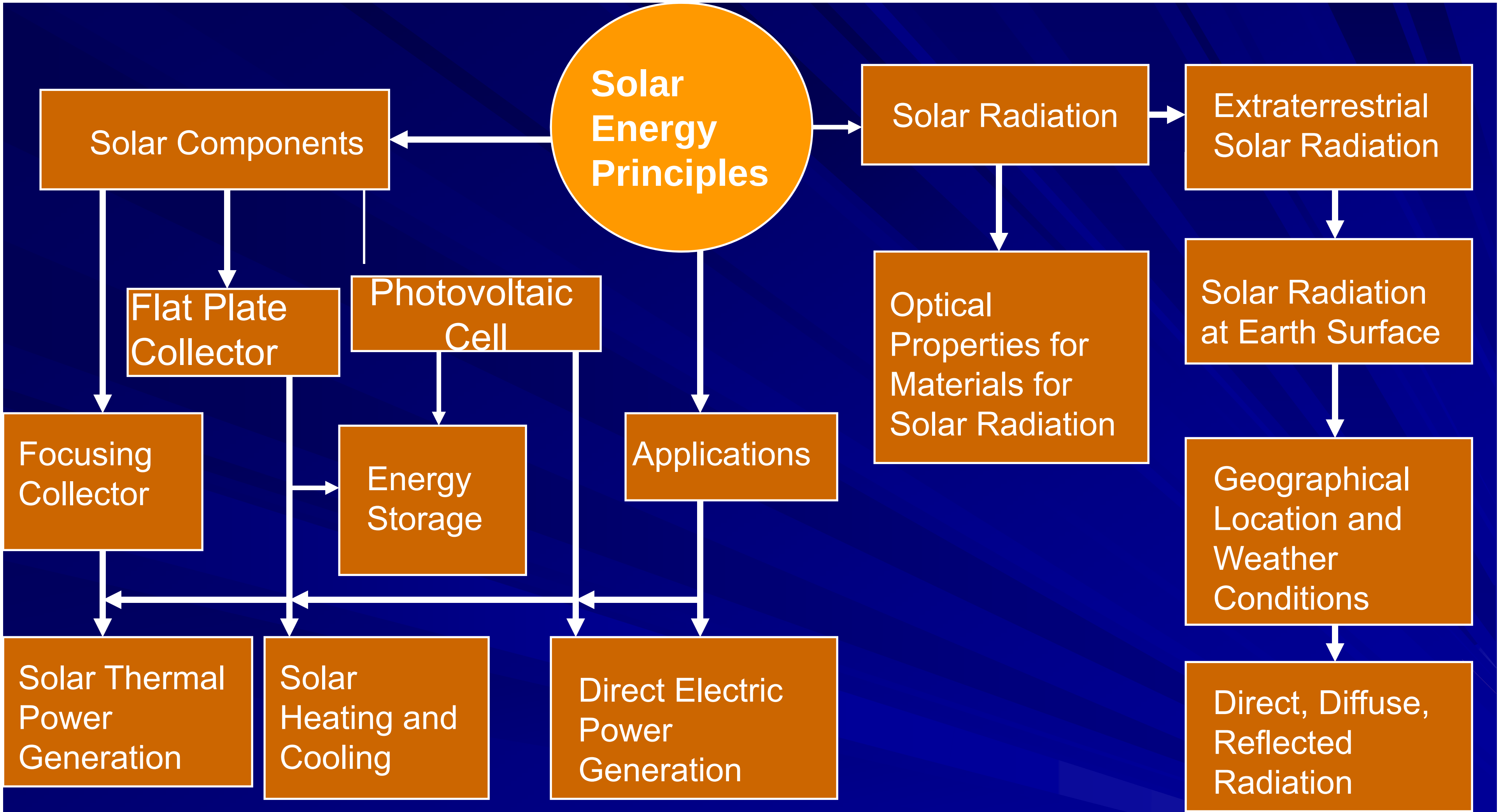
SOLAR RADIATION : SYSTEM AND ANGLES



ELEMENTS OF SOLAR ENERGY MODULE

Topics

- Solar energy and Application
- Major Characteristics of Sun and Earth
- Solar Radiation
- Solar and wall angles
- Estimation solar irradiation of a surface
- Optical properties of surface
- Solar collectors
- Solar thermal systems

Solar Energy and Applications

- Solar radiation is potential energy source for power generation through use of solar collector and photovoltaic cells.
- Solar energy can be used as thermal energy source for ***solar heating***, ***Airconditioning*** and ***cooling systems***.
- Solar radiation has important effects on both the heat gain and heat loss of a building.

Solar Radiation

- Intensity of solar radiation incident on a surface is important in the design of solar collectors, photovoltaic cells, solar heating and cooling systems, and thermal management of building.
- This effect depends on both the location of the sun in the sky and ***the clearness of the atmosphere*** as well as on the **nature and orientation of the building**.
- We need to know

  - *Characteristics of sun's energy* outside the earth's atmosphere, its intensity and its spectral distribution

  - *Variation with sun's location in the sky* during the day and with seasons for various locations on the earth's surface.

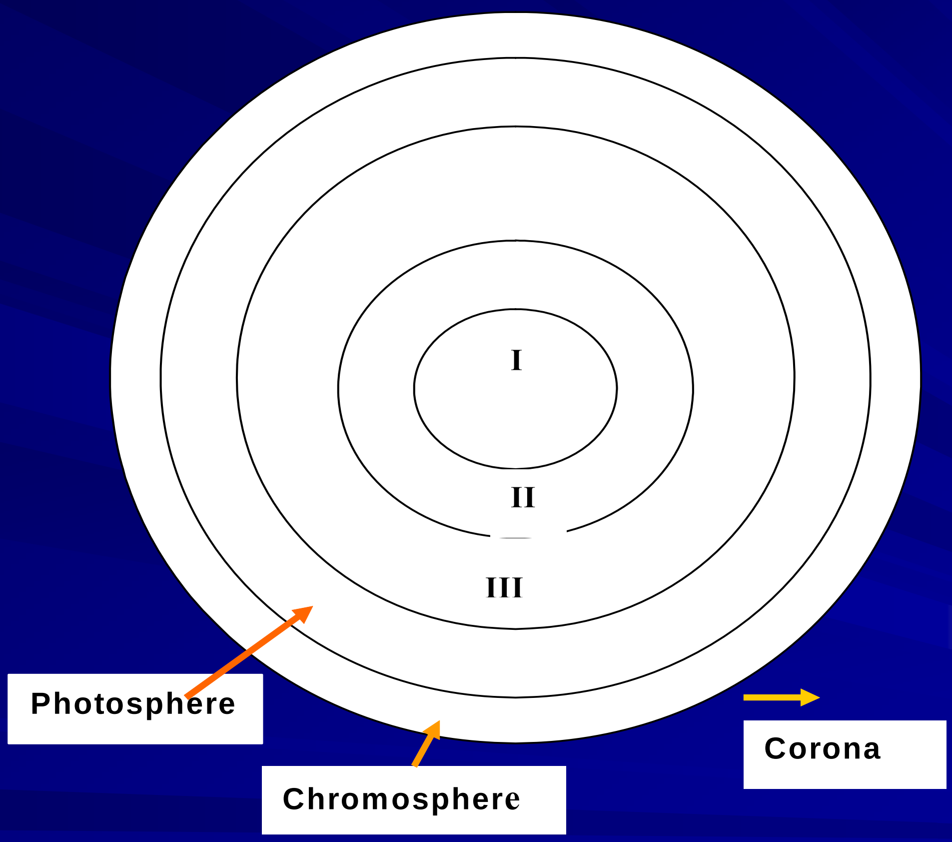
Solar Radiation

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

- Energy is released due to continuous fusion reaction with interior at a temperature of the order of million degrees.

- Radiation is based on sun's outer surface temperature of 5777 K.

Solar Geometry



Solar Geometry

The Sun: Major Characteristics

- A sphere of hot gaseous matter
- Diameter, D = (865400 miles) (Sharp circular boundary)
- Rotates about its axes (not as a rigid body)
- Takes 27 earth days at its equator and 30 days at polar regions.
- The sun has an *effective black body temperature of 5777 K*

  i.e. It is the temperature of a blackbody radiating the same amount of energy as does the sun.

- **Mean earth-sun distance:** D = (865400 miles) (Sharp circular boundary)

The Structure of Sun

Central Region: (Region – I)

Energy is generated due to fusion

Reaction of gases – transforms

hydrogen into helium.

- 90% of energy is generated within the core range of 0 – 0.23 R

- The temperature in the central region is in million degrees.

- The temperature drops to 130,000 K with in a range of 0.7R

Convection Region (Region – III)

- 0.7R to R where convection process involves

- The temperature drops to 5,000 K

Photosphere:

Upper layer of the convective zone

- Composed of strongly ionized gas
- Essentially opaque
- Able to absorb and emit continuous spectrum of radiation
- Source of the most solar radiation

Chromosphere (10,000km)

Further outer gaseous layer with temperature somewhat higher tan the Photosphere.

Corona

Still further outer layer

- extremity of sun.
- Consists of Rarified gases.
- Temperature as high as 1000,000 K

Thermal Radiation

- Thermal radiation is the intermediate portion (0.1 ~ 100μm) of the electromagnetic radiation emitted by a substance as a result of its temperature.
- Thermal radiation heat transfer involves transmission and exchange of electromagnetic waves or photon particles as a result of temperature difference.

