbol{\gamma} \cos\beta - \sin\delta \text{ Cos } \boldsymbol{\gamma} \sin\beta \cos\boldsymbol{\gamma}$

$+ \cos\delta \cos\boldsymbol{\gamma} \cos\beta \cos\boldsymbol{\gamma}$

$+ \cos\delta \sin\boldsymbol{\gamma} \sin\beta\ \text{coscos}\ cos\ \boldsymbol{\gamma}$

$+ \cos\delta \sin\beta \sin\boldsymbol{\gamma} \sin\boldsymbol{\gamma}$

= sin(-13)sin40cos30- sin(-13)cos40sin30cos180

+cos (-13)cos40cos30cos(-37.5)

+cos(-13) sin30sin180sin(-37.5)

+ cos(-13)sin30sin180sin(-37.5)

$\text{Cos}\Theta_z = \cos\delta \text{Cos}\boldsymbol{\gamma}\text{Cos}\omega + \sin\delta\sin\boldsymbol{\gamma}$

= cos(-13)cos40cos(-37.5) + sin(-13)sin40

= 0.4462

$R_b = \frac{cos\Theta}{Cos\theta_z}\ \frac{0.7223}{0.4462} = 1.618 \approx 1.62$

or

$R_b = \frac{\cos(40-30)\cos(-13)\cos(-37.5)+\sin(40-30)\sin(-13)}{cos40\cos(-13)\cos(-37.5)+sin40\sin(-13)}$

$= \frac{0.7613-0.039}{0.5922-0.039} = \frac{0.7223}{0.4462} = 1.618 \approx 1.62$

Example 11

Calculate R_b for a latitude 40^0N at a tilt of 50^0 toward the south, for the hour 9 to 10 solar time, on February 16.

$R_b = \frac{Cos\theta}{Cos\theta_z}$

Or $R_b = \frac{\cos(\emptyset-\beta)cos\delta\ cos\omega+\sin(\emptyset-\beta)sin\delta}{cos\emptyset cos\delta cos\omega+sin\emptyset sin\delta}$

$R_b = \frac{\cos(40-50)\cos(-13)\cos(-37.5)+\sin(40-50)\sin(-13)}{cos40\cos(-13)\cos(-37.5)+sin40\sin(-13)}$

$Rb = \frac{0.7613+0.039}{0.5922-0.146} = \frac{o.8003}{0.4462} = 1.79359 \approx 1.8$

Available Solar Radiation

Solar radiation data are used in several forms and for a variety of purposes. The most detailed information we have is beam and diffuse solar radiation on a horizontal surface, by hours, which is useful in simulations of solar processes. Daily data are more often available and hourly radiation on horizontal surface can be used in some process design methods.
Instruments for measuring solar radiation are of two basic types namely Pyrheliometer and Pyranometer.

1 Pyrheliometer is an instrument using collimated detector for measuring solar radiation from the sun and from a small portion of the sky around the sun(i.e; beam radiation) at normal incidence.

2. Pyranometer. An instrument for measuring total hemispherical solar (beam + diffuse) radiation, usually on a horizontal surface. If shaded from the beam radiation by a shade ring or disc, a pyranometer measures diffuse radiation.

3. In addition, the term solarimeter are encountered: solarimeter can generally be interpreted to mean the same as pyranometer. whereas actinometer usually refers to a pyrheliometric instrument.

Solar Radiation Data

Solar radiation data are available in several forms. The following information about radiation data is important in its understanding and use:

- Whether they are instantaneous measurements (irradiance) or values integrated over some period of time (irradiation) (usually hour or day).
- The time or time period of the measurements
- Whether the measurements are of beam, diffuse or total radiation, and the instruments used.
- The receiving surface orientation (usually horizontal, sometimes inclined at a fixed slope, or normal to the beam radiation).
- If averaged, the period over which they are averaged (e.g; monthly average of daily radiation).

Most data available are for horizontal surfaces, include both direct and diffuse radiation, and were measured with thermopile pyranometers (or in some cases, Robitzsch-type instruments). Most of these instruments provide radiation records as a function of time, and do not themselves provide a means of integrating the records.

Solar Thermal Systems and Applications

Solar thermal energy has been used for centuries by ancient people's harnessing solar energy for heating and drying. More recently, in a wide variety of thermal processes solar energy has been developed for power generation, water heating, mechanical crop drying and water purification, among others. Given the range of working temperatures of solar thermal processes, the most important applications are

- For less than 100^0C : water heating for domestic use and swimming pools, heating of buildings, and evaporative systems such as distillation and dryers;
- For less than 150^0 : air conditioning, cooling and heating of water, oil or air for industrial use;
- For temperatures between 200 and 2000^0C: generation of electric and mechanical power; and
- For less than 5000^0C: solar furnaces for the treatment of materials.

