Title: **Performance Alalysis of Solar Thermal Collectors**

Date: 23/03/2020

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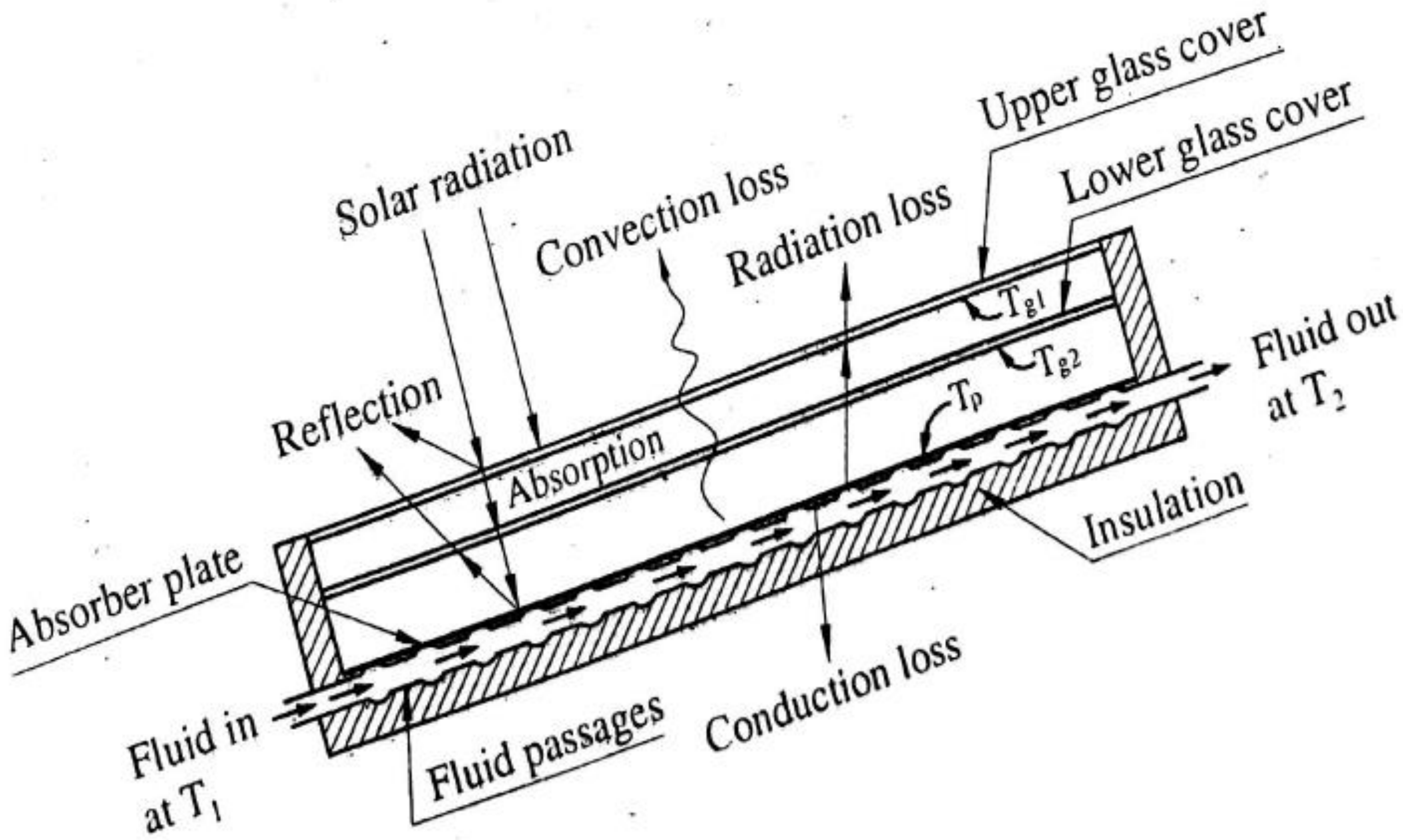
Lecture No :01(10.30 to 11.30 am)

Source of information : Solar Energy (A book by S P Sukhatme)