Planck's Spectral Distribution of Black Body Emissive Power

The thermal radiation emitted by a black substance covers a range of wavelength (λ), referred as spectral distribution and given as

$$E_{\lambda,b} = \frac{C_1}{\lambda^5\left[e^{(C_2/\lambda T)} - 1\right]}$$

$$C_1 = 2\pi\pi h_0^2 = 3.742 \times 10^8\ W.\mu m^4/m^2$$

$$C_2 = hc_0/k = 1.439 \times 10^4\ \mu m.K$$

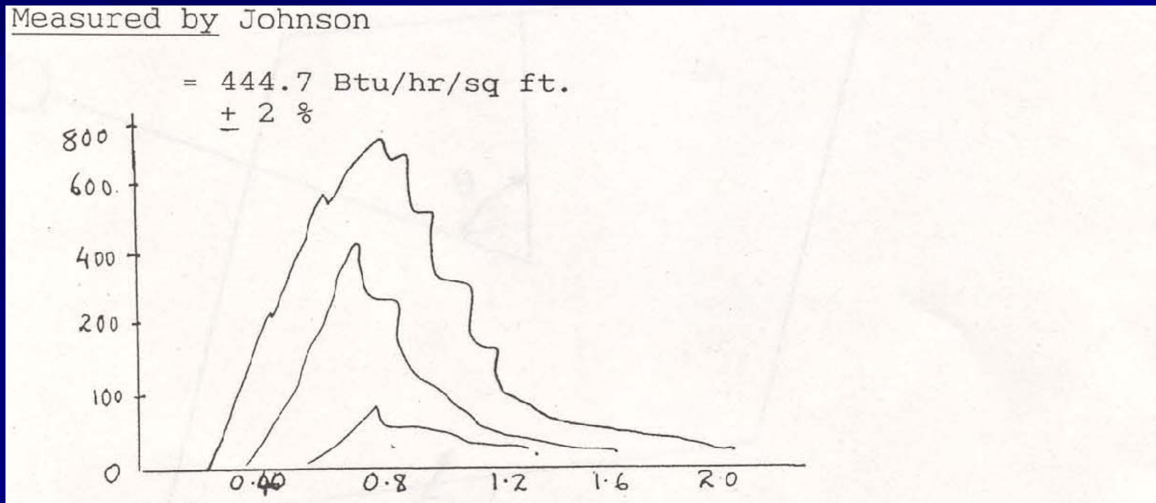
$$h = \text{Planck's constant} = 6.626 \times 10^{-24}\ J.s$$

$$k = \text{Boltzmann constant} = 1.381 \times 10^{-23}\ J/K$$

0.25 to 3.0 μm

Solar Intensity Distribution

Spectral distribution show the variation of solar radiation over the a bandwidth



Spectral distribution of solar radiation at outer atmosphere.

Black Body Emissive Power

The total black body emissive power is obtained by integrating the spectral emissive power over the entire range of wavelengths and derived as

$$\mathbf{E_b = \int_0^{\infty} E_{\lambda,b} = \frac{C_1}{\lambda^5 \left[e^{(C_2/\lambda T)} - 1 \right]} d\lambda}$$

$$E_b = \sigma T^4$$

Where σ = Stefan-Boltzman constant

= $5.6697 \times 10^{-8} W/m^2.K^4$

Real Body Emissive Power

Spectral Emissive Power

$$E_\lambda = \varepsilon_\lambda E_{b\lambda}$$

$$\varepsilon_\lambda = \frac{E_\lambda}{E_{b\lambda}} = \textit{Spectral hemispherical}\ \text{emissivity}$$

Total Emissive Power

$$E = \varepsilon E_b$$

$$\varepsilon = \frac{E}{E_b} = \text{Emissivity factor}$$

$$E = \varepsilon \sigma T^4$$

Extraterrestrial Radiation

Solar radiation that would be received in the absence of earth atmosphere.

Extraterrestrial solar radiation exhibit a spectral distribution over a

ranger of wavelength: 0.1- 2.5 μm

- Includes ultraviolet, visible and infrared

Solar Constant G_{sc}

Solar Constant = Solar radiation intensity upon a surface normal to sun ray and at outer atmosphere (when the earth is at its mean distance from the sun).

$$G_{SC} = 1367 W/m^2$$

$$= 433 \text{ Btu/ft}^2 hr$$

Variation of Extraterrestrial Radiation

Solar radiation varies with the day of the year as the sun-earth distance varies.

An empirical fit of the measured radiation data

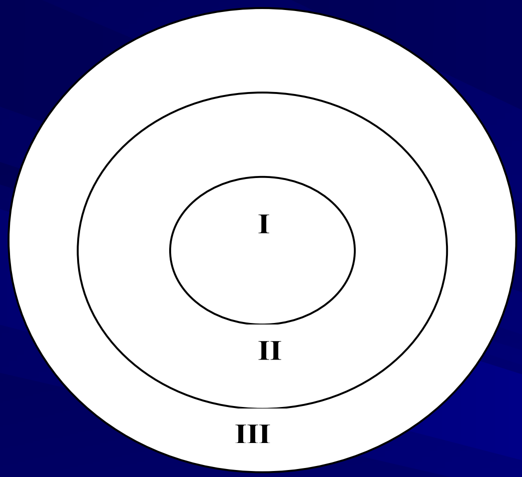
$$G_D = G_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right)$$

n = day of the year

$$G_D = G_{sc}\begin{pmatrix}1.000110 + 0.034221\cos B + 0.001280\sin B \\ + 0.000719\cos 2B + 0.000077\sin 2B\end{pmatrix}$$

$$\mathbf{B = (n-1)\frac{360}{365}}$$

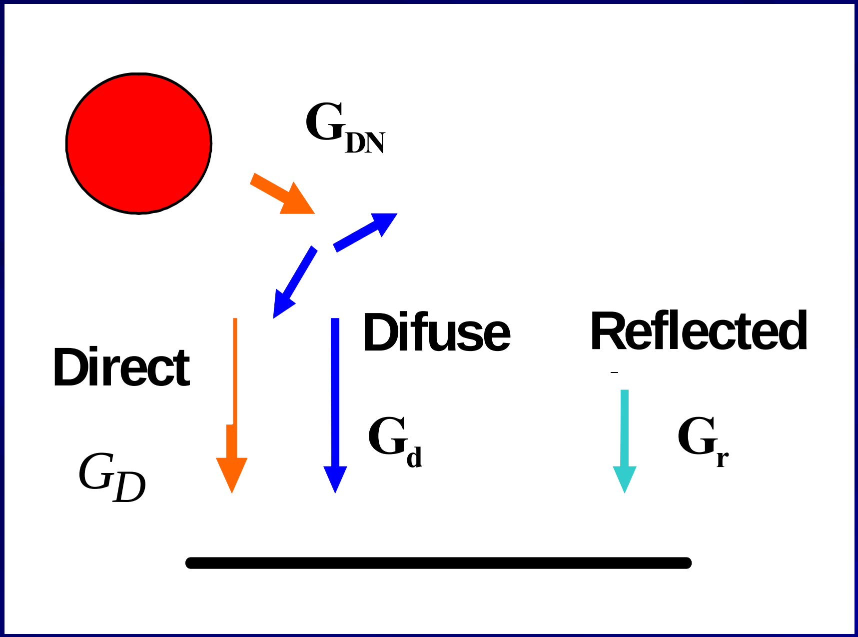
The Earth

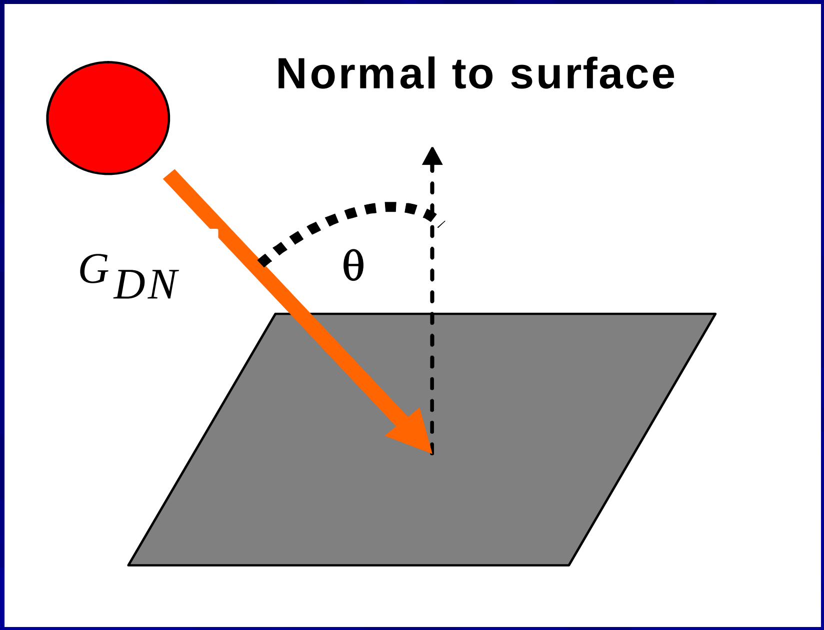


Diameter: 7900 miles
Rotates about its axis-one in 24 hours
Revolve around sun in a period of 365+1/4 days.
Density=5.52 times that of H_2O.

I: Central Core:1600 miles diameter, more rigid than steel.
II: Mantel: Form 70% of earth mass.
III: Outer Crust: Forms 1% of total mass.

Direct Radiation on Earth's Surface





Total radiation on a surface

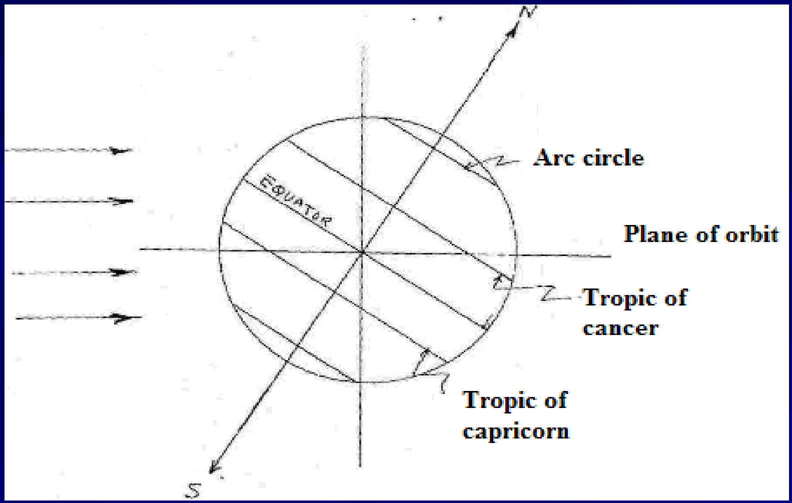
$$G_t = G_D + G_d + G_r$$

$$G_{D\theta} = G_{DN} \cos\theta$$

Orientation of a surface on earth with respect sun or normal to sun's ray can be determined in terms basic Earth-Sun angles.

Basic Earth-Sun Angles

Sun's Ray



The position of **a point P on earth's surface** with respect to sun's ray Is known at any instant if following angles are known:

Latitude (l), Hour angle (**h)**

and Sun's declination angle (**d)** .

Time

The earth is divided into 360^o of circular arc by longitudinal lines passing through poles.

The zero longitudinal line passes through Greenwich, England.