Solar Collectors

Solar collectors are distinguished as low , medium, or high- temperature heat exchangers. There are basically three types of thermal solar collectors: flat plate, evacuated tube, and concentrating. Although there are great geometric differences, their purpose remains the same: to convert the solar radiation into heat to satisfy some energy needs.

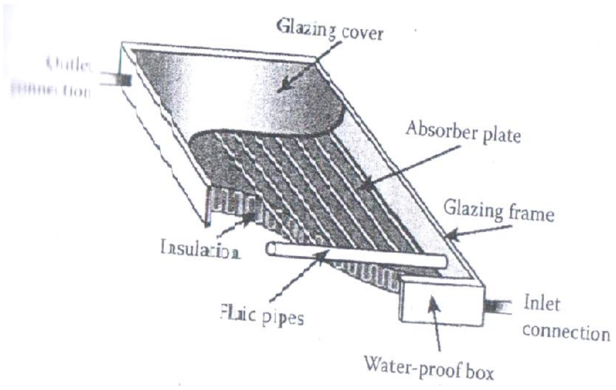
To evaluate the amount of energy produced in a solar collector properly, it is necessary to consider the physical properties of the materials. Solar radiation, mostly short wavelength, passes through a translucent cover and strike the energy receiver. Low – iron glass is commonly used as a glazing cover due to its high transmissivity; the cover also greatly reduces heat losses. The optical characteristics of energy receiver must be as similar as possible to those of a blackbody, especially high absorbtivity.

Flat Plate Collectors

A solar collector is a special kind of heat exchanger that transforms solar radiant energy into heat. A solar collector differs in several respects from more conventional heat exchangers. The latter usually accomplish a fluid - to – fluid exchange with high heat transfer rates and with radiation is an unimportant factor. In the solar collector, energy transfer is from a distant source of radiant energy to a fluid.

A flat plate collector is the simplest and most widely used means to convert the sun's radiation into useful heat.. It consists of a waterproof, metal or fiberglass insulated box containing a dark coloured absorber plate, the energy receiver, with one or more translucent glazing. Absorber plates are typically made out of metal due to its high thermal conductivity and painted with special selective coatings in order to absorb and transfer heat better than regular black paint can. The glazing covers reduce the convection and radiation heat losses to the environment. Figure 14(a) and (b) shows the typical components of a classic flat - plate collector and cross-section of a base flat plate solar collector respectively.

Flat- plate collectors are almost always mounted in stationary position (e.g as an integral part of a wall or roof structure with an orientation optimized for the particular location in question for the time of the year in which the solar device is intended to operate. In their most common forms, they are air or liquid heaters or low-pressure steam generators.



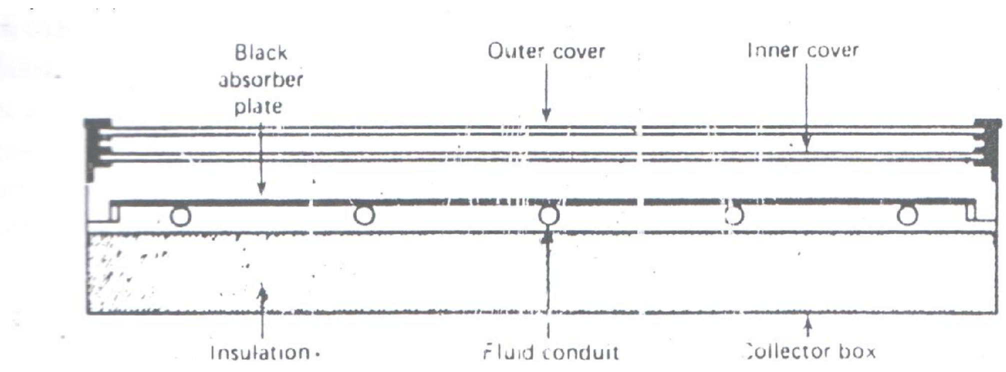


Fig.14(b)

The collector gains energy when the solar radiation travels through the cover; both beam and diffuse solar radiation are used during the production of heat. The greater the transmittance (τ) of the glazing is, the more radiation reaches the absorber plate. Such energy is absorbed in a fraction equal to the absorbtivity (α) of the blackened-metal receiver.

Collector Performance

In steady state, the performance of a solar collector is described by an energy balance that indicates the distribution of incident solar energy into useful energy gain, thermal losses and optical losses.

