Chapter Five

Flat−Plate Solar Collectors

Flat−plate solar collector is a unique type of heat exchangers. It receives energy from a far radiation source (sun) and converts the irradiance into useful thermal energy in the form of hot working fluid (water or air). Flat−plate collectors are usually used in low to medium temperature applications rarely exceeding 100^{o}C. They can be water or air collectors. The solar radiation does not undergo any concentration in flat−plate collectors.

5.1 Parts of a typical flat−plate collector

Absorber metal plate: It is the main part of the collector that is responsible on converting the solar radiation into thermal energy. The absorber plate is heated upon the exposure to solar radiation. The accumulated heat in the plate material is carried out of the collector by passing a suitable working fluid to cool the plate. The working fluid is circulated in pipes (risers) attached to the plate (in water collectors), or in conduits firmly attached to the plate (in air collectors) (Fig. 4.1). Absorber plate is made of a metal of high thermal conductivity (copper or aluminum) and the upper side facing the solar radiation is usually coated with a material or paint of high absorptance to short−wave radiation coming from the sun and low emissivity to long−wave radiation emitted by the plate.

Transparent cover: The absorber plate must be covered by a transparent sheet of glass which is placed parallel to the plate with an air gap of 2−10 cm between them. The glass cover traps the incident solar radiation by a phenomenon called (Green−House Effect) at which glass becomes transparent to short−wave solar radiation and opaque to long−wave radiation re−emitted by the plate. As a result, radiation thermal losses is greatly decreased due to Green−House effect. The existence of the air gap between the plate and the cover also decreases convection thermal losses from the plate to environment.

Working fluid pipes: These pipes are firmly welded or attached to the absorber plate to ensure maximum heat transfer to the working fluid. For water collectors the pipes are called (risers) with diameters from 0.5 to 1.5 cm. the risers are connected to a common lower header to evenly distribute working fluid among them, and to an upper header that collects the hot working fluid from all risers.

Insulation layer: The absorber plate and the working fluid pipes should be well insulated to minimize thermal losses to the surrounding environment. An insulating layer of 5 to 10 cm are placed at the back side of the absorber plate with other layers at the sides of the plate.

Assembling case: All collector parts are placed in a suitable metal or wooden case that ensures mechanical durability and thermal insulation.

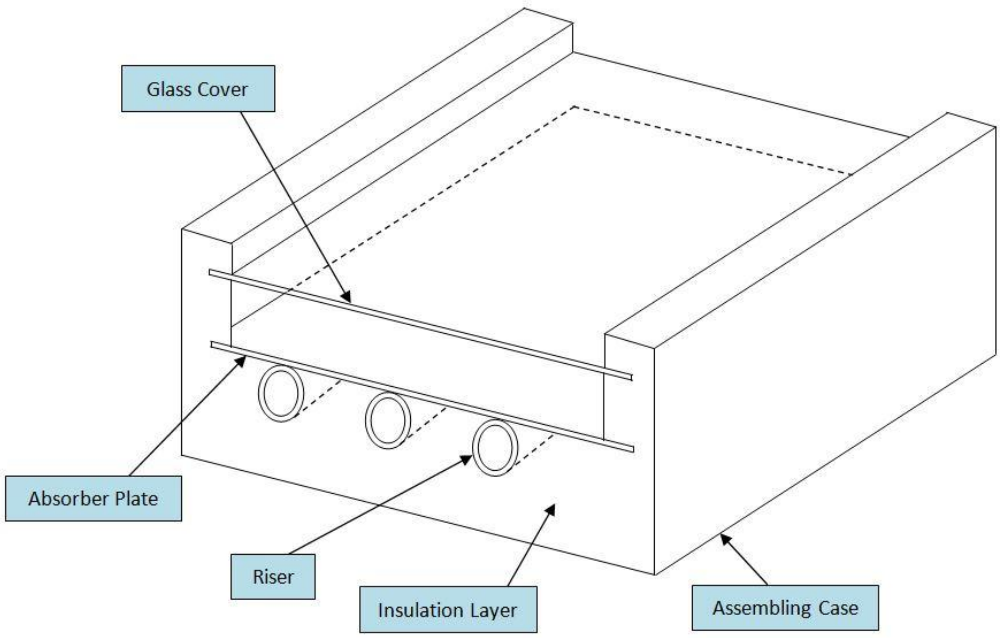

Fig. (4.1): Parts of a flat−plate solar collector

5.2. Some important definitions

Transmittance Coefficient (τ): It is the ratio of the solar radiation penetrating the glass cover to the total radiation incident on the glass cover. The value of τ is always less than one and depends on the purity of the glass and the incidence angle.

Absorptance Coefficient (α): It is the ratio of the solar radiation absorbed by the absorber plate to the solar radiation reaching the plate. The value of (α) is always less than one and depends on the nature of the absorber plate surface. It is a common practice to paint the surface with a (selective coating) that has a high absorptance to solar radiation in the short wave domain and low emissivity to the long waves radiation out of the absorber surface.

The coefficients (τ) and (α) are usually combined as a single factor called (transmittance−absorptance product τα).

Overall heat loss coefficient U_L: It is a heat transfer coefficient that combines all thermal losses from the collector considering it at a representative temperature called (mean plate temperature T_{pm}).