Since the earth takes 24 hours to complete rotation, 1 hour = 15^o of longitude

What it means?

A point on earth surface exactly 15^o west of another point will see the sun in exactly the same position after one hour.

Local Civil Time (LCT)

Universal Time or Greenwich Civil Time (GCT)

Greenwich Civil Time: GCT time or universal time

Time along zero longitude line passing through Greenwich, England. Time starts from midnight at the Greenwich

Local Civil Time (LCT)

Determined by longitude of the observer. Difference being 4 minutes of time for each degree or 1-hr for 15 °

Example: What is the LCT at 75° degree west longitude corresponding to 12:00 noon at GCT

75° degree corresponds to 75 ° / 15 ° = 5 hours

LCT at 75° degree west longitude = 12:00 PM – 5 hrs= 7 AM

Standard Time

Local civil time for a selected meridan near the center of the zone. Clocks are usually set for the same time throughout a time zone, covering approximately 15° of longitude.

Example

For U.S.A different standard time is set over different time zone based on the meridian of the zone. Following is a list of meridian line.

EST: 75° CST: 90°

MST: 105° PST: 120°

Also, there is Day Light Savings Time

Solar Time

Time measured by apparent daily motion of the sun

Local Solar Time, LST = LCT + Equation of time (E)

Equation-of-time takes into account of non-symmetry of the earthly orbit, irregularity of earthly rotational speed and other factors.

$$E = 220.2(0.000075 + 0.001868 \cos B - 0.032077 \sin B$$

$$- 0.0014615 \cos 2B - 0.04089 \sin 2B)$$

$$\mathbf{B} = (\mathbf{n} - \mathbf{1})\frac{\mathbf{360}}{\mathbf{365}}$$

Equation of Time and Sun's Declination Angle

THE SUN'S DECLINATION AND EQUATION OF TIME

Day ⟶	1		8		15		22	
Month	Dec. Deg: Min	Eq. of Time Min: Sec	Dec. Deg: Min	Eq. of Time Min: Sec	Dec. Deg: Min	Eq. of Time Min: Sec	Dec. Deg: Min	Eq. of Time Min: Sec
January	−(23:08)	− (3:16)	−(22:20)	− (6:26)	−(21:15)	− (9:12)	−(19:50)	−(11:27)
February	−(17:18)	−(13:34)	−(15:13)	−(14:14)	−(12:55)	−(14:15)	−(10:27)	−(13:41)
March	−(7:51)	−(12:36)	− (5:10)	−(11:04)	− (2:25)	− (9:14)	0:21	− (7:12)
April	4:16	− (4:11)	6:56	− (2:07)	9:30	− (0:15)	11:57	1:19
May	14:51	2:50	16:53	3:31	18:41	3:44	20:14	3:30
June	21:57	2:25	22:47	1:15	23:17	− (0:09)	23:27	− (1:40)
July	23:10	− (3:33)	22:34	− (4:48)	21:39	− (5:45)	20:25	− (6:19)
August	18:12	− (6:17)	16:21	− (5:40)	14:17	− (4:35)	12:02	− (3:04)
September	8:33	− (0:15)	5:58	2:03	3:19	4:29	0:36	6:58
October	− (2:54)	10:02	− (5:36)	12:11	− (8:15)	13:59	−(10:48)	15:20
November	−(14:12)	16:20	−(16:22)	16:16	−(18:18)	15:29	−(19:59)	14:02
December	−(21:41)	11:14	−(22:38)	8:26	−(23:14)	5:13	−(23:27)	1:47

Example: Local Standard Time

Determine local solar time (LST) corresponding to 11:00 a.m. CDST on February 8 in USA at 95° west longitude.

CST (Central Standard Time) = CDST - 1 hour = 11:00-1 = 10:00 a.m.

This time is for 90° west longitudinal line, the meridian of the central time zone.

Local Civil Time (LCT) at 95° west longitude is 5 X 4 = 20 minutes less advanced

LCT = CST - 20 minutes = 10:00 am – 20 min= 9:40 am

LST = LCT + Equation of Time (E)

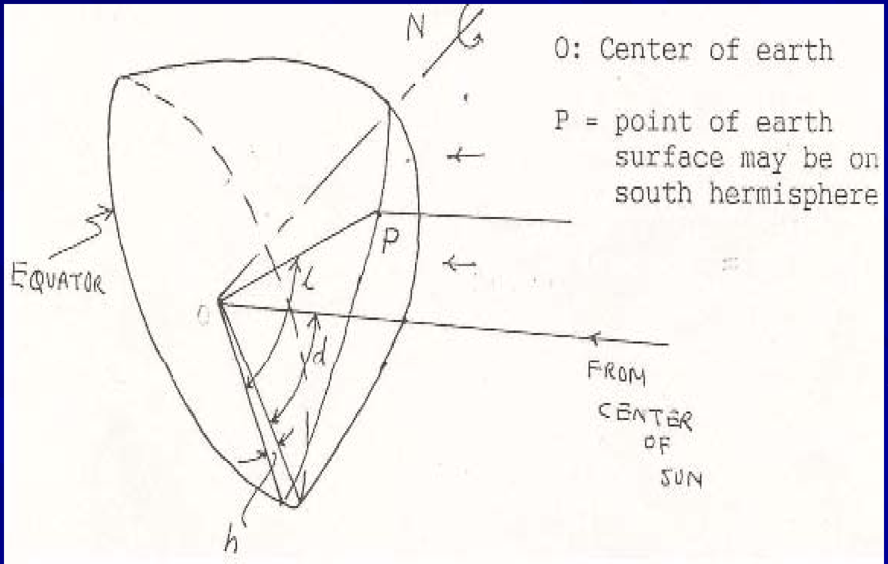
From Table: For February 8 the Equation of time = -14:14

LST = 9:40-14:14 = 9:26 a.m.

Solar and Wall Angles

Following solar and wall angles are needed for solar radiation calculation:

Latitude angle, l
Sun's Zenith angle , ψ
Altitude angle, β
Azimuth angle, γ or ϕ
Suns incidence angle θ
Wall-solar azimuth angle, γ'
Wall azimuth angle, ψ



Latitude (l) is defined as the angular distance of the point P north (or south) of the equator.

l = angle between line **op** and projection of op on the equatorial plane.

Declination (d)

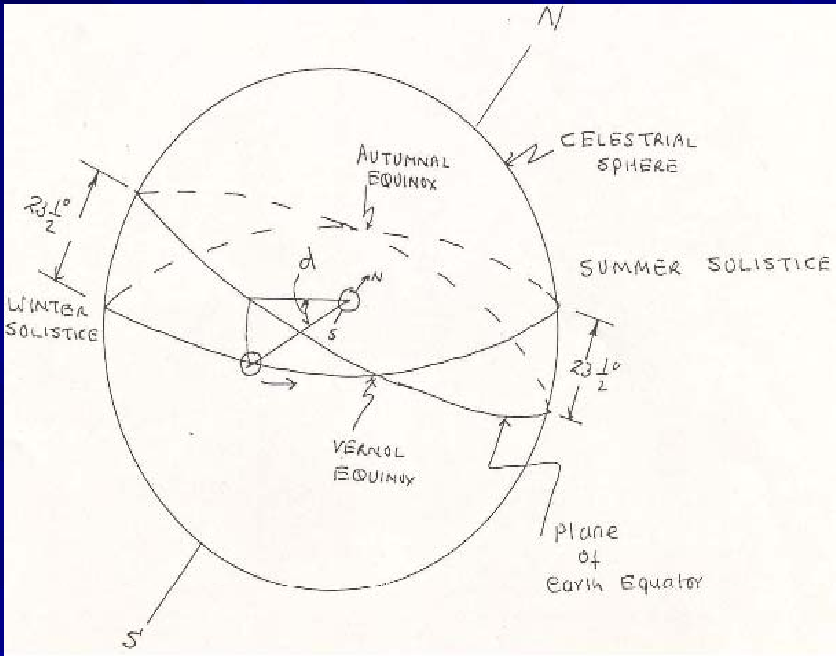
- Angle between a line extending from the center of the sun to the center of the earth and the projection of this line upon the earth equatorial plane.

- It is the angular distance of the sun's rays north (or south) of the equator.
- Figure shows the sun's angle of declination.

  d = - 23.5° C at winter solstice, i.e. sun's rays would be 23.5° south of the earth's equator

  d = +23.5° at summer solstice, i.e. sun's rays would be 23.5° north of the earth's equator.

  d = 0 at the equinoxes



Celestrial sphere showing apparant path of sun and sun's declination angle

$$d = 23.45 \sin [360(284+n)/365]$$

Hour Angle: 'h'

Hour Angle is defined as the angle measured in the earth's equatorial plane between the projection of **op** and the projection of a line from center of the sun to the center of earth.

- At the solar room, the hour angle (h) is zero, Morning: negative and Afternoon: positive

- The hour angle expresses the time of the day with respect to solar noon.
- One hour time is represented by 360/24 or 15 degrees of hour angle

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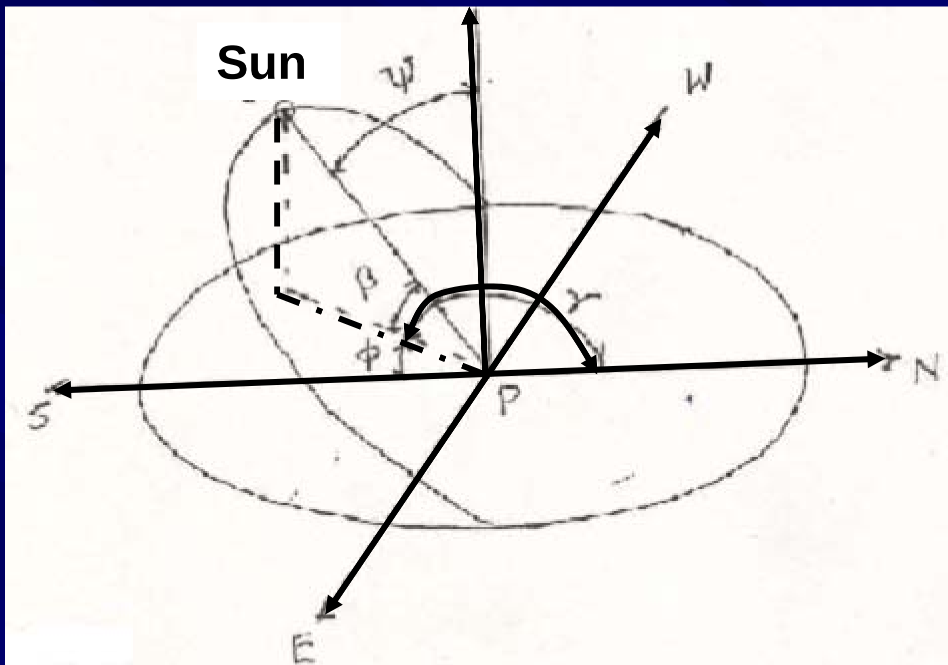
SOLAR ANGLES



ψ = **Zenith Angle** = Angle between sun's ray and a line perpendicular to the horizontal plane at P.