Heat Balance

The starting point for analysis of a solar collector is a simple heat balance. Assuming that the collector is operating in the steady state that is, that the system is not changing with time, the heat collected will equal the heat absorbed minus the losses to the environment.

$$Q = Q_a - Q_t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (29)$$

The heat absorbed is equal to the product of the radiation flux I, the collector area A_C , and the cover plate-absorber transmissivity- absorptivity product rα, referred to as the **optical efficiency**.

$$Q_a = \tau\alpha IA_a \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (30)$$

The heat lost from the system is that lost from the collector absorber plate at temperature T_c to the surrounding at the temperature $T_{a.}$ There are small losses from the collector to the sides and back via conduction and major losses by convection and radiation to the ambient temperature and by radiation to the sky and surroundings. To keep the relationship simple, a combined collector heat loss coefficient U_L is defined in the customary way so that

$$Q_t = U_LA_c(T_c - T_a) \quad \ldots\ldots\ldots\ldots\ldots\ldots (31)$$

Combining terms according to eqn. 29, the overall heat balance is

$$Q = \tau\alpha IA_c - U_LA_c(T_c - T_a) \quad \ldots\ldots\ldots\ldots\ldots (32)$$

Notice that the arriving irradiance I is expressed as a flux in energy rate per unit area while the collected heat Q is the net energy collection rate from all A_c. This can be confusing. The collector analysis is the most versatile if all the terms are expressed as fluxes, that is per unit of collector area. If eqn. 32 is divided by the area A_c , the resultant expression is

$$q = \tau\alpha I - U_L(T_c - T_a) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (33)$$

Where $Q/A_c \equiv q$. Lowercase q is defined to be the heat flux collected (energy collection rate per unit area), and should not be confused with uppercase Q, the energy collection rate for all the area. Equation (33) Hottel – whillier equation, in which each term is expressed per unit of collector area, is most important equation and will be used as the starting point for analysis of many collector situations.

Collector Efficiency (η)

This is the ratio of the rate of heat collected to that available.

$$\eta = q/I \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 34$$

The value of the collector efficiency is usually between 2ero and one, but negative values result when the radiation flux cannot make up for the losses. If equation s is divided by I, the efficiency is expressed as

$$\eta = \tau\alpha - U_L \frac{(T_c - T_a)}{I} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 35$$

This equation is useful because it can be plotted to give a very informative curve. If U_L is constant, a straight line results when η is plotted on the ordinate with the **collector operating point or efficiency function**

$$f_c = (T_c - T_a)/I \quad \ldots\ldots\ldots\ldots\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots 36$$

on the abscissa. The y- axis intercept is then $r\alpha$ and the (negative) slope is U_L. The x – axis intercept is $\tau\alpha/ U_L$.

A plot of equation (36) is called collector efficiency curve.

When the efficiency curve is given, collector performance can be predicted with no need to refer to or even be aware of the value for $r\alpha$ or U_L. All that is needed is to evaluate the collector operating point $f_c= (T_c - T_a)/I$, read the efficiency from the plot (as shown below) and apply a rearranged form of equation (34) .

Example 1

The collector having the $r\alpha = 0.8$ and $U_L= 5.22\ W/m^2$ is located at 40^0N latitude and tilted at 50^0 to the horizontal on March 21.The sky is clear and the collector temperature is 48.9^0 C and $I= 967.7\ W/m^2$.

(a) What is the collector efficiency and the rate of heat collection at 11 A M. If the ambient temperature is 1.7^0 C?

(b) What is the lowest radiation level at which heat can be collected? This is called the threshold radiation level.

(c) At 11.00AM, what is the stagnation temperature of the collector – the temperature that is reached if no heat is collected?

Solution.

(a) using equations 33 and 34

$$q = \tau\alpha I - U_L(T_c - T_a)$$

$$q = 0.8 \times 967.7 W/m^2 - 5.22\ W/^0 c .m \times (48.9-1.7)\ ^0C$$

$$q = 527.8\ W/m^2.$$

$$\eta = q/ I= 527.8/967.7 = 0.5$$

Or using equation (35)

$$\eta = \tau\alpha - U_L \frac{(T_c - T_a)}{I}$$

$$\eta = 0.8 - \left[5.22\ W/^0 C.m^2 \times \frac{(48.9 - 1.7)^0c}{967.7\ W/m^2}\right]$$

$$= 0.545$$

$$q = \eta I = 0.545 \times 967.7\ W/m^2 = 527.7\ W/m^2.$$

(b) The collector will have zero efficiency as it begins to deliver heat. From Fig.1, the efficiency is zero when the collector operating point is 0.1532^{0} C.m$^{2/}$W .

$$f_c = \frac{T_c - T_a}{I_{th}}$$

$$I_{th} = \frac{T_c - T_a}{f_c} = \frac{48.9 - 1.7^{0}C}{0.1532^{0}C.m^{2}/W} = 308.2 \text{ W/m}^{2}$$

Or

By solving equation 33 and 35 for I with q or $\eta = 0$, respectively.

$$I_{th} = \frac{U_L (T_c - T_a)}{\tau\alpha} = \frac{5.22 (48.9 - 1.7)}{0.8} = 308{,}0 \text{W/m}^{2}$$

(c) At stagnation temperature, the collector efficiency and heat collected are zero, and therefore the collector operating point is the some. Now, however, the radiation level is known but the collector temperature unknown.

