EN671: Solar Energy Conversion Technology

Fundamentals of Flat Plate Collectors

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Solar Collector

- Solar collector is a device to collect solar energy and transform it into thermal energy by using heat transfer fluid like water, air, ethylene glycol etc.
- Solar thermal system provides thermal energy for various processes
  - ✓ For cold climates, low grade thermal energy is required to heat air for comfort, hot water for washing, cleaning and other domestic and industrial needs.
  - ✓ Even in high-temperature heating applications, a significant amount of fuel can be saved by using solar collector for preheating.

Classification

Solar collectors

- **Non concentrating type**
  (Flat plate collector)
  (a) Liquid flat plate collector
  (b) Flat plate air heater
- **Concentrating type**
  - **Focus type**
    - **Line focus (One tracking)**
      (a) Cylindrical parabolic concentrator
      (b) Fixed mirror solar concentrator
      (c) Linear Fresnel collector
    - **Point focus (Two axis tracking)**
      (a) Parabolic dish collector
      (b) Hemispherical bowl mirror concentrator
      (c) Circular Fresnel lens concentrator
      (d) Central tower receiver
  - **Non focus type**
    (a) Modified flat plate collector
    (b) Compound parabolic concentrating (CPC) type

Comparison of concentrating and non-concentrating collectors

Concentrating collectors

- Solar radiation is converged from a large area into a small area using optical means.
- Beam radiation (unique direction) and travels in a straight line, can be converted by reflection or refraction techniques.
- Diffuse radiation has no unique direction and so does not obey optical principles.
- Diffuse component cannot be concentrated.
- Make use of the beam radiation component and little diffuse component coming directly over the absorber.

- Main advantage: High temperature can be attained due to concentration of radiation (yields high temperature thermal energy).

Non-concentrating collectors

- Utilizes both beam as well as diffuse radiation.

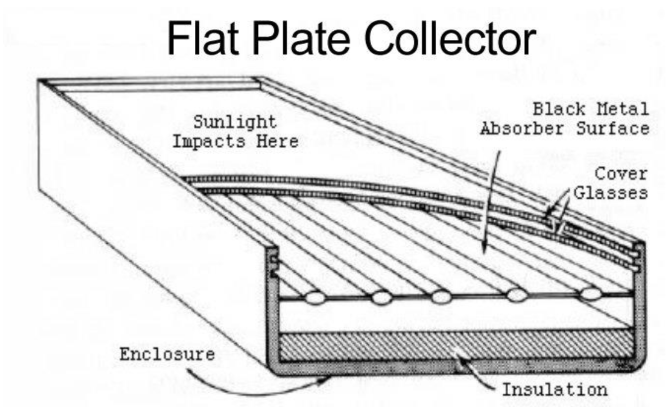
Flat Plate Collector

- A flat-plate collector is simple in construction and does not require sun tracking.
- It can properly secured on a rigid platform and thus becomes mechanically stronger than those requiring flexibility for tracking purpose.
- The collectors are installed outdoors and exposed to atmospheric disturbances.