β = **Altitude Angle** = Angle in vertical plane between the sun's rays and projection of the sun's ray on a horizontal plane.

It follows $\beta + \psi = \pi/2$

ϕ

γ = Azimuth angle = Angle measured from north to the horizontal projection of the sun's ray.

$$\gamma + \phi = 180$$

ϕ = Azimuth Angle = angle measured from south to the horizontal projection of the Sun’s ray.

Solar Angles

From ***analytical geometry***

Sun's zenith angle

$\cos(\psi) = \cos(l)\cos(h)\cos(d) + \sin(l)\sin(d)$

Also $\beta = \pi/2 - \psi$

Sun's altitude angle:

$\sin(\beta) = \cos(l)\cos(h)\cos(d) + \sin(l)\sin(d)$

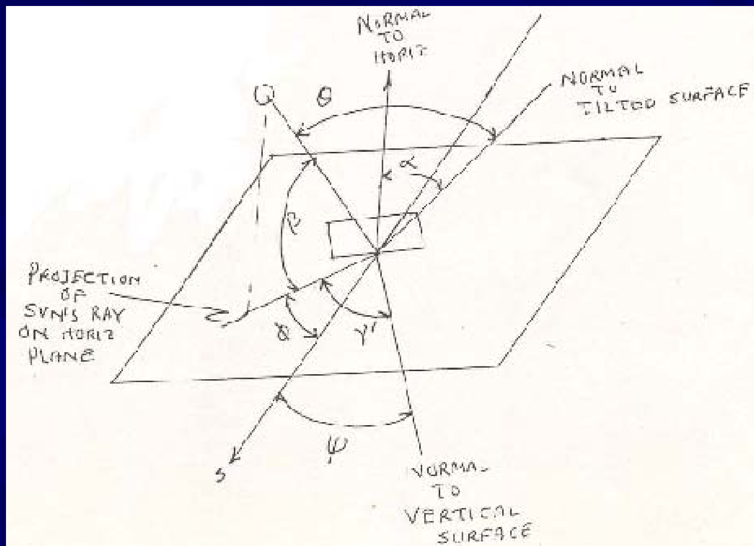
Sun's azimuth (γ) is given by

$\cos(\gamma) = \sec(\beta)\{\cos(l)\sin(d) - \cos(d)\sin(l)\cos(h)\}$

Or

$\cos\phi = (\sin\beta \sin l - \sin d)/(\cos\beta \cos l)$

Tilted Surface



α = angle of tilt
= normal to surface and normal to horizontal surface

***ψ* = Wall azimuth angle**
= Angle between normal to vertical surface and south

=

γ' = wall-solar azimuth angle
= For a vertical surface the angel measured in horizontal plane between the projection of the sun's ray on that plane and a normal to that vertical surface

$$\gamma' = \phi \pm \psi$$

Where

ϕ = Solar Azimuth Angle

γ'

Angle of Incidence (θ)

Angle of incidence is the angle between the sun's rays and normal to the surface

$\cos\theta = \cos\beta \cos\gamma' \sin\alpha + \sin\beta \cos\alpha$

For ***vertical surface***

$\cos\theta = \cos\beta \cos\gamma'$, $\alpha = 90°$

For ***horizontal surface***

$\cos\theta = \sin\beta$, $\alpha = 0°$

Solar Radiation Intensity at Earth Surface

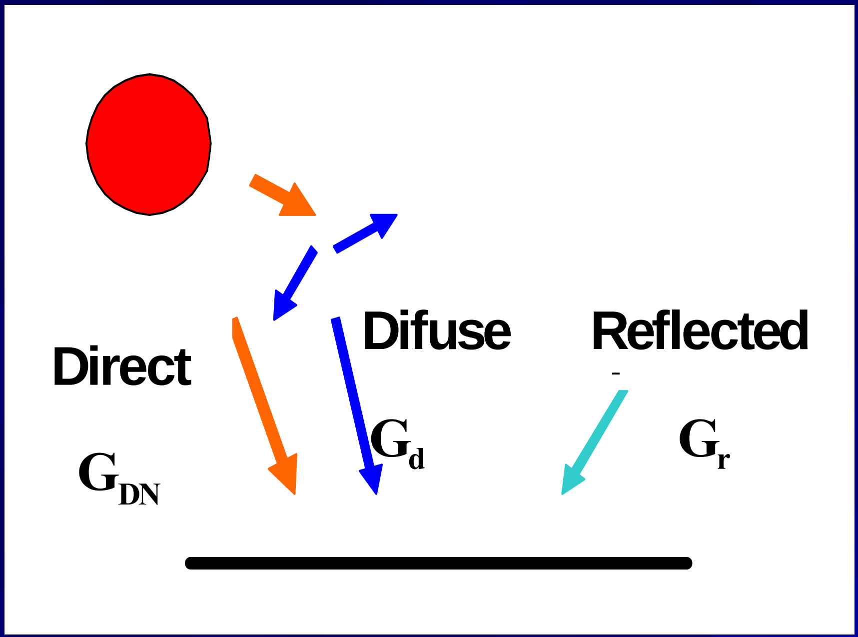
Solar radiation incident on a surface at earth has three different components:

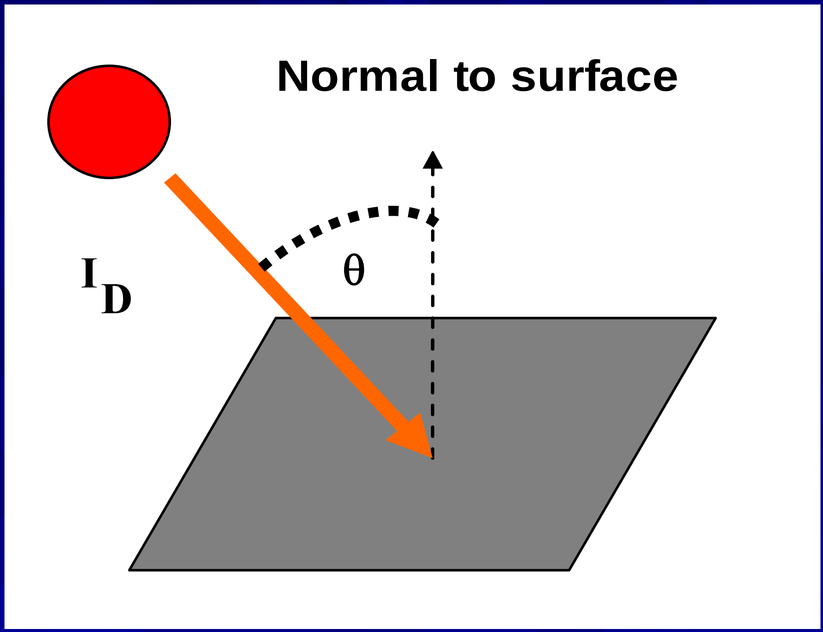
1. **Direct radiation:**
   The solar radiation received from the sun without having been scattered by the atmosphere.

2. **Diffuse radiation:**
   Radiation received and remitted in all directions by earth atmosphere:

3. **Reflected radiation:**
   Radiation reflected by surrounding surfaces.

Total Incident Radiation





$$G_t = G_{ND}\cos\theta + G_d + G_r$$

ASHRAE Clear Sky Model

<u>Normal Direct Radiation:</u> G_{ND}

The value of solar irradiation at the surface of the earth on a clear day is given by the empirical formula:

$G_{ND} = A/[\exp(B/\sin \beta)]$ = Normal direct radiation

A = apparent solar irradiation at air mass equal to zero, w/m2

B = Atmosphere extinction co-efficient

β = Solar altitude

Above equation do not give maximum value of G_{ND} that can occur in any given month, but are representation of condition on average cloudiness days.

Constants A, B and C for Estimation of Normal direct and diffuse radiation

EXTRATERRESTRIAL SOLAR RADIATION AND RELATED DATA FOR TWENTY-FIRST DAY OF EACH MONTH, BASE YEAR 1964[a]

	G_0 Btu/(hr-ft^2)	Equation of Time, min	Declination, deg	A Btu/(hr-ft^2)	B (Dimensionless Ratios)	C (Dimensionless Ratios)
Jan	442.7	−11.2	−20.0	390	0.142	0.058
Feb	439.1	−13.9	−10.8	385	0.144	0.060
Mar	432.5	− 7.5	0.0	376	0.156	0.071
Apr	425.3	+ 1.1	+11.6	360	0.180	0.097
May	418.9	+ 3.3	+20.0	350	0.196	0.121
June	415.5	− 1.4	+23.45	345	0.205	0.134
July	415.9	− 6.2	+20.6	344	0.207	0.136
Aug	420.0	− 2.4	+12.3	351	0.201	0.122
Sep	426.5	+ 7.5	0.0	365	0.177	0.092
Oct	433.6	+15.4	−10.5	378	0.160	0.073
Nov	440.2	+13.8	−19.8	387	0.149	0.063
Dec	443.6	+ 1.6	−23.45	391	0.142	0.057

[a]To convert Btu/(hr-ft^2) to W/m^2, multiply by 3.1525.