From equation 36

$$f_c = (T_c - T_a)/I$$

$$T_c = f_c I + Ta$$

$$T_c = 0.1532^{0}C.\ m^{2}/W \times 967.7 \text{ W/m}^{2} + 1.7^{0}C = 150^{0}C$$

Or from equation 5 or 7

$$T_c = \frac{\tau\alpha I}{U_L} + Ta = \frac{0.8 \text{x} 967.7 \text{w/m}}{5.22 \text{ w/m}} + 1.7^{0}\ C = 150^{0}C.$$

Long – Term Collector Performance

The analysis above is valid for any particular time, but does not tell much about long –term performance. The sun's irradiance and the outside ambient temperature (and even the collector temperature) change continually during the day making the instantaneous heat collection rate or efficiency difficult to interpret effectively. Furthermore, it is the total radiation collected that is of most interest, which is a direct function of weather, radiation, and collector parameters.

Consider the operation of a collector over the course of a time period t_T. Assume that the storage tank for the collected heat is quite large so that the collector temperature is always the temperature of the stored fluid and is thus unchanging with time.

Rewriting equation 33 to emphasize the time-varying quantities,

$$q(t) = \tau\alpha\ I(t) - U_L [T_c - T_a(t)] \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 37$$

For an instantaneous time differential dt, the equation takes the form

$$q(t)\ dt = \tau\alpha I(t)\ dt - U_L[T_c - T_a)\ (t)\ ]\ dt \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ 38$$

which may be integrated term by term over a period of interest give a new form of the equation,

$$q_r = \tau\alpha \int_0^{tr} I(t)dt - U_L \int_0^{tr} [T_c - T_a(t)]\, dt \quad \text{………………… (39)}$$

Equation 39 can be evaluated by formulating the expressions for the time average values of $I_{(T)}$ and $T_a(t)$ over the time period t_r

$$I = \frac{\int_0^{tr} I(t)dt}{t_r} \quad \text{…………………………………… (40)}$$

$$T_a = \frac{\int_0^{tr} T_a(t)dt}{t_r} \quad \text{……………………………………(41)}$$

Each of these can be solved for its integral, and when both are substituted into eqn. 39 they give a new form of the equation

$q_T = \tau\alpha I t_T - U_L(T_c - T_a)t_T$ …………………………………… (42)

where

q_T = total radiation (heat) collected

$\tau\alpha$ = optical efficiency

I_T = radiation in time T

U_L = combine collector heat loss coefficient

T_c = absorber temperature

$\check{T}_a$ = average ambient temperature over time T=$\frac{\sum_{i=1}^{i=n} T_a(i)}{n}$: n = no of hours.

$\check{T}c$ = average absorber temperature over time T.

Radiation Heat Transfer

When two solid surfaces touch, they assume the same temperature at the common surface. It they do not touch, the temperatures need not be the same. When they are not the same, there will be heat transfer from the hot surface to the cold surface by radiation (and by convection as well if there is a gas between them). The origin of radiation is emission by matter and its transfer does not require the presence of any matter. Therefore, it is maximized in a vacuum. The nature of radiation heat transfer is by photons, according to some theories, or by electromagnetic emissions according to others. In both cases, wave standard properties like frequency (f) and wavelength (λ) are attributed to radiation. Thus, solar energy (light) has both wave and particle (photon) components. The type of radiation pertinent to heat transfer is thermal radiation – the portion that extends from 0.1 to 100μ m.

The heat transfer by radiation with an infinitely perfect absorber can be accurately predicted by a dimensional equation.

$$Q = 5.673\, \varepsilon A \left[\left(\frac{T_H}{100}\right)^4 - \left(\frac{T_L}{100}\right)^4\right]$$

where Q is the heat transfer rate in watts, A the area in m^2, and T_H and T_L the absolute temperatures in degrees Kelvin (k = °C + 272.15).

Expressions are available for calculation of radiation exchange between surfaces with varying emissivities, areas and orientations. In each equation ε is the emissivity of the surface. This is its propensity to lose heat by radiation to the surroundings, which are assumed to be perfectly absorbing. This is a good assumption for the sky, earth and vegetation to which radiation loss usually occurs.

Emissivity varies from almost 1.0 for very black surfaces to as little as 0.02 for highly polished metals. Most common material have an emissivity of about 0.8.

Example 1

A 2.44m x 3.05m glass outside surface at 23.9 ^{0}C is radiating to the sky which is at -3.9^{0}C. If the emissivity of the glass is 0.8, what is the heat transfer rate by radiation? (The sky is a good absorber of radiation).

Solution

$$Q = 5.673\ \varepsilon A\ [(\frac{T_H}{100})^4 - (\frac{T_L}{100})^4]$$

$$Q = 5.673 \text{ x } 2.44 \text{ x } 3.05 \text{ x } 0.8\ [(\frac{273+23.9}{100})^4 - (\frac{273+(-39)}{100})^4]$$

$$Q = 853.3\text{W}$$

Heat Transfer by Fluid Flow

If water cools a solar collector or carries heat to a radiator, or if hot air heats a house, the heat transfer is by fluid flow forced convection. The basic equation describing such heat transfer is:

$$Q = \omega c\ \ \Delta T$$

where ω is the mass flow rate of the fluid, c the specific heat of the fluid at constant pressure, and ΔT, the temperature rise.