Energy balance equation of flat plate collector



Under steady state conditions, the useful heat delivered by a solar collector is equal to the energy absorbed in the metal surface minus the heat losses from the surface to surroundings. Mathematically,

$$H_T \cdot A_c \cdot (\tau\alpha)_e = Q_u + Q_L \qquad ...(2.21)$$

where, H_T = total solar radiation incident on the collector per unit area and time, W/m^2

A_c = colector area, m^2

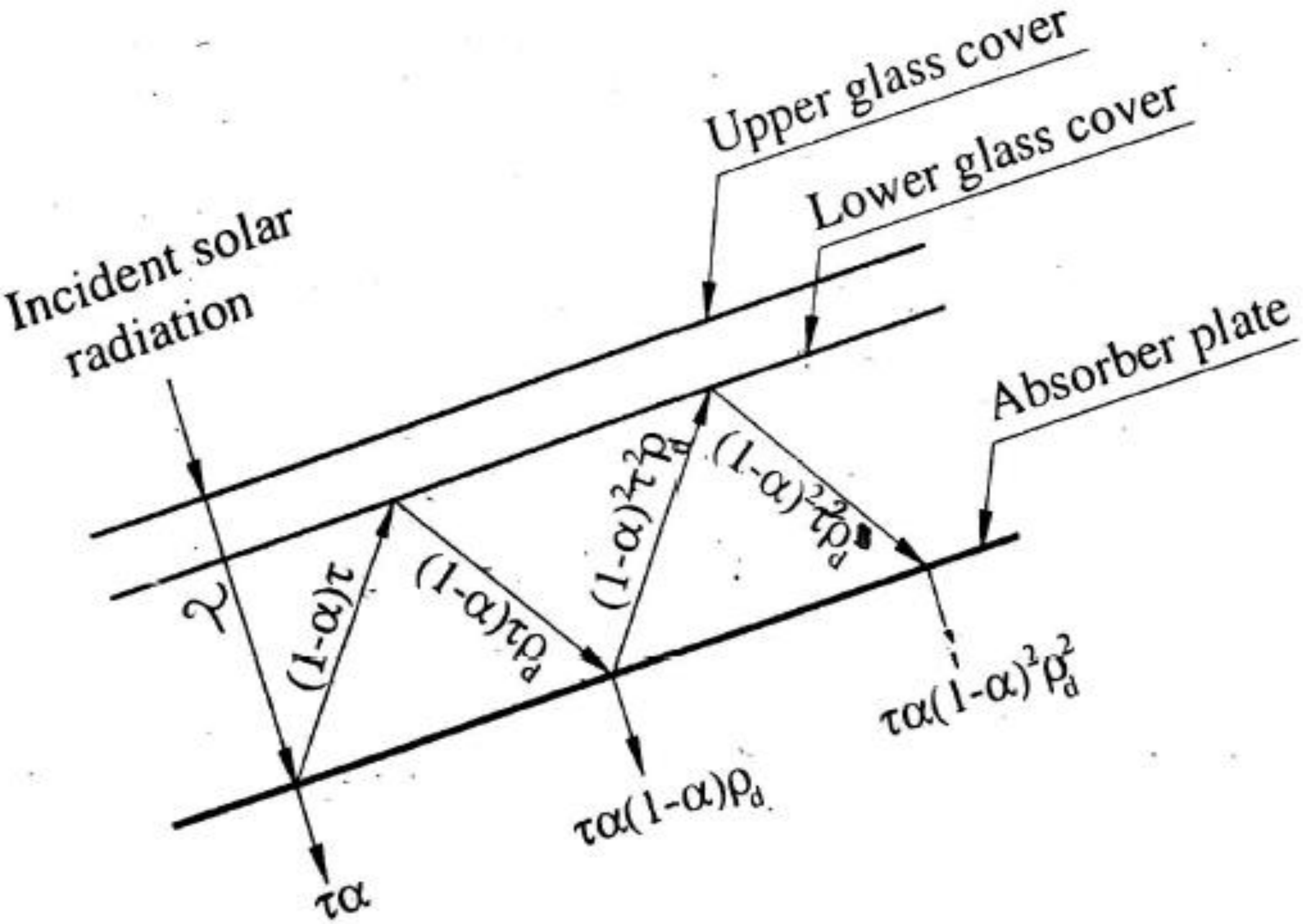
Q_u = rate of useful heat collected from the collector, W

Q_L = rate of heat lost from the collector, W

$(\tau\alpha)_e$ = effective transmittance - absorptance product of cover system for beam and diffused radiation

τ = fraction of incoming solar radiation that reaches the absorbing surface (transmissivity).