Modified equation:

$$G_{ND} = A/[\exp(B/\sin \beta)] \times C_N$$

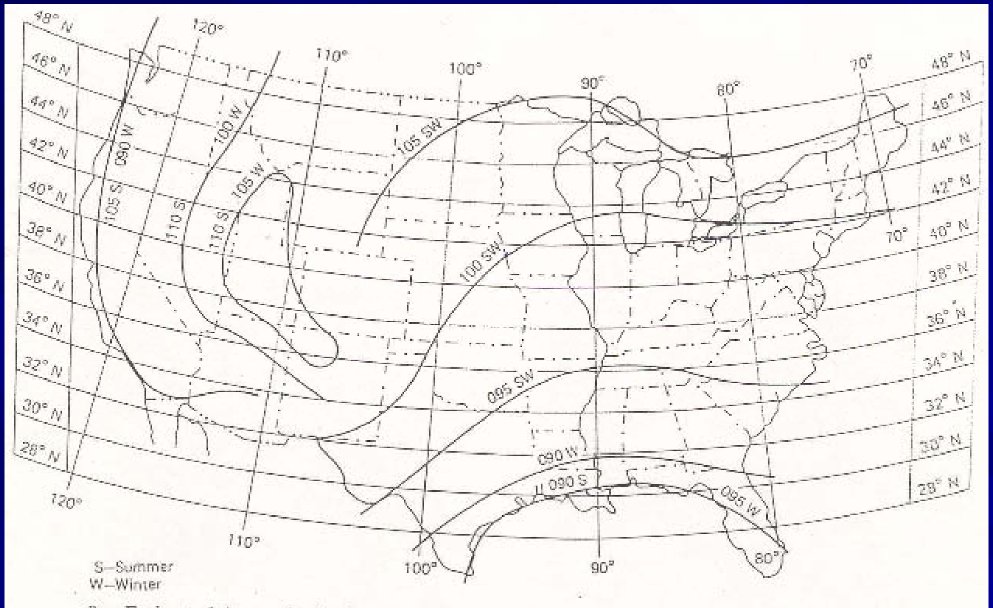
C_N = Clearness factor
=multiplying factor for nonindustrial location in USA

$$G_D = G_{ND} \cos \theta$$

= Direct radiation on the surface of arbitrary Orientation.

θ = Angle of incident of sun's ray to the surface

Clearness factor (C_N)



Estimated Atmospheric Clearness Numbers in the U.S. for Nonindustrial Localities.

Diffuse Radiation: G_d

Diffuse radiation on a ***horizontal surface*** is

$$G_d = C\ G_{ND}$$

Where

C = ratio of diffuse to normal radiation on a horizontal surface = Assumed to be constant for an average clear day for a particular month.

Diffuse Radiation on Non Horizontal Surface:

$$Gd\theta = C\ GND\ FWS$$

FWS = Configuration factor between the wall and the sky .

$$FWS = (1+ \cos \varepsilon)/2$$

Where ε = Tilt angle of the wall from horizontal = $(90-\alpha)$.

***Reflected Radiation (**GR)

Reflection of solar radiation from ground to a tilted surface or vertical wall.

$$GR = GtH\ \rho g\ FWg$$

Where,

GtH = Ratio of total radiation (direct + diffuse) on horizontal or ground in front of the wall.

ρg = Reflectance of ground or horizontal surface

FWg = Angles or Configuration factor from wall to ground

FWg = (1- *cos ε*)/2.

ε = Wall at a tilt angle ε *to* the horizontal.

Example: Estimation of Solar Radiation

Calculate the clear day direct, diffuse and total solar radiation on horizontal surface at 36 degrees north latitude and 84 degrees west longitude on June 1 at 12:00 noon CST

Local Solar Time: LST = LCT + E_{qu} of time

LCT = LCT + (90-84)/15 * 60 = 12:00 + (90-84)/15 * 60

At Mid 90 degree

LST = 12:00 + (90-84)/15 *60+ 0:02:25 = 12:26

Hour angle: h = (12:00 - 12:26) * 15/60 = 65 degrees

Declination angle: d = 21 degrees 57 minutes

Sun's altitude angle:

Sin β = Cos (l) Cos (d) Cos (h) + Sin (l) Sin (d)

= Cos (36) X Cos (21°57 min) *+ Sin (36) Sin (21°57)* =(0.994) (0.928) (0.809)+ 0.588 XS 0.376, *Sin β* = 0.965

Incidence angle *for a horizontal surface*: *Cos θ = Sin β = 0.965*

Direct Normal Radiation: G_{ND} = A/ [exp (B/sin β)]

= 345/ [exp (0.205/0.965)]

G_{ND} = 279 Btu/hr-ft^2

The direct radiation

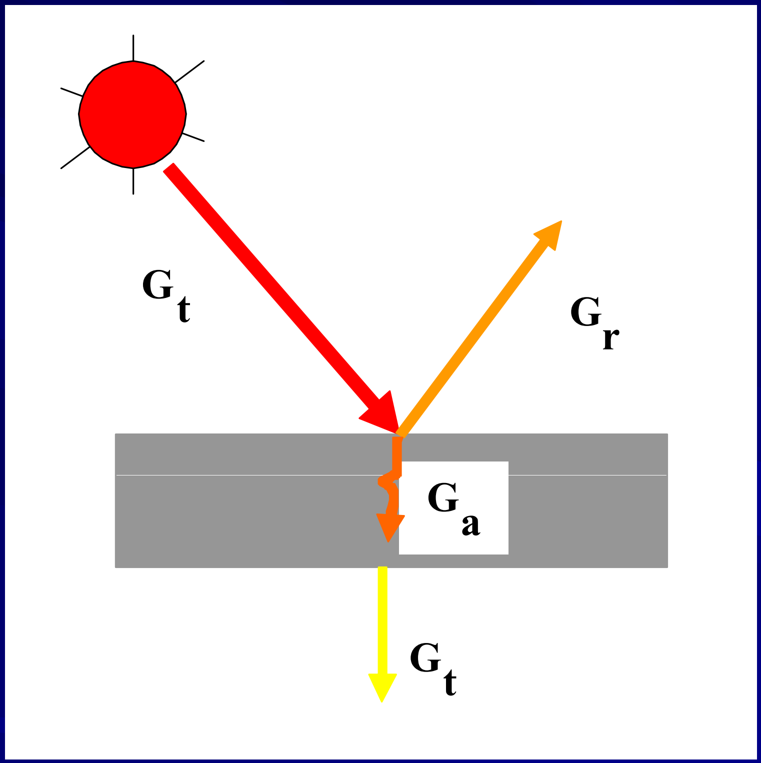
$G_D = G_{ND}$ *Cos θ* = 279 X 0.965 = 269 Btu/hr-ft^2,

The diffuse radiation

$G_d = C\ G_{ND}$ = 0.136 X 279 = 37.4 Btu/hr-ft^2

Total Irradiation G = $G_D + G_d$ = 269 + 37.6 = 300 Btu/hr-ft^2

Solar Radiation – Material Interaction



$$G_t = G_{re} + G_{tr} + G_{ab}$$

Where

G_{re} = Reflected radiation

G_{ab} = Absorbed radiation

G_{tr} = Transmitted radiation

$$\rho + \tau + \alpha = 1$$

Material Optical Properties

$$\rho = \text{Reflectivity} = \frac{G_{re}}{G}$$

$$\tau = \text{Transmissivity} = \frac{G_{tr}}{G}$$

$$\alpha = \text{Absorptivity} = \frac{G_{tr}}{G}$$

$$\varepsilon = \text{Emissivity} = \frac{E}{E_b} = \frac{\text{Energy Emitted by a real body}}{\text{Energy emitted by a black body}}$$

The Khirchoff's law

In equilibrium: $\alpha = \varepsilon$

In general $\rho = \rho(\lambda, \theta)$ $\tau = \tau(\lambda, \theta)$

$\alpha = \alpha(\lambda, \theta)$ $\varepsilon = \varepsilon(\lambda, \theta)$

λ = Wavelength

θ = Angle of incident

Solar Radiation – Material Interaction

Opaque Surface: $\tau = 0$ $\rho = 1 - \alpha$

$$\text{Energy absorbed, } G_{ab} = \alpha G$$

Transparent Surface: $\rho = 1 - \tau - \alpha$

$$\text{Energy absorbed, } G_{ab} = \alpha G$$

$$\text{Energy transmitted, } G_{tr} = \tau G$$

Solar Heat Gain

Solar Heat gain through a transparent Glass Cover:

$$q_{sg} = A\left(\tau G_t + N_f \alpha G_t\right)$$

Solar Heat gain Through a Glass Window:

$$q_{sg} = A\left(\tau G_t + N_f \alpha G_t\right)Sc$$

Solar Heat gain opaque wall:

$$q_{sg,w} = A\left(N_{fw} \alpha G_t\right)$$

Where

A = Surface area of glass

G_t = Total solar irradiation

N_f = Fraction of absorbed solar radiation that enters Inward = $\frac{U}{h_o}$

Sc = Shading coefficient

N_{fw} = Fraction of absorbed solar radiation that enters Inward = $\frac{U}{h_o}$

Use of Solar Energy

1. Solar Thermal Energy:

Converts solar radiation in thermal heat energy

- Active Solar Heating
- Passive Solar Heating
- Solar Thermal Engine

2. Solar Photovoltaics

Converts solar radiation directly into electricity

Solar Thermal Energy System

- The basic purpose of a solar thermal energy system is to collect solar radiation and convert into useful thermal energy.

- The system performance depends on several factors, including availability of solar energy, the ambient air temperature, the characteristic of the energy requirement, and especially the thermal characteristics of solar system itself.

Classification Solar System

The solar collection system for heating and cooling are classified as passive or active.

Active System

- Active systems consist of components which are to a large extent independent of the building design
- Often require an auxiliary energy source (Pump or Fan) for transporting the solar energy collected to its point of use.
- Active system are more easily applied to existing buildings

Passive System

Passive systems collect and distribute solar energy without the use of an auxiliary energy source.