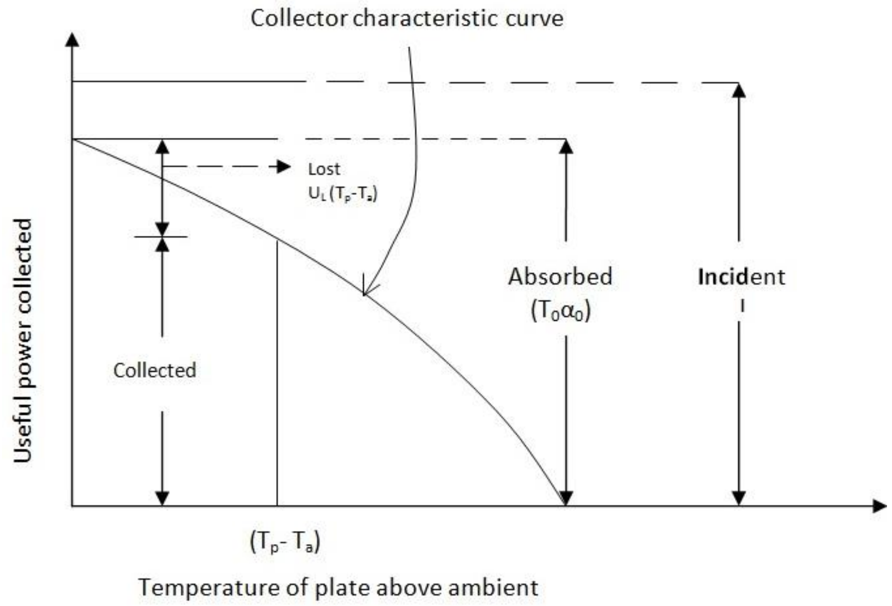
Performance Indices

- **Collector efficiency:** ratio of energy actually absorbed and transferred to the heat transfer fluid by the collector (useful energy) to the energy incident on the collector.
- **Concentration ratio:** ratio of the area of aperture of the system to the area of the receiver. The aperture area of the system is the projected area of the collector facing the beam.
  - CR for FPC = 1 ($T<100^oC$), CR for line focus collectors up to 100 (T: 150-400^oC), CR for point focus collectors of the order of 1000 (T: 500-1000^oC).
- **Temperature range:** range of temperature to which the heat-transport fluid is heated up by the collector.

FPC construction



- The absorber plate
- The tubes fixed to the absorber plate
- Transparent cover
- Collector box



Advantages

✓ Utilizes both beam and diffuse components of the solar radiation

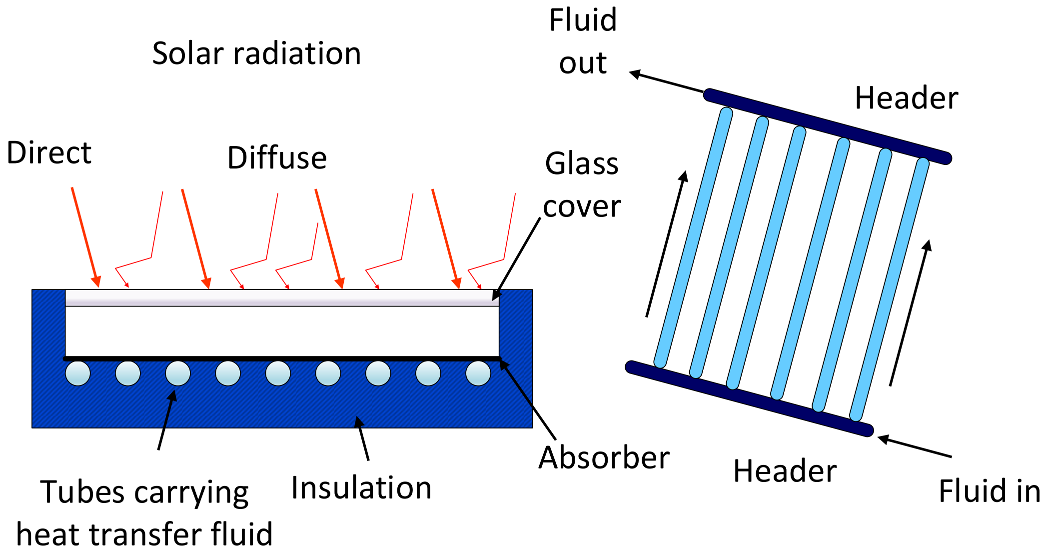
✓ Little maintenance due to simple stationary design

Disadvantages

- Collection efficiency is generally low – due to absence of optical concentration (area from which heat lost is large)