α = fraction of solar energy reaching the surface that is absorbed (absorptivity).



Upper glass cover
Lower glass cover
Absorber plate
Incident solar radiation
τ
(1-α)τ
(1-α)τρ_d
(1-α)²τ²ρ_d
(1-α)²τ²ρ_d²
τα
τα(1-α)ρ_d
τα(1-α)²ρ_d²

Total energy absorbed by absorber plate

$$= H_T[\tau\alpha + \tau\alpha(1-\alpha)\rho_d + T\alpha(1-\alpha)^2\rho_d{}^2 + ...]$$

$$= H_T\left[\frac{\tau\alpha}{1-(1-\alpha)\rho_d}\right]$$

$$= H_T(\tau\alpha)_e, \text{ where } (\tau\alpha)_e = \frac{\tau\alpha}{1-(1-\alpha)\rho_d}$$

Now, total heat loss from collector is given by

$$Q_L = A_c U_L (T_p - T_a)$$

where, U_L = overall heat loss co-efficient (W/m² K)

T_p = average temperature of upper surface of the absorber plate

T_a = atmospheric temperature.

Now, equation (2.21) becomes

$$H_T A_c (\tau\alpha)_e = Q_u + A_c U_L (T_p - T_a)$$

$$\therefore Q_u = A_c[H_T(\tau\alpha)_e - U_L(T_p - T_a)]$$

Overall loss coefficient

The overall heat loss from the collector is difficult to determine since it depending on the mode of heat transfer (conduction, convection and radiation), it also depends on the temperature of plate, temperature of air, temperature of sky, temperature of cover system, number of glass cover, conductivity, thickness of rear and edge insulation, tilt of the collector, absorptivity and emissivity of absorber plate coating and emittance of glass cover. The rate of heat loss can be expressed as :

$$Q_L = U_L A_C (T_m - T_a) \quad ...(2.30)$$

where, Q_L = rate of heat loss from collector

U_L = overall heat loss co-efficient

T_m = mean absorber plate temperature

T_a = ambient temperature

The heat lost from the collector is the sum of the heat lost form the top, the bottom and the sides as :

$$Q_L = Q_t + Q_b + Q_s \quad ...(2.31)$$

where Q_t = rate of heat loss from the top

Q_b = rate of heat loss from the bottom

Q_s = rate of heat loss from the sides

Each of these losses is also expressed in terms of co-efficients called the top loss co-efficient (U_t), bottom loss co-efficient (U_b) and side loss co-efficient (U_s) as :

$$Q_t = U_t A_c (T_m - T_a)$$

$$Q_b = U_b A_c (T_m - T_a)$$

$$Q_s = U_s A_c (T_m - T_a) \quad \text{...(2.32)}$$

From equation (2.30), (2.31) and (2.32) we get

$$U_L A_c (T_m - T_a) = U_L A_c (T_m - T_a) + U_b A_c (T_m - T_a) + U_s A_c (T_m - T_a)$$

$$\therefore U_L = U_t + U_b + U_s$$

These losses can be expressed in terms of thermal resistance as shown in Fig. 2.32.