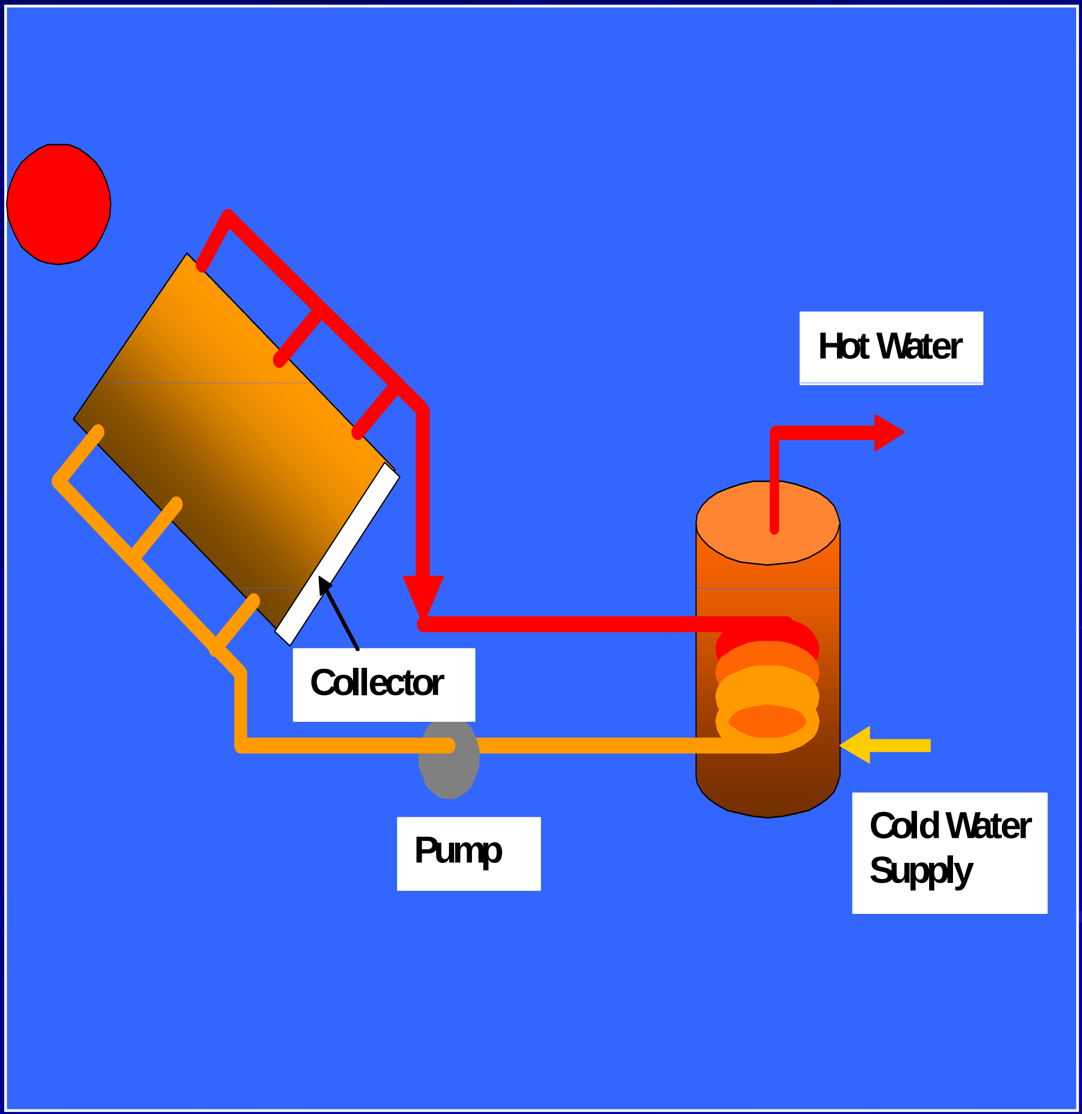
Dependent on building design and the thermal characteristics of the material used.

Solar Water Heating System

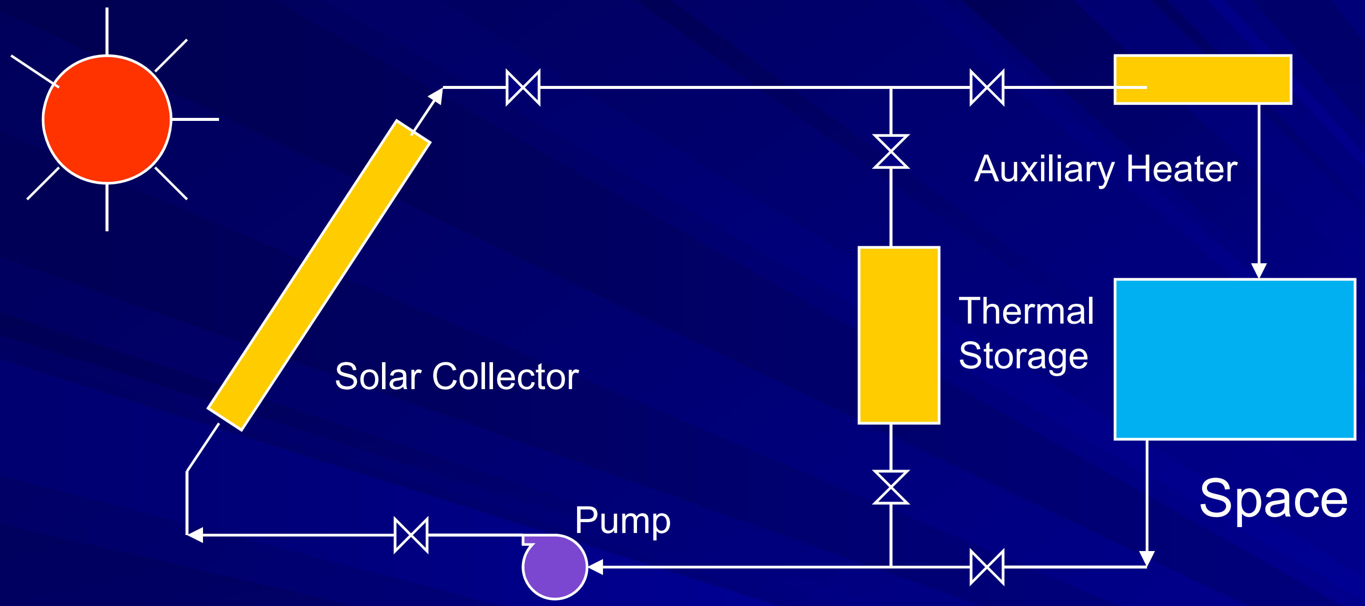
Uses solar collector mounted on roof top to gather solar radiation

Low temperature range: 100 C

Applications involves domestic hot water or swimming pool heating



Solar Space Heating System



A collector intercepts the sun’s energy.

A part of this energy is lost as it is absorbed by the cover glass or reflected back to the sky.

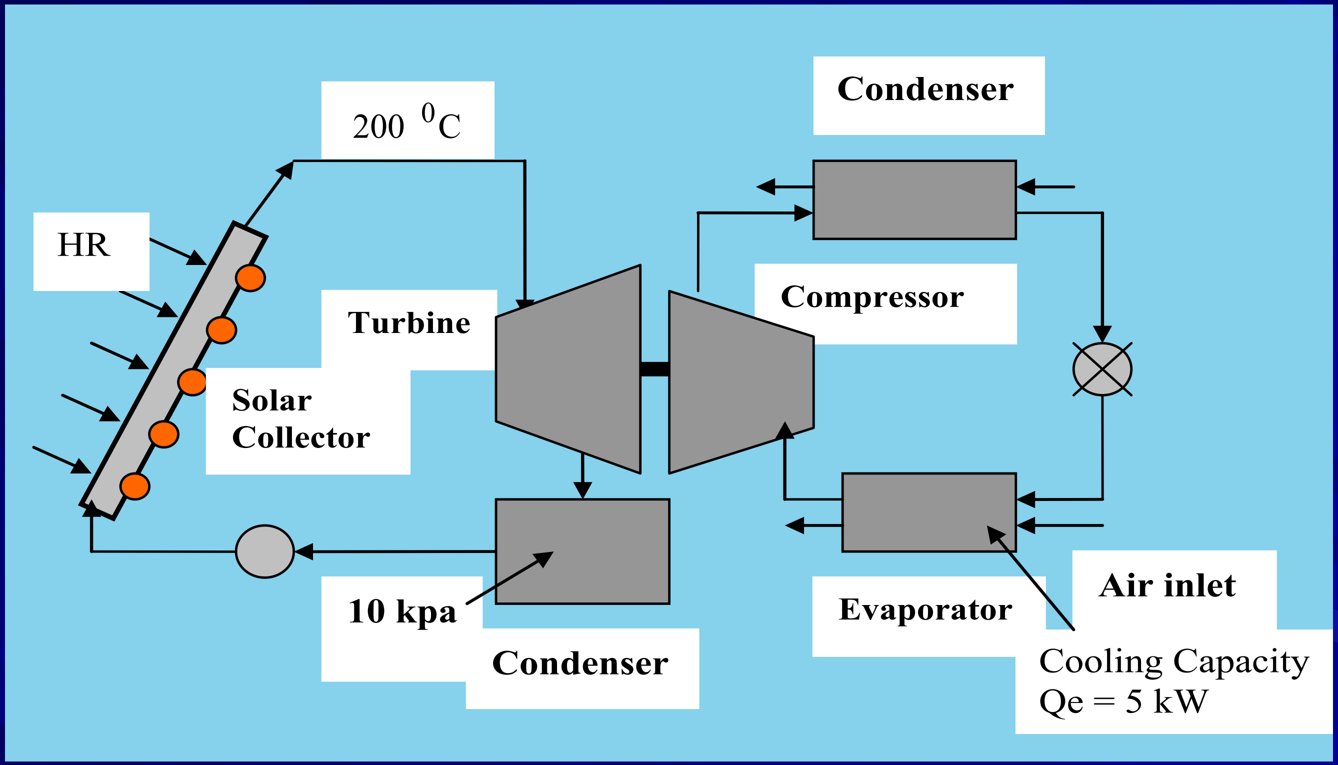
Of the remainder absorbed by the collector, ***a small portion is lost by convection and re-radiation***, but most is useful thermal energy, which is then transferred via pipes or ducts to a storage mass or directly to the load as required

An energy storage is usually necessary since the need for energy may not coincide with the time when the solar energy is available.

Thermal energy is distributed either directly after collection or from storage to the point of use.