Absorber plate, tube and header

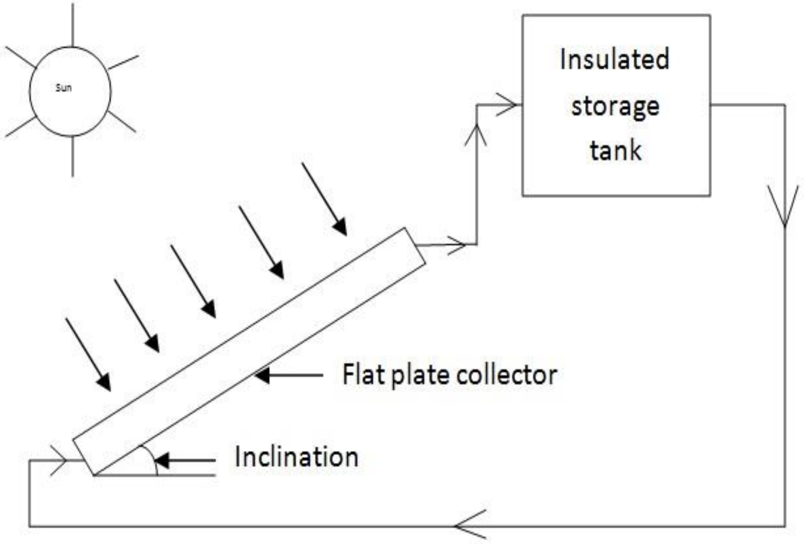
- Usually absorber plate is made from a thin metal sheet – Copper, (thickness 0.2 to 0.7 mm).
- Tubes are also made of metal (diameter varies from 1 to 1.5 cm)
- Tubes are soldered, brazed or pressure bonded to the bottom of the absorber plate (pitch: 5 to 12 cm).
- In some design tubes are bonded to the top or are in-line and integral with the absorber plate.



✓ Header pipes which lead the liquid in and out of the collector and distribute it to the tubes are made of copper and have slightly larger diameter (2-2.5 cm) than tube.

The role of absorber plate

- To absorb the maximum possible solar radiation incident on it through the glazing.
- To minimize heat losses from the absorber to the atmosphere from the top, bottom, and sides of the FPC.
- To transfer maximum heat to the fluid.



Cover system

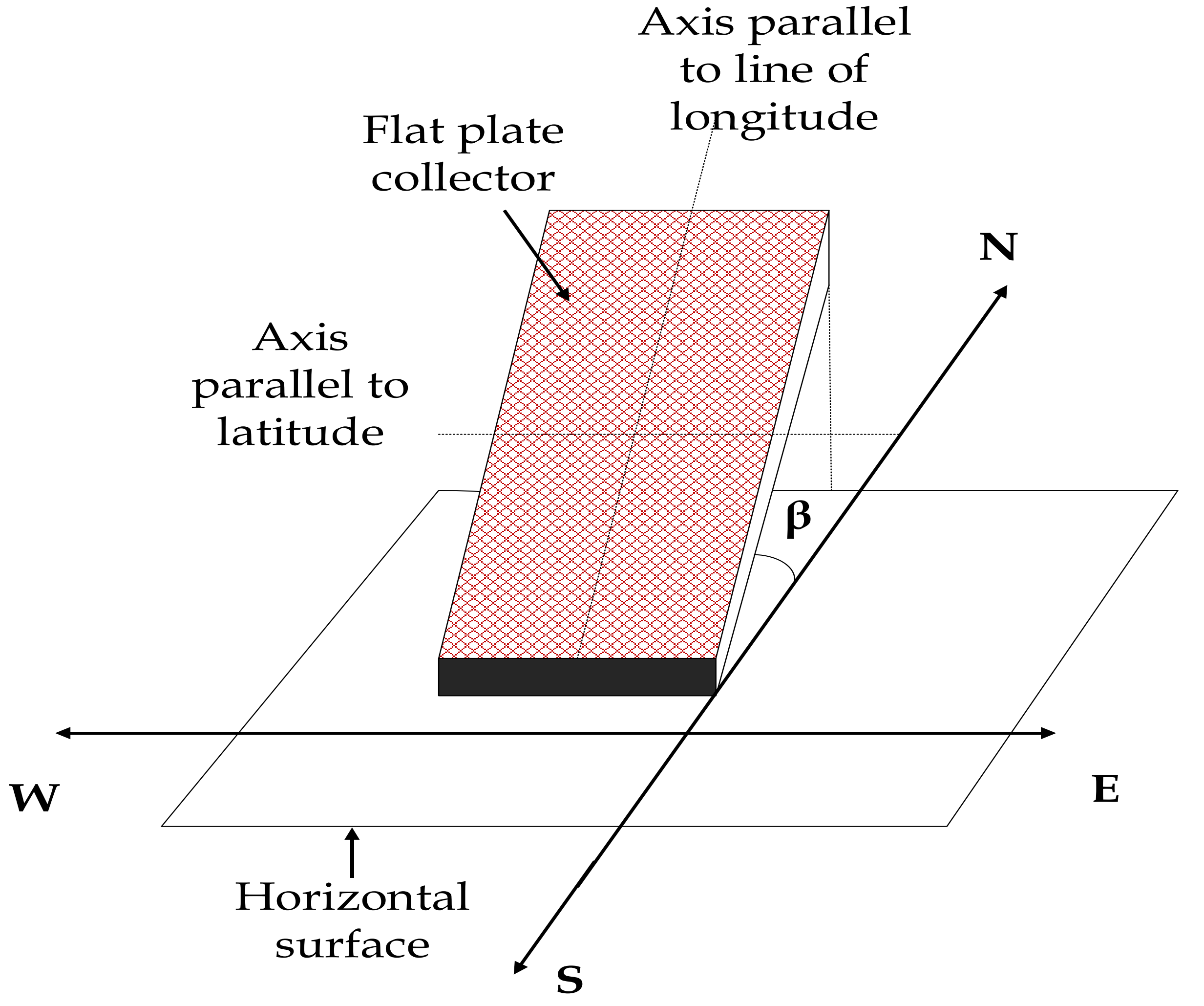
- The cover should be made of a material which is highly transparent to incoming solar radiation and at the same time, opaque to long wavelength re-radiation emitted by the absorber plate.
- Cover Material: Toughened glass of 4 or 5 mm thickness.
- Glass is able to withstand thermal shock as well as the impact o objects which may fall on the collector face.
- Normally a gap of 1.5 to 3 cm is maintained between cover and absorber plate.