Example 2

0.0252kg/s of water is heated from 15.6^0 to 32.2^{0}C in a solar collector, what is the heat removal rate? (c_w = 4.19kJ.kg^{-1}. ^{0}C^{-1}).

Solution

$$Q = \omega c\ \ \Delta T$$

$$= \frac{0.0252\text{kg}}{\text{s}} \text{ x } \frac{4.19\text{k}3}{\text{kg.0C}} \text{ x } (32.2 - 15.6)^0\text{C} \text{ x } \frac{\omega.\text{s}}{\text{J}}$$

$$= 1.75\text{kw.}$$

Radiation Properties and Thermal Transport Properties of Solar Energy Materials

Thermal radiation is the emission of electromagnetic waves from all matter that has a temperature greater than absolute zero. It represents a conversion of thermal energy into electromagnetic energy. Thermal energy results in kinetic energy in the random movements of atoms and molecules in matter. All matter with a temperature by definition is composed of particles which have kinetic energy, and which interact with each other. These atoms and molecules are composed of charged particles, i.e., protons and electrons, and kinetic interactions among matter particles result in charge-acceleration and dipole-oscillation. This results in the electrodynamic generation of coupled electric and magnetic fields, resulting in the emission of photons, radiating energy away from the body through its surface boundary. Electromagnetic radiation, including light, does not require the presence of matter to propagate and travels in the vacuum of space infinitely far if unobstructed.

The characteristics of thermal radiation depend on various properties of the surface it is emanating from, including its temperature, its spectral absorptivity and spectral emissive power, as expressed by Kirchhoff's law. The radiation is not monochromatic, i.e., it does not consist of just a single frequency, but comprises a continuous dispersion of photon energies, its characteristic spectrum. If the radiating body and its surface are in thermodynamic equilibrium and the surface has perfect absorptivity at all wavelengths, it is characterized as a black body. A black body is also a perfect emitter. The radiation of such perfect emitters is called black-body radiation. The ratio of any body's emission relative to that of a black body is the body's emissivity, so that a black body has an emissivity of unity.

Absorptivity, reflectivity, transmisivity and emissivity of all bodies are dependent on the wavelength of the radiation. The temperature determines the wavelength distribution of the electromagnetic radiation. For example, fresh snow, which is highly reflective to visible light (reflectivity about 0.90), appears white due to reflecting sunlight with a peak wavelength of about 0.5 micrometers. Its emissivity, however, at a temperature of about -5 °C, peak wavelength of about 12 micrometers, is 0.99.

If the amounts of radiation energy absorbed, reflected, and transmitted when radiation strikes a surface are measured in percentage of the total energy in the incident electromagnetic waves. The total energy would be divided into three groups, they are called absorptivity (α), reflectivity (ρ) and transmissivity (t)

$\alpha + \rho + t = 1$

- Absorption is the fraction of irradiation absorbed by a surface.
- Reflectivity is the fraction reflected by the surface.
- Transmissivity is the fraction transmitted by the surface.

A body is considered transparent if it can transmit some of the radiation waves falling on its surface. If electromagnetic waves are not transmitted through the substance it is therefore called opaque. When radiation waves hit the surface of an opaque body, some of the waves are reflected back while the other waves are absorbed by a thin layer of the material close to the surface. For engineering purposes all materials are thick enough that they can be considered opaque reducing equation 1 to:

$\alpha + \rho = 1$

Reflectivity deviates from the other properties in that it is bidirectional in nature. In other words, this property depends on the direction of the incident of radiation as well as the direction of the reflection. Therefore, the reflected rays of a radiation spectrum incident on a real surface in a specified direction forms an irregular shape that is not easily predictable. In practice, surfaces are assumed to reflect in a perfectly specular or diffuse manner. In a specular reflection, the angles of reflection and incidence are equal. In diffuse reflection, radiation is reflected equally in all directions. Reflection from smooth and polished surfaces can be assumed to be specular reflection, whereas reflection from rough surfaces approximates diffuse reflection. In radiation analysis a surface is defined as smooth if the height of the surface roughness is much smaller relative to the wavelength of the incident radiation.

The emissivity of a given surface is the measure of its ability to emit radiation energy in comparison to a blackbody at the same temperature. The emissivity of a surface varies between zero and one. This is a property that measures how much a surface behaves as a blackbody. The emissivity of a real surface varies as a function of the surface temperature, the wavelength, and the direction of the emitted radiation. The fundamental emissivity of a surface at a given temperature is the spectral directional emissivity, which is defined as the ratio of the intensity of radiation emitted by the surface at a specified wavelength and direction to that emitted by a blackbody under the same conditions. The total directional emissivity is defined in the same fashion by using the total intensities integrated over all wavelengths. In practice, a more convenient method is used: hemispherical properties. These properties are spectrally and directionally averaged. The emissivity of a surface at a specified wavelength may vary as temperature changes since the spectral distribution of emitted radiation changes with temperature. Finally the total hemispherical emissivity is defined in terms of the radiation energy emitted over all wavelengths in all directions. Radiation is a complex phenomenon, the dependability of its properties in wavelength and direction makes it even more complicated.