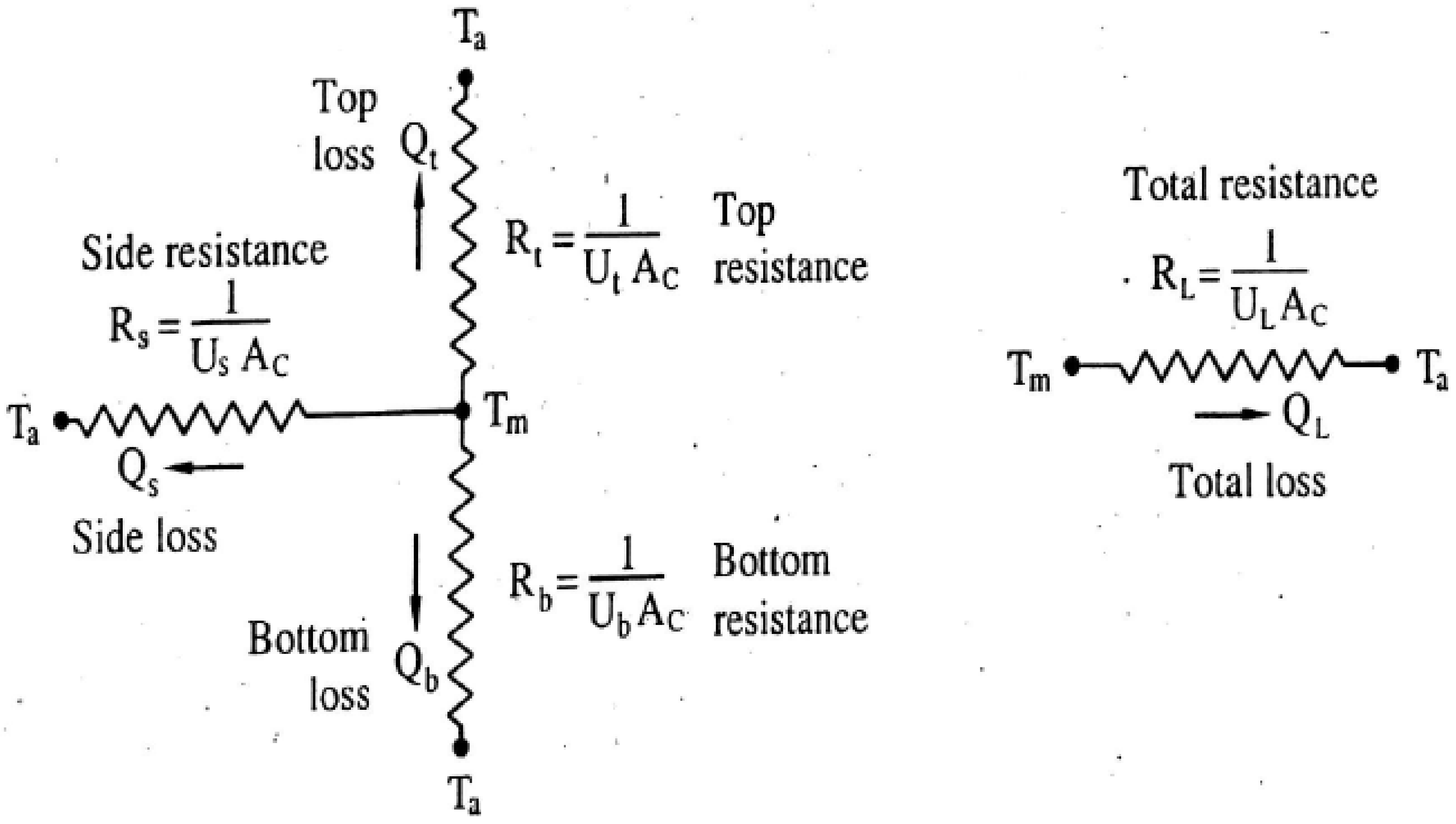


Fig. 2.32 Overall heat loss from collector

Top Loss :

The heat loss from the top of collector is due to convection (both natural and forced) and radiation. The heat loss from the absorber plate first takes place from plate to the first glass cover, then first cover to second glass cover and so on last cover to the surroundings as shown in Fig. 2.33.