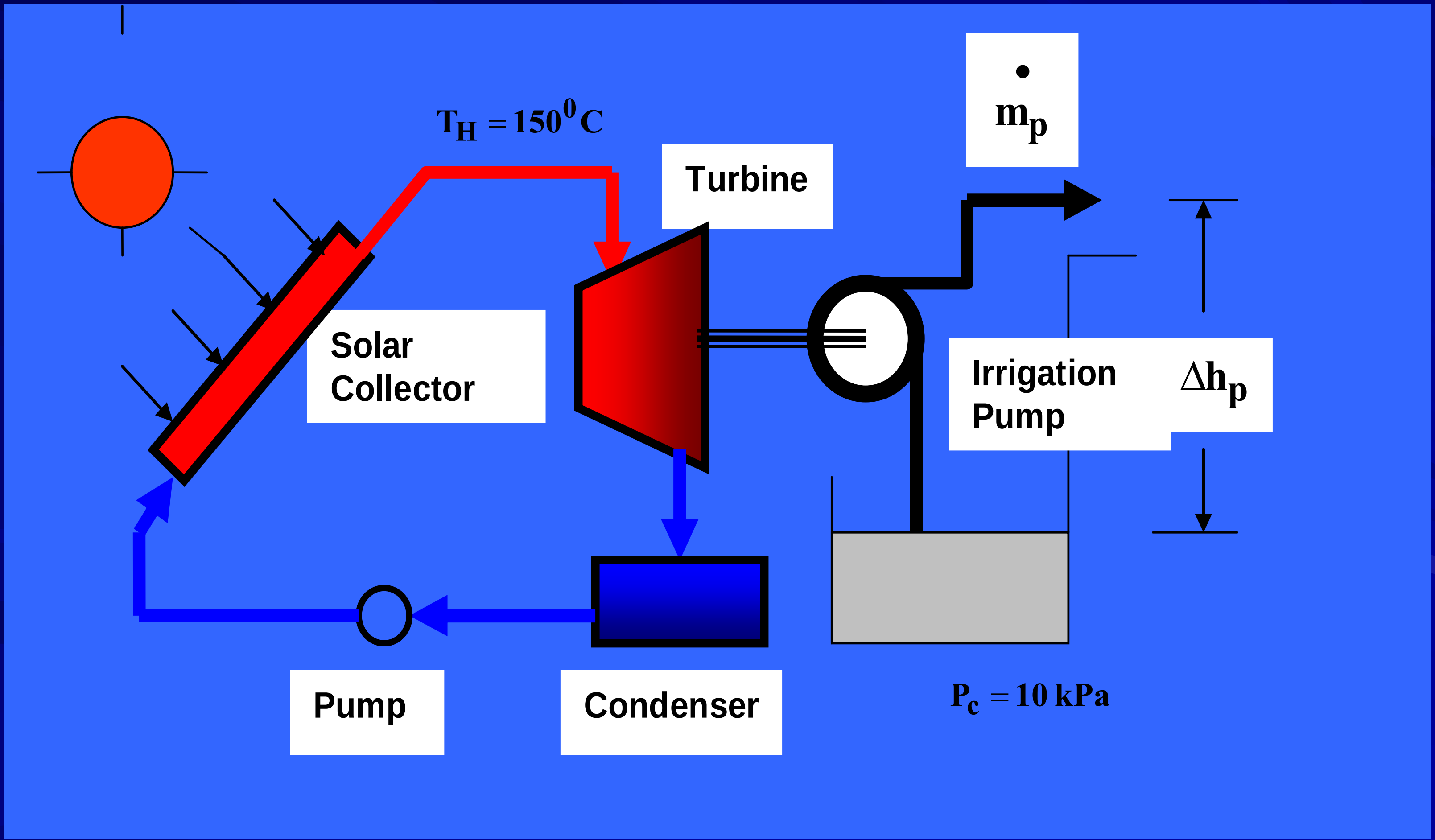
The sequence of operation is managed by automatic and/or manual system controls.

Solar Cooling System



A Solar-driven Irrigation Pump

A solar-energy driven irrigation pump operating on a solar driven heat engine is to be analyzed and designed.



Solar Collector

Several types are available

- Flat Plate Collector
  - Glazed and unglazed
  - Liquid-based
  - Air-based
- Evacuated Tube
- Concentrating
  - Parabolic trough

Fixed Vs Tracking

A *tracking collectors* are controlled to follow the sun throughout the day.

A tacking system is rather complicated and ***generally only used for special high-temperature applications***.

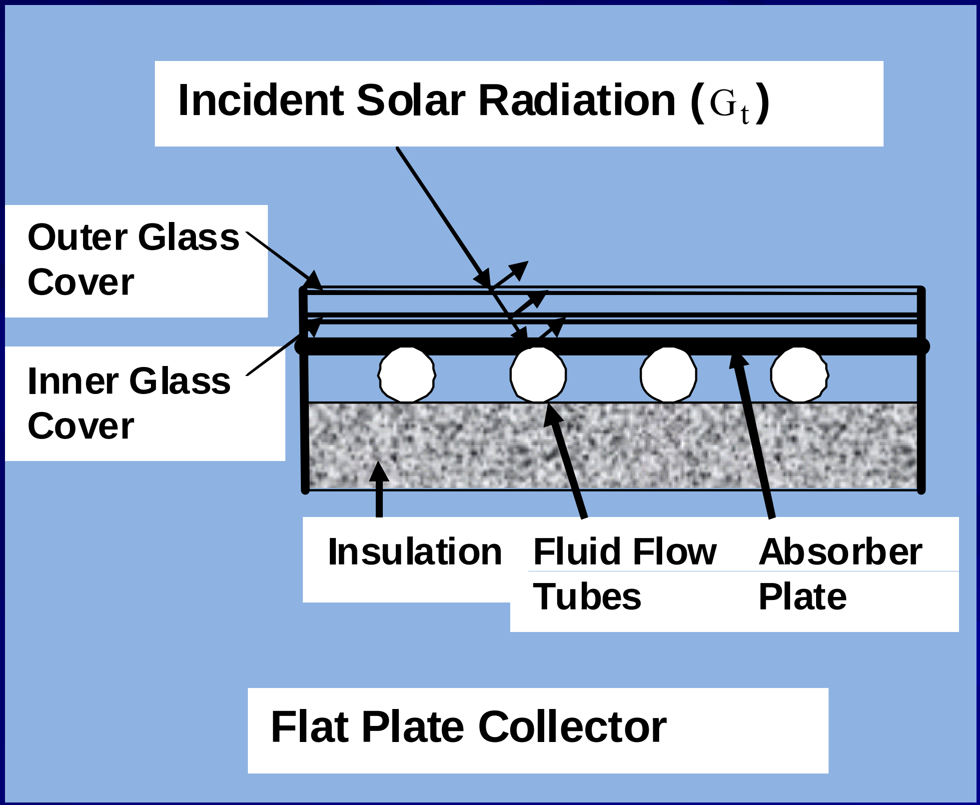
Fixed collectors are much simpler - their position or orientation, however, ***may be adjusted on a seasonal basis***. They remain fixed over a day's time

Fixed collector are less efficient than tracking collectors; nevertheless they are generally preferred as they are less costly to buy and maintain.

Flat-plate and Concentrating

- Concentrating collectors uses mirrored surfaces or lenses to focus the collected solar energy on smaller areas to obtain higher working temperatures.
- Flat-plate collectors may be used for water heating and most space-heating applications.
- High-performance flat-plate or concentrating collectors are generally required for cooling applications since higher temperatures are needed to drive chiller or absorption-type cooling units.

Flat Plate Solar Collector



Consists of an **absorber plate**, ***cover glass***, ***insulation*** **and** ***housing*****.**

- Used for moderate temperature up to 100 C
- Uses both direct and diffuse radiation
- Normally do not need tracking of sun
- Use: water heating, building heating and air-conditioning, industrial process heating.
- Advantage: Mechanically simple

Characteristics of Flat Plate Collector

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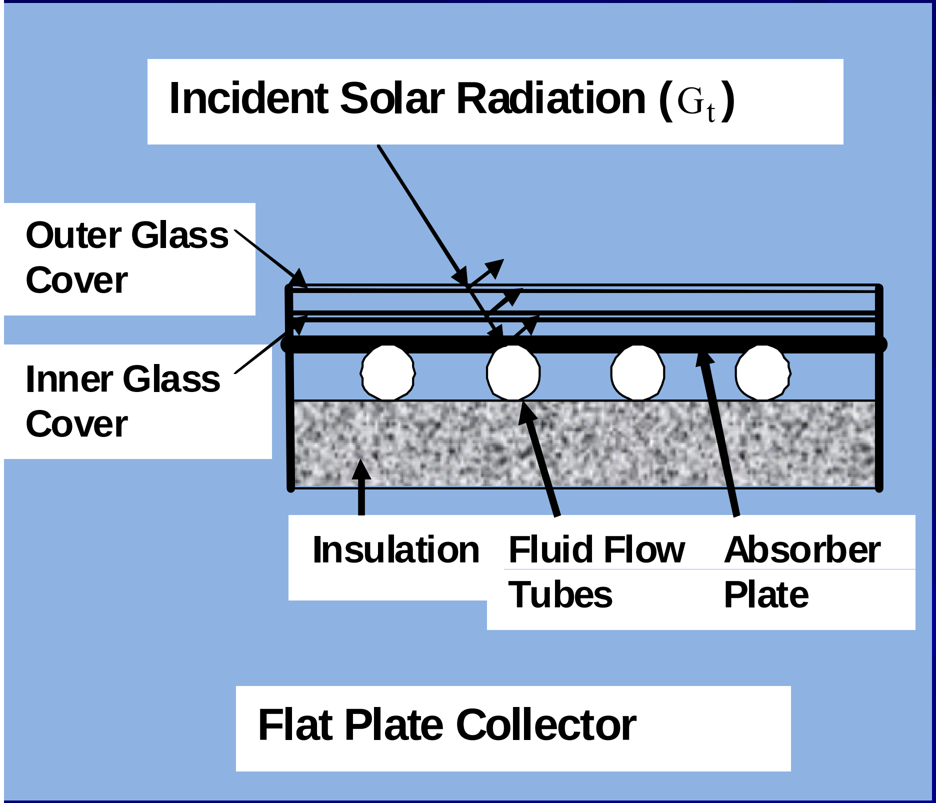
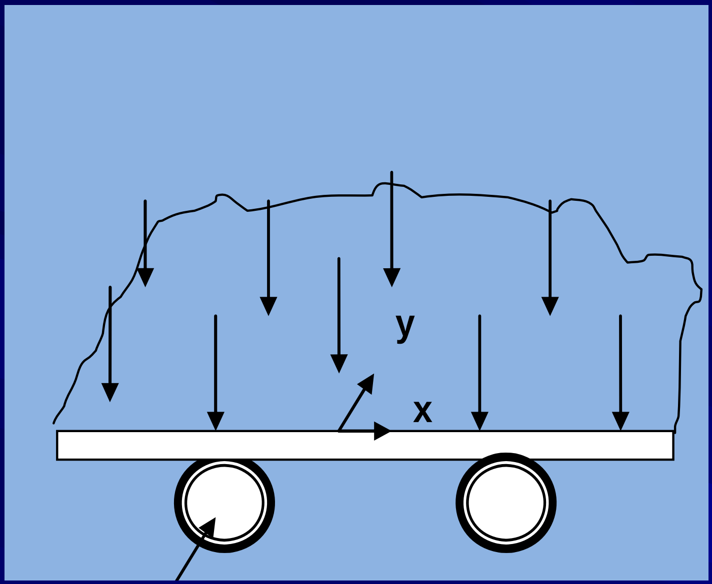
Flat Plate Solar Collector