- Plastic transparent sheets are also used - low cost, light weight
- Originating from fossil based material

Insulation and collector box

- Bottom and sides are usually insulated by mineral wool, rock wool or glass wool (with a covering of aluminum foil) **(Thickness: 2.5 to 8 cm)**
- The whole assembly is contained within a box which is tilted at a suitable angle.
- The collector box is usually made of Aluminum with a epoxy coating on the outside for protection.
- The face areas of collectors are around $2m^2$ with the length being larger than the width.

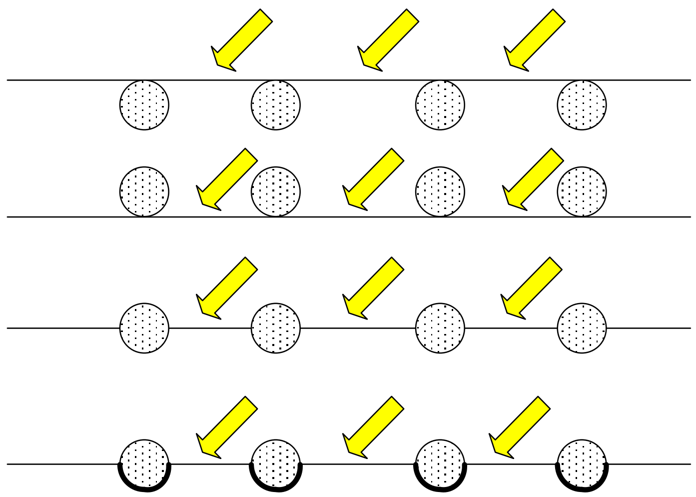
Positioning of Flat Plate Collector



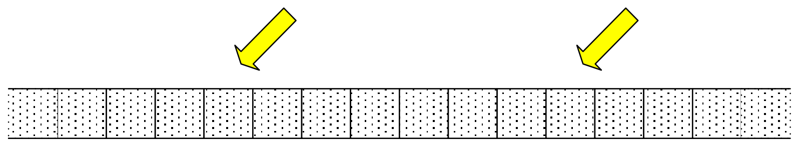
Types of absorber plates

✓ Classified based on the extent of wetted area relative to the absorbing surface area.