Therefore, the gray and diffuse approximation methods are commonly used to perform radiation calculations. A gray surface is characterized by having properties independent of wavelength, and a diffuse surface has properties independent of direction.

The distribution of power that a black body emits with varying frequency is described by Planck's law. At any given temperature, there is a frequency f_{max} at which the power emitted is a maximum. Wien's displacement law, and the fact that the frequency of light is inversely proportional to its wavelength in vacuum, mean that the peak frequency f_{max} is proportional to the absolute temperature T of the black body. The photosphere of the sun, at a temperature of approximately 6000 K, emits radiation principally in the (humanly) visible portion of the electromagnetic spectrum. Earth's atmosphere is partly transparent to visible light, and the light reaching the surface is absorbed or reflected. Earth's surface emits the absorbed radiation, approximating the behavior of a black body at 300 K with spectral peak at f_{max}. At these lower frequencies, the atmosphere is largely opaque and radiation from Earth's surface is absorbed or scattered by the atmosphere. Though some radiation escapes into space, most is absorbed and subsequently re-emitted by atmospheric gases. It is this spectral selectivity of the atmosphere that is responsible for the planetary greenhouse effect, contributing to global warming and climate change in general (but also critically contributing to climate stability when the composition and properties of the atmosphere are not changing).

The common household incandescent light bulb has a spectrum overlapping the black body spectra of the sun and the earth. Some of the photons emitted by a tungsten light bulb filament at 3000 K are in the visible spectrum. However, most of the energy is associated with photons of longer wavelengths; these do not help a person see, but still transfer heat to the environment, as can be deduced empirically by observing a household incandescent light bulb. Whenever EM radiation is emitted and then absorbed, heat is transferred. This principle is used in microwave ovens, laser cutting, and RF hair removal.

Unlike conductive and convective forms of heat transfer, thermal radiation can be concentrated in a tiny spot by using reflecting mirrors. Concentrating solar power takes advantage of this fact. In many such systems, mirrors are employed to concentrate sunlight into a smaller area. In lieu of mirrors, lenses can also be used to concentrate heat flux. (In principle, any kind of lens can be used, but only the Fresnel lens design is practical for very large lenses.) Either method can be used to quickly vaporize water into steam using sunlight.

Application of Solar Energy.

Solar Heating System

Solar heating System include the use of solar energy to produce domestic hot water, space heating, swimming pool heating in the temperate climate, drying of agricultural product etc. Solar heating techniques may be either passive (natural) or active (forced). Passive solar heating techniques (natural convention circulation systems) employ larger south facing windows, attached sun spaces, right insulations and internal storage capacity to store the sun’s energy. In passive water heater, the tank is located above the collector and water circulates by natural convection (i.e. no fans or pumps are used to move fluids around). Whenever solar energy in the collector adds energy to the water in the collector leg and so establishes a density difference. The active system for space, water swimming pool and drying systems have separate devices for collecting solar energy, transporting it, storing it, and releasing it to the load.

Four Methods of Transferring Heat from Collector to the Tank

(a) **Natural circulation system**: Tank is located above the collection and water circulates by natural convection wherever solar energy in the collector adds energy to the water in the collector leg and so establishes a density difference. Auxiliary energy is added to the water in the tank near the top to maintain a supply of hot water as shown in fig. 15 (a).

(b) **One tank forced circulation system:** A pump is required, which is usually controlled by a differential thermostat turning on the pump when the temperature at the top header is higher that the temperature of water in the button of the tank by a sufficient margin to assure continuous stability. A check valve is needed to prevent reverse circulation and resultant nighttime thermal loss from the collector. Auxiliary energy is added to water in the pipe leaving the tank to the load as shown in fig. 15 (b).

(c) **System with antifreeze loop and internal heat exchanger:** In climate where freezing temperature occur these design are modified. Example of such system using non freezing fluids is shown in fig. 15 (c). The collector heat exchanger can be external or internal to the tank. Auxiliary energy is added to the water in the storage tank by a heat exchanger in the tank.

(d) **System with antifreeze loop and external heat exchanger:** As in fig. 15(c)an auxiliary energy supply can also be provided by a standard electric, oil, or gas water heater with storage capacity of its own; this is the two-tank system shown in fig. 15(d.)

Any of these systems may be fitted with tempering valves that mix cold supply water with heated water to put an upper limit on the temperature of the hot water going to the distribution system. Other equipment not shown can include surge tanks and pressure relief valves.