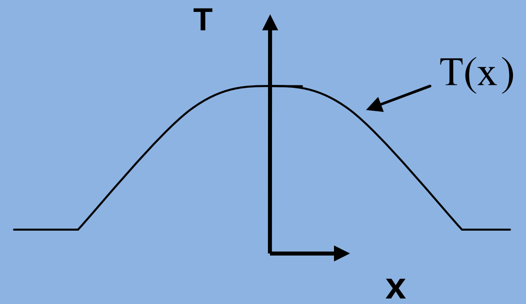


Consists of an **absorber plate**, ***cover glass***, ***insulation*** **and** ***housing*****.**

- The ***absorber plate*** is usually made of copper and coated to increase the absorption of solar radiation.
- The ***cover glass or glasses*** are used to reduce convection and re-radiation losses from the absorber.
- Insulation is used on the back edges of the absorber plate to reduce conduction heat losses.
- The housing holds the absorber with insulation on the back and edges, and cover plates.
- The working fluid (water, ethylene glycol, air etc.) is circulated in a serpentine fashion through the absorber plate o carry the solar energy to its point of use.

Collector Performance

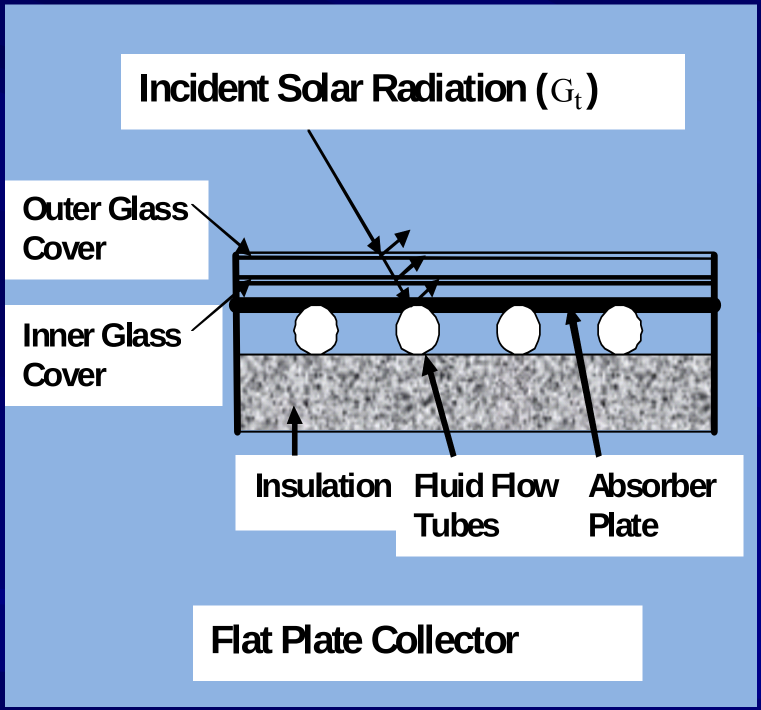




Temperature Distribution in the Absorber Plate

- The temperature of the working fluid in a flat-plate collector may range from 30 to 90C, depending on the type of collector and the application.
- The amount of solar irradiation reaching the top of the outside glazing will depend on the location, orientation, and the tilt of the collector.
- Temperature of the absorber plate varies along the plate with peak at the mid section
- Absorbed heat diffuses along the length towards the tube with and transferred to the circulating fluid.

Collector Performance



- The collector efficiency of flat-plate collectors varies with design orientation, time of day, and the temperature of the working fluid.
- The amount of useful energy collected will also depend on
  - the optical properties (transmissivity and reflectivity) of cover glasses,
  - the properties of the absorber plate (absorptivity and emissivity) and
  - losses by conduction, convection and radiation.

Collector Performance

An energy balance for the absorber plate is

$$q_a = A_c \left[I_{sol}\tau_{c1}\tau_{c2}\alpha_a - \frac{T_a^4 - T_{c2}^4}{R_{rad}} - \frac{T_a - T_{c2}}{R_{conv}} - \frac{T_a - T_\infty}{R_{cond}} \right]$$

A simplification leads to

$$q_a = A_c \left[I_{sol}\tau_{c1}\tau_{c2}\alpha_a - U\left(T_{fi} - T_\infty\right) \right]$$

Where

T_{fi} = temperature of the fluid at inlet to collector

U = over all heat transfer coefficient

empirically determined heat collection factor

A_c = Collector plate

Collector Performance

Useful energy output of a collector

$$Q_u = A_c\{G_{tp} - U_c(T_p - T_a)\}$$

Where

G_{tp} = Total absorbed incident radiation at the absorber plate

U_c = Overall heat transfer coefficient (Represents total heat loss from the collector.

T_p = Temperature of the absorber plate

T_a = Temperature of ambient air

- One of the major problem in using this equation is the estimation and determination of the collector plate temperature

.

Heat Removal Factor

A more useful form is given in terms of fluid inlet temperature, and a parameter called collector heat removal factor (F_R), which can be evaluated analytically from basic principles or measured experimentally

The heat removal factor in defined as

$$F_R = \frac{Q_u}{A_c\left[G_{tp} - U_c\left(T_p - Ta\right)\right]}$$

Where the heat removed by the circulating fluids through the tubes is given as

$$Q_u = \dot{m}\,C_p\left(T_{fi} - T_{fo}\right)$$

$$F_R = \frac{\dot{m}\,C_p\left(T_{fi} - T_{fo}\right)}{A_c\left[G_{tp} - U_c\left(T_p - Ta\right)\right]}$$

$(\tau\alpha)_e = (\tau\alpha) + (1-\tau_a)\sum_{i=1}^{n} a_i \tau^{i-1}$

Effective Transmittance-Absortance Product

In order to take into account of the ***multiple absorption, transmission by the multiple layer of glass covers*** and reduced loss of by the overall heat transfer coefficient, an ***effective transmittance – absorptance product*** is Introduces and expressed as

$$(\tau\alpha)_e = (\tau\alpha) + (1-\tau_a)\sum_{i=1}^{n} a_i \tau^{i-1}$$

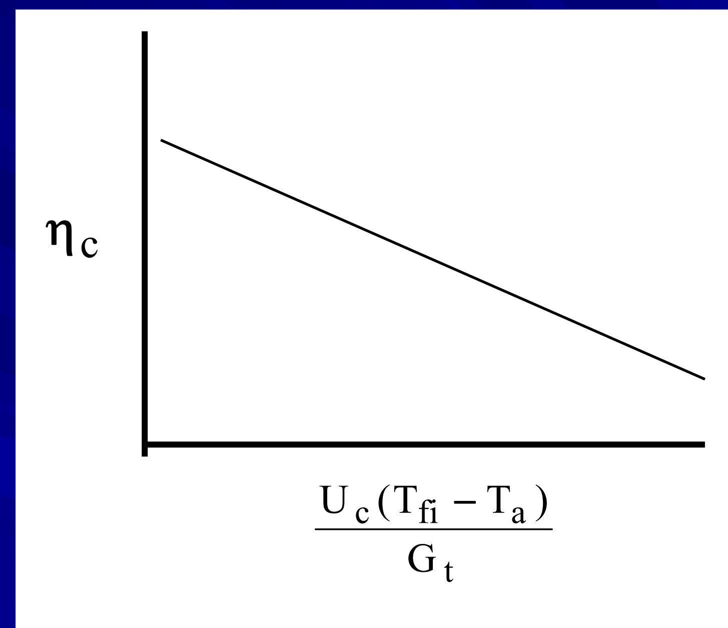
An effective transmittance-absorptance product can be ***approximated*** for collectors with ordinary glass

$$(\tau\alpha)_e = 1.01\tau\alpha$$

Collector Efficiency

$$\eta_c = F_R\left[(\tau\alpha)_e - \frac{U_c(T_{fi} - T_a)}{G_t}\right]$$

Typical collector efficiency curves:



- As absorber temperature increases, the losses increases and the efficiency drops.

$F_R(\tau\alpha)_n$

- At lower ambient temperatures the efficiency is low because of higher loss.

- As the solar irradiation on the cover plate increases, the efficiency increases because the loss from the collector is fairly constant for given absorber and ambient temperature and becomes a smaller fraction.

A collector is characterized by the intercept, $F_R(\tau\alpha)_e$ and the slope $F_R U_c$

Example: Flat Plate Solar Collector Efficiency

A 1 by 3 flat-plate double-glazed collector is available for a solar-heating applications. The transmittance of each of the two cover-plates is 0.87 and the aluminum absorber plate has an absorptivity of α=0.9. Determine the collector efficiency when , $I_{Sol} = 800W/m^2$ $T_{fi} = 55^0C$ and $T_\infty = 10^0C$. Use $U = 3.5W/m^2.K$ and $F_R = 0.9$

$$\eta_{col} = F_r\left(\tau_{c1}\tau_{c_2}\alpha_a - \frac{U\left(T_{fi} - T_\infty\right)}{I_{sol}}\right)$$

$$\eta_{col} = 0.9\left(0.87\times0.87\times0.9 - \frac{3.5(55-10)}{800}\right)$$

$$\eta_{col} = 0.435 = 43.5\%$$

Concentrating Solar Collector

- Parabolic Trough
  - Line focus type

    Focuses the sun on to a pipe running down the center of trough.
  - Can produce temperature upto 150 – 200 C
  - Used to produce steam for producing electricity
  - Trough can be pivoted to track the sun

Concentrating Solar Collector

- Parabolic Trough
  - Line focus type

    Focuses the sun on to a pipe running down the center of trough.
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  - Used to produce steam for producing electricity
  - Trough can be pivoted to track the sun

Concentrating Solar Collector

- Parabolic Dish Concentrator

  - Point focus type

    Focuses the sun on to the heat engine located at the center of the dish.

  - Can produce very high temperature 700-1000C
  - Used to produce vapor for producing electricity
  - Dish can be pivoted to track the sun