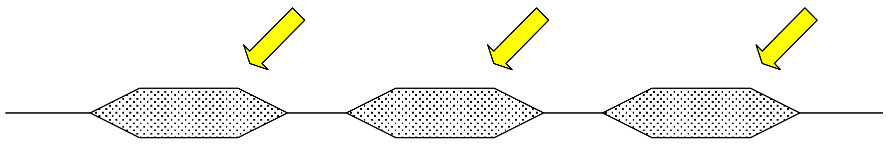
- Pin-and-fin type
  - Liquid flows only in the pipe
  - comparatively low wetted area and liquid capacity
  - Applications in domestic and industrial use (High temperature)
- Rectangular or cylindrical full sandwich
  - Both the wetted area and water capacity are high
  - Application in warming of swimming pool (low temperature)
- Roll-bond or Semi-sandwich Type
  - Intermediate between pin-and –fin type and rectangular full sandwich.



(a) Pipe- and-fin type



(b) Water sandwich type



(c) Semi-water-sandwich type

Performance Analysis of FPC

An energy balance on the absorber plate under steady state condition yields

$$\boldsymbol{q_u = A_p S - q_l}$$

$$q_u = useful\ heat\ gain = rate\ of\ heat\ transfer\ to\ the\ working\ fluid$$

$$S = incident\ solar\ flux\ absorbed\ in\ the\ absorber\ plate$$

$$A_p = area\ of\ the\ absorber\ plate$$

$$q_l = \ rate\ at\ which\ heat\ is\ lost\ by\ convection\ and\ re - radiation\ from\ the\ top\ surface$$

$$and\ by\ conduction\ and\ convection\ from\ the\ bottom\ and\ sides.$$

The flux incident on the top cover of the collector is given by:

$$\boldsymbol{I_T = I_b r_b + I_d r_d + (I_b + I_d) r_r}$$

The flux absorbed in the absorber plate

$$\boldsymbol{S = I_b r_b (\tau\alpha)_b + \{I_d r_d + (I_b + I_d) r_r\} (\tau\alpha)_d}$$

$(\tau\alpha)_b$= transmissivity-absorptivity product for beam radiation falling on the collector

$(\tau\alpha)_d$= transmissivity-absorptivity product for diffuse radiation falling on the collector

Transmissivity of the cover system

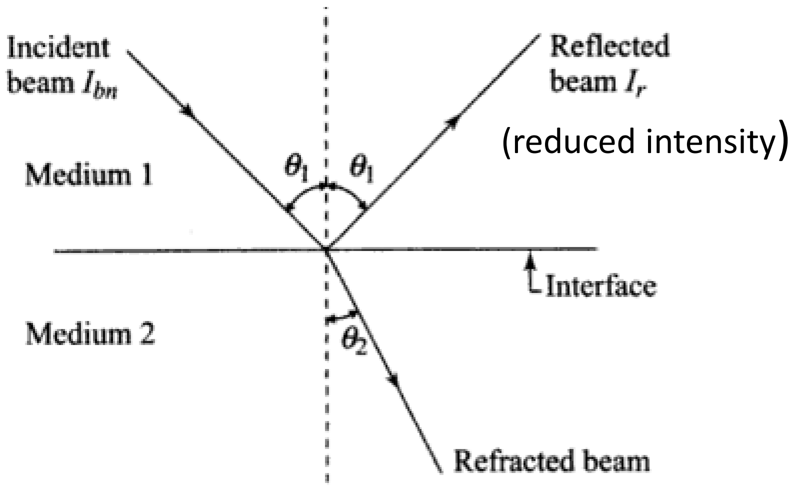
$$\tau = \tau_r \tau_a$$

τ_r Transmissivity obtained by considering only reflection and refraction

τ_a Transmissivity obtained by considering only absorption

- Transmissivity based on reflection-refraction (Snell's Law)
- Transmissivity based on Absorption (Bouguer's Law)
- Transmissivity for diffused radiation