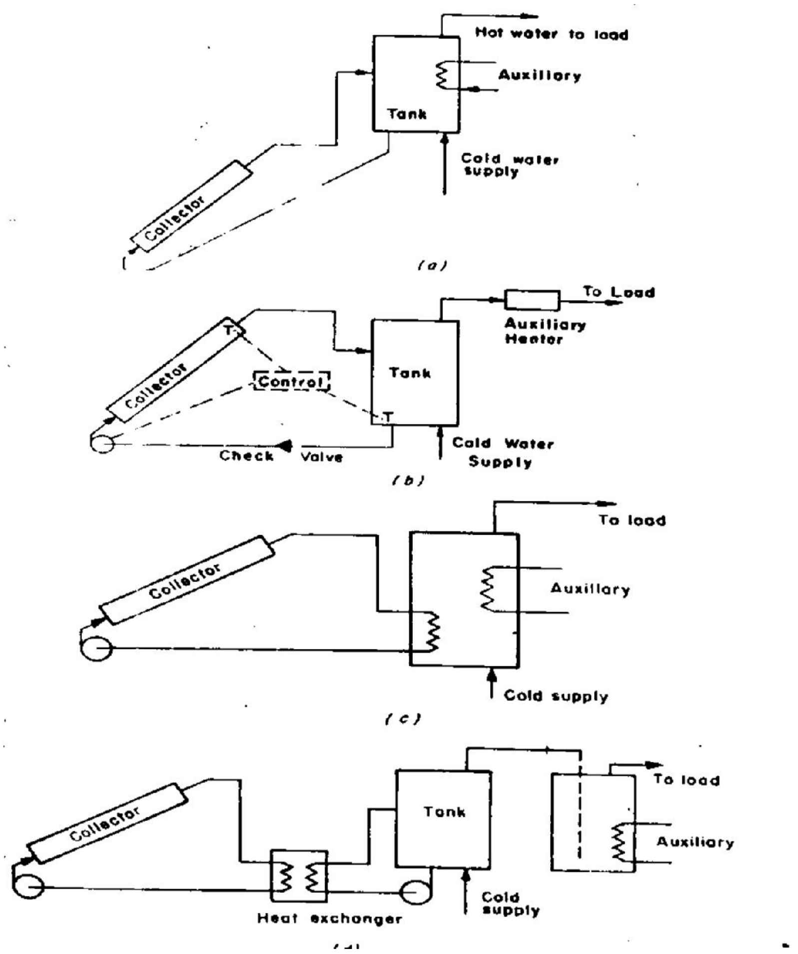


Fig. 15(a) – (d) Solar water heating systems

The future of many of the methods will depend on developments beyond the cooling process itself. Temperature constraints in the operation of collectors limit what can be expected of solar cooling processes. As collectors operating temperatures are pushed upward, storage may then become a critical problem.

Cooling is expensive, as is heating,. Reduction in cooling loads through careful building design and insulation will certainly be warranted and, within limits will be less expensive than providing additional cooling.

Solar Absorption Cooling

Two approaches have been taken to solar operation coolers

(i) Continues coolers (ii) Intermittent coolers

The first is similar in construction and operation to conventional gas or steam- fired units, with energy supplied to the generator from the solar collector-storage-auxiliary system where conditions in the building dictate the need for cooling. The second is similar in concept to that of commercially manufactured food coolers used many years ago in rural areas before electrification and mechanical refrigerator were wide spread.

Continuous Absorption Cycles

Continuous absorption cycles can be adopted to operation from flat-plate collection.

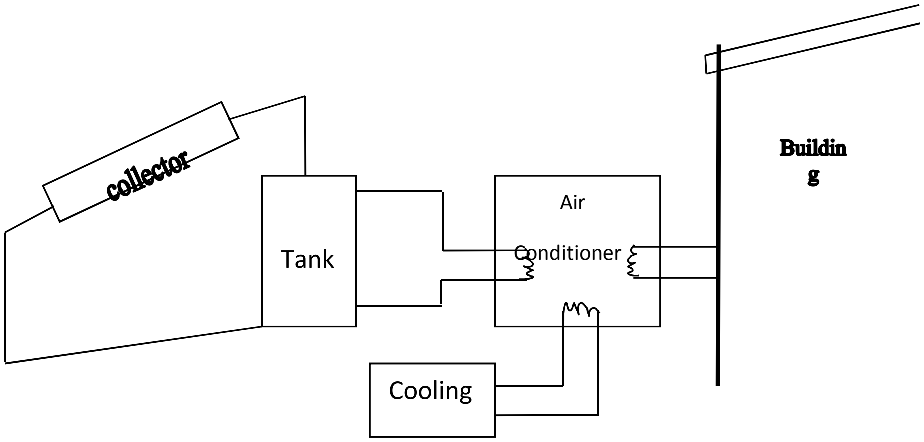
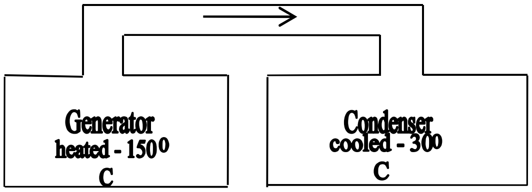


Fig. 16. Simplified Schematic of a solar absorption and conditioning system

Intermittent Absorption Cooling

This may be an alternative to continuous systems. Most work to date on these cycles has been directed at food preservation rather than comfort cooling. These cycles may be of interest in air conditioning because they offer potential solution to the energy storage problem. In these cycles, distillation of refrigerant from the absorbent occurs during the regeneration stage of operation, and the refrigerant is condensed and stored.