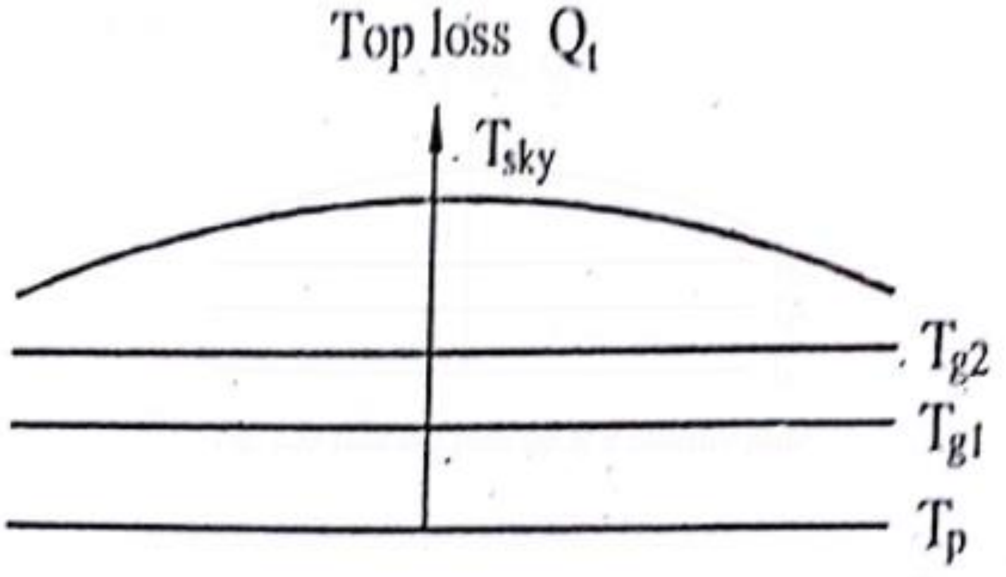


Fig. 2.33 Heat loss from top of a collector plate

Hence, total heat loss from top of collector

Q_t = Convection loss + Radiation loss

$$= h_{pg_1} A_c (T_p - T_{g_1}) + \frac{A_c \sigma (T_p^4 - T_{g_1}^4)}{\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_{g_1}} - 1\right)}$$

(Convection and radiation heat transfer from absorber plate to first glass cover)

$$= h_{g_1 g_2} A_c (T_{g_1} - T_{g_2}) + \frac{A_c \sigma (T_{g_1}^4 - T_{g_2}^4)}{\left(\frac{1}{\varepsilon_{g_1}} + \frac{1}{\varepsilon_{g_2}} - 1\right)}$$

(Convection and radiation heat transfer from first glass to second glass cover)

✓ $$= h_a A_c (T_{g2} - T_a) + \frac{A_c \sigma (T_{g2}^4 - T_{sky}^4)}{\left(\frac{1}{\varepsilon_{g2}} + \frac{1}{\varepsilon_{sky}} - 1\right)}$$

(Convection and radiation heat transfer from second glass cover to surroundings)

where,

h_{pg_1} = convective heat transfer co-efficient between the absorber plate and first glass cover

$h_{g_1 g_2}$ = convective heat transfer co-efficient between the first glass cover and second glass cover

h_a = convective heat transfer co-efficient between second glass cover and surroundings

T_p = temperature of absorber plate

T_{g_1} = temperature of first glass cover

T_{g_2} = temperature of second glass cover

T_a = temperature of atmospheric air

T_{sky} = effective temperature of the sky with which the radiative heat exchange takes place

$= T_a - 6$

ϵ_p = emissivity of the absorber plate

ϵ_{g_1} , ϵ_{g_2} = emissivities of first and second glass covers

The convective heat transfer co-efficients h_{pg} , and $h_{g_1 g_2}$ are calculated with help of equation of Nusselt Number of natural convection between two parallel surfaces. The convective heat transfer co-efficient h_a is calculated with help of Nusselt Number of forced convection, since outside wind having certain velocity. Generally, $h_a = 2.8 + 3V$, where V = velocity of wind (m/s) is taken.

The top loss co-efficient can be calculated by following equation.

$$U_T = \left[\frac{n}{\left(\frac{C}{T_m}\right)\left(\frac{T_m - T_a}{n+f}\right)^{0.252}} + \frac{1}{h_a} \right]^{-1} + \left[\frac{\sigma(T_m^2 - T_a^2)(T_m + T_a)}{\frac{1}{\varepsilon_p + 0.0425n(1-\varepsilon_p)} + \frac{2n+f-1}{\varepsilon_g} - n} \right] \quad \text{...(2.33)}$$

where, n = no. of glass covers

$$f = \left(\frac{9}{h_a} - \frac{30}{h_a^2} \right)\left(\frac{T_a}{316.9} \right)(1 + 0.091n)$$

$$C = \frac{204.429(\cos\beta)^{0.252}}{L^{0.24}}$$

β = collector tilt from horizontal

L = spacing between plates

Bottom loss :