Transmissivity based on reflection-refraction



Reflectivity $\rho = I_r / I_{bn}$ is related to the angles of incidence and refraction by the equations:

$$\rho = \frac{1}{2}(\rho_I + \rho_{II}) \qquad \rho_I = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)}$$

$$\rho_{II} = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)}$$

Reflectivities of two components of polarization

For normal incidence,

$$\theta_1 = 0^o$$

$$\rho = \rho_I = \rho_{II} = \left[\frac{n_1 - n_2}{n_1 + n_2}\right]^2$$

The directions of the incident and reflected beams are related to each other by Snell's law:

Snell's Law:
$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

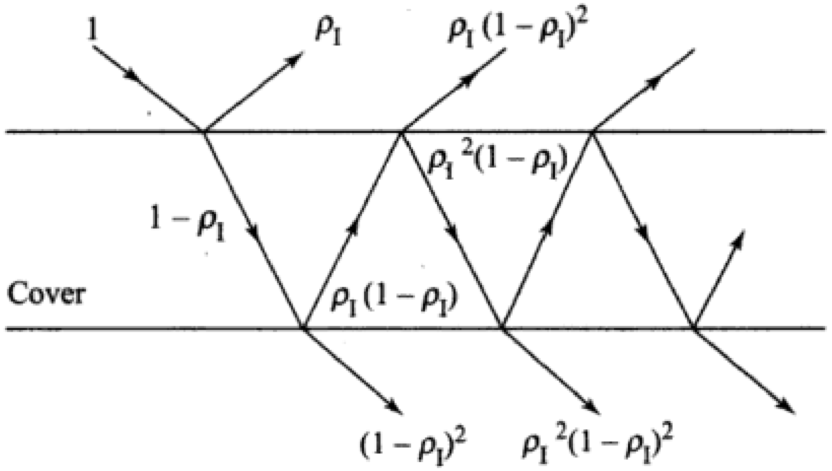
Transmissivity τ_r is expressed as:

$$\tau_r = \frac{1}{2}(\tau_{rI} + \tau_{rII}) \qquad \tau_{rI} \quad \tau_{rII}$$

Transmissivities of two components of polarization

Transmissivity based on reflection-refraction

- Considering one components of polarization of a beam incident on a single over (Two interfaces, multiple reflections and refractions)



$$\tau_{rI} = (1-\rho_I)^2 + \rho_I^2(1-\rho_I)^2 + \rho_I^4(1-\rho_I)^2 + \ldots$$

$$= (1-\rho_I)^2(1+\rho_I^2+\rho_I^4+\ldots) = \frac{(1-\rho_I)^2}{1-\rho_I^2} = \frac{1-\rho_I}{1+\rho_I}$$

$$\tau_{rII} = \frac{1-\rho_{II}}{1+\rho_{II}}$$

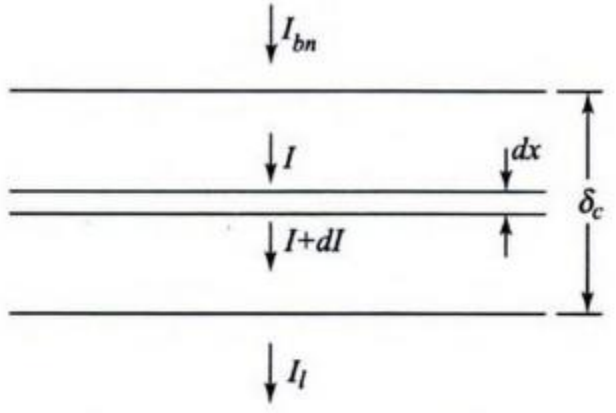
For N number of covers:

$$\tau_{rI} = \frac{1-\rho_I}{1+(2M-1)\rho_I}$$

$$\tau_{rII} = \frac{1-\rho_{II}}{1+(2M-1)\rho_{II}}$$

Transmissivity based on Absorption

- **Obtained by assuming that the attenuation due to absorption is proportional to the local intensity**
- **Bouger's law:**



When beam radiation is falling normally

$$\boxed{dI = -KIdx}$$

K = Constant of proportionality called extinction coefficient (independent of wavelength)