"Storage" is in the form of separated refrigerant and absorbent. Refrigerant absorbent systems used in intermittent cycles have been H_2S0_4 – H_20, NH_2-H_20 and NH_3- NaSCN. In the latter system, the absorbent is a solution of NaSCN in NH_3, with NH_3 the refrigerant.



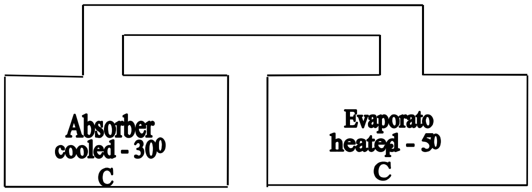


Fig. 17.

Solar Distillation

Distillation is a process that allows purifying some components of a solution based on differences of volatilities. In general terms, when solute have much smaller volatilities than the solvent, distillation is carried out by evaporating the in a particular region of the device and then condensing the vapour in a different region to obtain as pure a solvent as possible. When conventional energy is replaced by solar radiation, the process is called solar distillation. For the conventional process, the production rate remains constant under stable conditions of pressure, temperature, energy consumption, composition, and flow rate of the inlet stream. For the solar process, although predictable, it varies during the course of a day, showing a maximum during the hours with the highest irradiance. The variation is not only hourly but also daily over thr whole year.

The most widely used application for solar water distillation has been for water purification. The advantage of solar over conventional systems in purification of simple substances, such as brine or well water, is that operation and maintenance are minimal because no moving parts are involved. Also, there is no consumption of fossil fuel in solar distillation, leading to zero green-house –gas emission. Most importantly, these types of system can be installed in remote sites to satisfy freshwater needs of small communities that do not have conventional electric service.

Solar distillation represents one of the simplest yet most effective solar thermal technologies. Currently several solar still prototypes exist; differences lie in their geometries and construction materials. All designs are distinguished by the same operation principles and three particular elements: solar collector, evaporator, and condenser.

A solar still is an isolated container where the bottom is a blackened surfaced with high thermal absorbtivity and the cover is a transparent material, generally tempered glass. Purification is carried out when solar radiation crosses the glazing cover and reaches the solar collector , the black surface, and majority of this energy is absorbed. During this process, the electromagnetic radiation is converted into heat, causing an increment in the temperature of the collector, which is then available to be transferred into the water. The heat is trapped within the system due to the green-house effect. The convective heat losses to the environment should be minimized by adequate insulation.

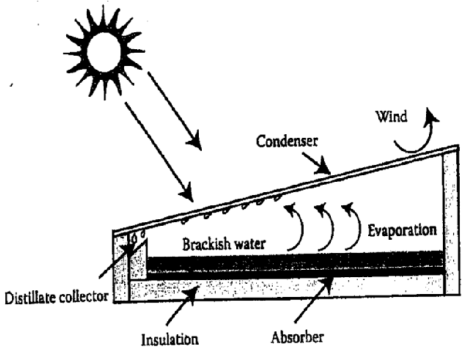


Fig.18 . Basic operation of a solar still

Because radiation is continuously entering the system, the temperature rises. As water temperature rises, diffusion of water into the air starts to take place. Evaporation occurs; no boiling is involved because the maximum temperatures experienced are always below 80^0C. These conditions favour the water not transporting components of higher solubilities or suspended solids. The glazing works as the condenser as well; because it is in direct contact with the environment, its temperature is lower than that of the collector and the water. The colder the surface is, the more easily condensation occurs. The glazing cover must be tilted for the distilled water to migrate toward a collection system. This process removes impurities such salts and heavy metals, as well as destroys microbiological organisms. The most common solar still is a passive basin solar distiller that needs only sunshine to operate.

The intensity of solar energy falling on the still is the single most important parameter affecting production. The daily distilled-water output (M_e) is the amount of energy utilized in vaporizing water in the still over the latent heat of vaporization of water. Solar still efficiency (η_{se}) is amount of energy utilized in vapourizing water in the still over the amount of incident solar energy on the sill.

$$M_e = \frac{Q_e}{L}$$

$$\eta_{se} = \frac{Q_e}{Q_s}$$

where, Qe = energy utilized in vapouurizing water

L = =latent heat of vapourization of water

Qs = incident solar energy on the still.