The heat loss from the bottom of collector is due to conduction, convection and radiation. In most of cases, the thickness of insulation provided is such that the thermal resistance associated with conduction dominates, and hence assuming heat transfer due to convection

on is negligible.

$$Q_b = k_i A_c \frac{dt}{dx}$$

$$= k_i A_c \frac{(T_m - T_a)}{\delta_i}$$

where, k_i = thermal conductivity of insulation, δ_i = thickness of insulation

$$= \frac{k_i}{\delta_i} A_c (T_m - T_a)$$

$$= U_b A_c (T_m - T_a)$$

Hence, bottom loss co-efficient

$$U_b = \frac{k_i}{\delta_i} \quad \text{...(2.34)}$$

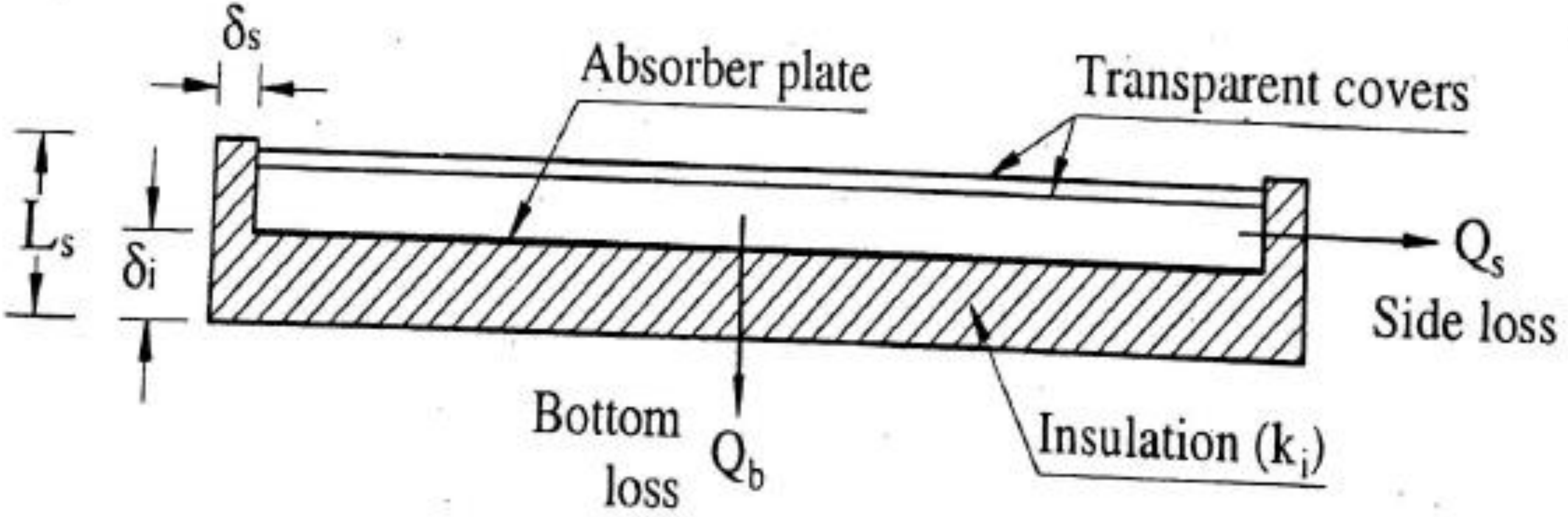


Fig. 2.34 Bottom and side losses from collector

Side loss :

As in case of the bottom loss co-efficient, it will assumed that the conduction resistance dominates and that the flow of heat is one dimensional and steady. The one dimensional approximation can be justified on the grounds that the side loss co-efficient is always much smaller, than the top loss co-efficient.

$$Q_s = 2L_s(L_1 + L_2)k_i \frac{T_m - T_a}{2\delta_s}$$

Hence, $$U_s = \frac{(L_1 + L_2)L_3}{L_1 L_2} \frac{k_i}{\delta_s} \qquad ...(2.35)$$

where, L_1 and L_2 is dimensions of absorber plate

Collector efficiency

Collector efficiency η_c is defined as the ratio of the useful heat gain over a time period to the incident solar radiation on the collector over the same time period. Thus the **instantaneous collector efficiency** is given by:

$$\eta_i = \frac{\text{Useful heat gain}}{\text{Incident solar radiation on the collector}} = \frac{Q_u}{A_a I_t}. \quad ...(3.27)$$