δ_c = Thickness of the transparent cover system

I_{bn} = Incident beam intensity in the transparent cover

I_l = Intinsity going out of the transparent cover

$$\boxed{\frac{I_l}{I_{bn}} = \tau_a = e^{-K\delta_c}}$$

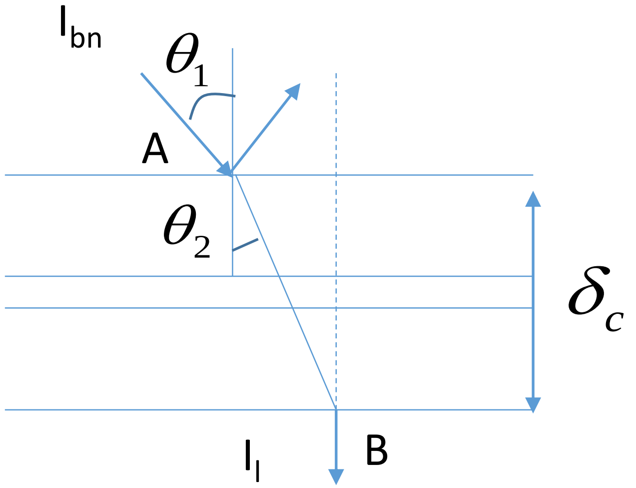
Extinction coefficient is property of the cover material, value varies from: 4 to 25 m^{-1} for glass (low value is desirable)

Expression for transmissivity when beam radiation is inclined at certain angle

When the solar beam is incident at an angle of θ_1 with the normal to the horizontal surface, the path traveled through the cover would be $(\delta_c/\cos\theta_2)$, θ_2 angle of refraction.

$$AB\cos\theta_2 = \delta_c$$

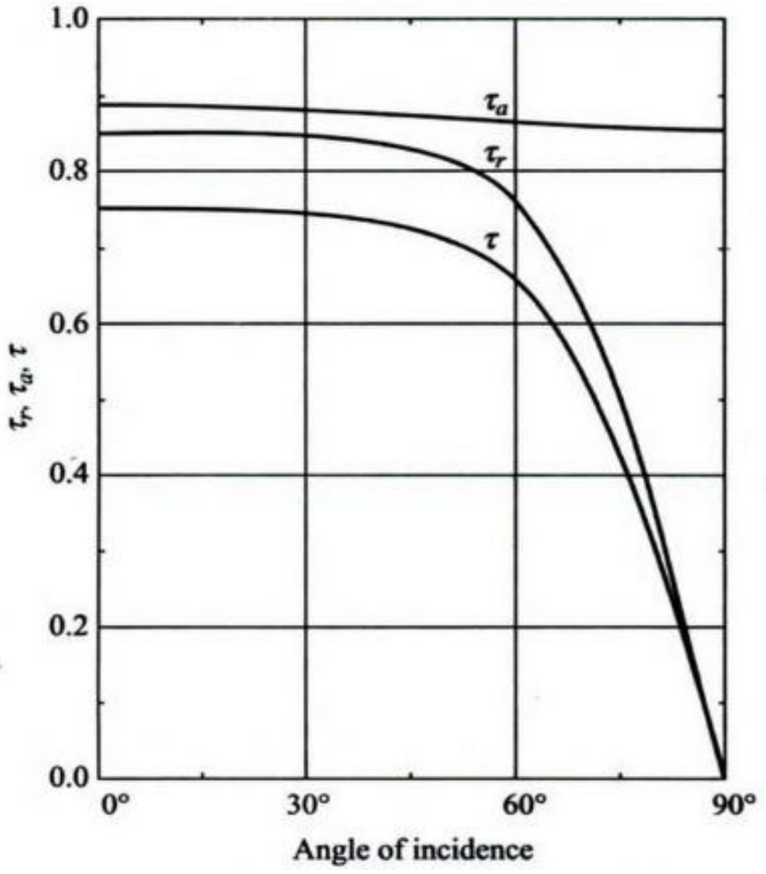
$$\Rightarrow AB = \frac{\delta_c}{\cos\theta_2}$$



$$\boxed{\tau_a = e^{-K\delta_c/\cos\theta_2}}$$

Transmissivity for diffused radiation

- Diffused radiation is equivalent to beam radiation coming at an angle of 60°. This angle is arrived at by considering the variation of transmissivity and by assuming that the amount of diffuse radiation coming from all the directions is the same.



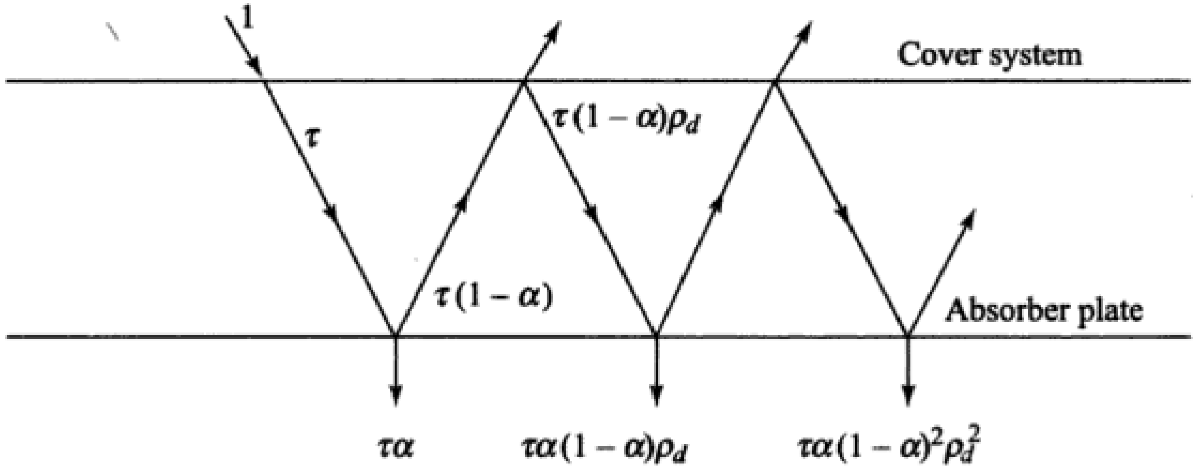
Ex.7-1 Plot the variation of τ_r, τ_a, τ

- Material: Glass
- No. of Covers: 2
- Thickness of each cover: 4 mm
- Reflective index of glass relative to air : 1.52
- Extension coefficient of glass: 15 m^{-1}

Calculate: $\rho_I, \rho_{II}, \tau_{rI}, \tau_{rII}$ then τ_r, τ_a, τ

Transmissivity-absorptivity product

Defines as the ratio of the flux absorbed in the absorber plate to the flux incident on the cover system



Net fraction absorbed $= \tau\alpha\left[1+(1-\alpha)\rho_d+(1-\alpha)^2\rho_d^2+\ldots\right] = \dfrac{\tau\alpha}{1-(1-\alpha)\rho_d}$

ρ_d Diffuse reflectivity of the cover system: 0.21 for two-glass cover system, 0.15 for one glass cover system

ρ_d Can be found by determining the value of $\tau_a(1-\tau_r)$ for the cover system for an incidence angle of 60°.

Performance analysis of FPC

- Instantaneous efficiency and Stagnation temperature

Instantaneous collection efficiency:

$$= \frac{useful\ heat\ gain}{Radiation\ incident\ on\ the\ collector} = \frac{q_u}{A_c I_T}$$

$A_c = collector\ gross\ area =$ 15-20% more than A_p

If $q_u = 0, efficiency\ is\ zero$. In this case absorber plate attains a temperature such that $A_p S = q_l$, this temperature is the highest that the absorber plate can attain and is sometimes referred to as stagnation temperature.

Significance:

- **Stagnation temperature is useful as an indicator for comparing different collector designs**
- **Choosing proper materials for construction of the collector.**

Summary

- Classification.
- FPC components (Liquid - water, mixture of water and ethylene glycol), Absorber plate, Tube, Header pipes Cover, Insulation, Collector box which is tilted at a suitable angle).
- Performance analysis of a FPC.
- Transmissivity estimation based on reflection-refraction.
- Transmissivity based on absorption.
- Transmissivity-absorptivity product.
- Instantaneous efficiency and stagnation temperature.

Thank you