The useful heat gain Q_u is given by eqn. (3.9) as:

$$\frac{Q_u}{A_a} = [I_t(\tau\alpha)_e - U_l\,(T_p - T_a)] \quad ...(3.28)$$

where the average absorber plate temperature T_p is generally not known. Therefore, a parameter called collector efficiency factor F' is introduced in the above equation to determine collector performance without T_p . F' is defined as the ratio of actual useful energy gain per riser tube per unit length to the useful energy gain if the entire absorber plate is at the local fluid temperature T_f. Hence eqn. (3.28) can be written as:

$$\frac{Q_u}{A_a} = F'\,[I_t\,(\tau\alpha_e - U_l\,(T_f - T_a)] \quad ...(3.29)$$

where $T_f = (T_i + T_o)/2$, and T_i and T_o are the inlet and outlet fluid temperatures.

The plate efficiency factor F' is expressed as [5]:

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The plate efficiency factor F' is expressed as [5]:

$$F' = \frac{1}{\left[WU_l\left(\frac{1}{U_l[W - D_o)F + D_o]} + \frac{\delta_a}{k_a D_o} + \frac{1}{\pi D_i h_f}\right)\right]} \quad \text{...(3.30)}$$

Act

Go t

where W is the tube spacing, *i.e.*, the centre to centre distance between the riser tubes

D_i and D_o are the inner and outer diameters of the riser tubes

δ_a is the average thickness of the adhesive (bonding) material

k_a is the thermal conductivity of the adhesive (bonding) material

h_f is the heat transfer coefficient on the inside of the tube

F is the fin efficiency factor and is given by:

$$F = \frac{\tanh[C(W - D_o)/2]}{[C(W - D_o)/2]}$$

where $C = \left(\frac{U_l}{k_p \delta_p}\right)^{1/2}$

k_p is the thermal conductivity of the absorber plate material

δ_p is the thickness of the absorber plate.

Thus the instantaneous efficiency of the flat-plate collector in terms of mean fluid temperature is expressed as:

$$\eta_i = F'(\tau\alpha)_e - F'U_l \frac{(T_f - T_a)}{I_t}. \quad \ldots(3.31)$$

Also, another parameter F_R, called the collector heat removal factor, can be introduced in the eqns. (3.29) and (3.31) in place of F'. The F_R is defined as the ratio of actual useful heat energy gain to the useful energy gain if the entire absorber plate is at the temperature of the fluid entering the collector. Thus,

$$\frac{Q_u}{A_a} = F_R\,[I_t(\tau\alpha)_e - U_l(T_i - T_a)] \quad \ldots(3.32)$$

and
$$\eta_i = F_R(\tau\alpha)_e - F_R U_l \frac{(T_i - T_a)}{I_t} \quad ...(3.33)$$

where T_i is the inlet temperature of the fluid entering the collector.

The heat removal factor F_R is expressed as:

$$F_R = \frac{\dot{m}C_p}{U_l A_a}\left[1 - \exp\left(-\frac{U_l A_a F'}{\dot{m}C_p}\right)\right] \quad ...(3.34)$$

where $\dot{m}$ is the mass flow rate of the fluid (kg/s) and C_p is the specific heat of the fluid (kJ/kg K). F_R is the measure of the thermal resistance encountered by the absorbed solar radiation.

Equation (3.34) indicates that a straight line is obtained with a slope of $F_R U_l$ and an intercept of $F_R(\tau\alpha)_e$ if η_i is plotted against $(T_i - T_a)/I_t$. The actual performances of solar collectors are presented in this form. The procedure for performance testing has been proposed by the ASHRAE Standard 93–77 and IS 12933 (Part 5) 1990. Figure 3.4 presents the performance of typical liquid flat-plate collectors.

Assignment

1. Derive the expression of collector efficiency factor, heat removal factor and useful heat gain for flat plate & cylindrical parabolic Solar Collector.

2. Derive the expression for governing energy balance equation for Solar Collector.

Hard copy submission date (31/3/2020)

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