Mean plate temperature T_{pm}: This temperature is the mathematical average of the whole temperature distribution in the absorber plate that is generated when the working fluid flows in the risers.

Mean fluid temperature T_{fm}: This temperature is the mathematical average of the temperature distribution of the working fluid inside a single riser along the flow direction.

5.3 Thermal analysis of flat−plate solar collectors

Thermal analysis of any solar collector involves estimating the useful heat gain from that collector referred to as (Q_u). In flat−plate collectors the following energy balance can be written: −

Useful heat gain = Irradiance reaching absorber – Thermal losses from absorber

In mathematical terms: −

$$Q_u = \tau\alpha I_T A_c - U_L A_c\left(T_{pm} - T_a\right)$$

$$Q_u = A_c\left[\tau\alpha I_T - U_L\left(T_{pm} - T_a\right)\right] \qquad 5.1$$

Where:
Q_u : Useful Heat gain (W)
A_c : Absorber plate area (m^2)
τ : Glass cover transmittance coefficient
α : Absorber plate absorptance coefficient
I_T : Irradiance incident normal to the absorber plate (W/m^2)
U_L : Overall heat loss coefficient ($W/(m^2\ {}^oC)$)
T_{pm} : Absorber plate mean temperature (^oC)
T_a : Ambient temperature (^oC)

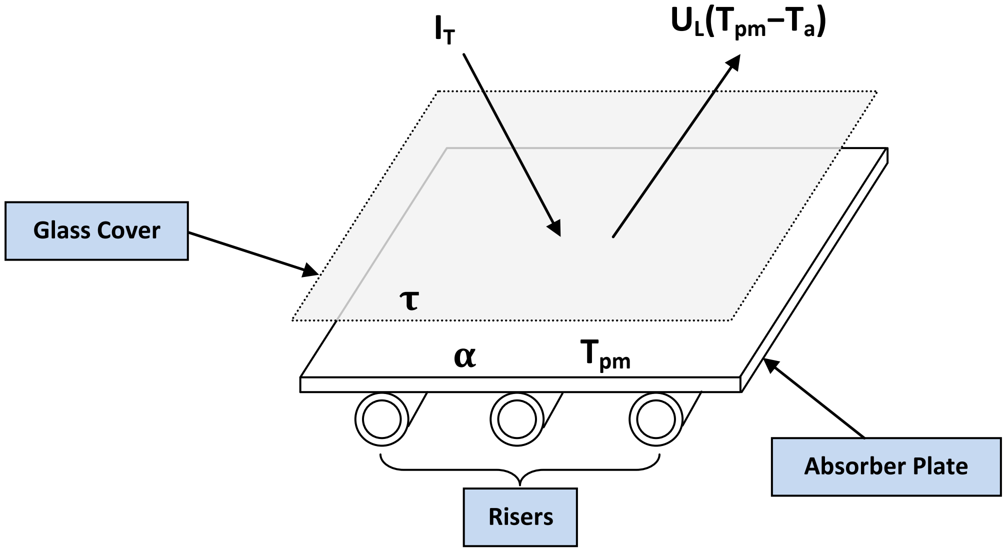

Fig. (5.2): Energy interactions on an absorber plate.

5.4 Collector thermal efficiency η_c

It is the ratio of the useful heat gain Q_u carried by the working fluid to the irradiance incident on the solar collector, namely: −

$$\eta_c = \frac{Q_u}{A_c I_T} = \frac{A_c\left[\tau\alpha I_T - U_L\left(T_{pm} - T_a\right)\right]}{A_c I_T}$$

$$\eta_c = \tau\alpha - \frac{U_L\left(T_{pm} - T_a\right)}{I_T} \qquad 5.2$$

The useful heat gain Q_u can be represented in terms of working fluid mass flow rate $\dot{m}$ inlet and outlet temperatures T_{fi} and T_{fo} respectively as follows: −

$$Q_u = \dot{m}C_{pf}(T_{fo} - T_{fi}) \qquad 5.3$$

5.5 Collector stagnation temperature T_{st}

It is the maximum temperature attained by the solar collector when the mass flow rate is zero. The thermal losses at stagnation temperature equals the incident solar radiation and the useful heat gain is zero, accordingly: −

$$Q_u = 0 = \tau\alpha I_T A_c - U_L A_c (T_{st} - T_a)$$

$$T_{st} = T_a + \frac{\tau\alpha I_T}{U_L} \qquad 5.4$$

Ex. 5.1 A flat−plate solar collector is subjected to a normal irradiance of 850 W/m^2 with an overall heat loss coefficient of 5 $W/(m^2\ ^oC)$. The transmittance−absorptance product of the collector is 0.8 which makes the collector efficiency 60%. If the ambient temperature is 10 ^oC and collector area is 3 m^2 then find: −

a) Useful heat gain. b) Plate mean temperature. c) Stagnation temperature.

Sol.

$Q_u = \eta_c A_c I_T = 0.6 \times 3 \times 850$

$\mathbf{Q_u = 1530\ W}$

$\eta_c = \tau\alpha - U_L (T_{pm} - T_a) / I_T$

$0.6 = 0.8 - 5 (T_{pm} - 10) / 850$

$\mathbf{T_{pm} = 44\ ^oC}$

$T_{st} = T_a + \tau\alpha\ I_T / U_L = 10 + 0.8 \times 850 / 5$

$\mathbf{T_{st} = 146\ ^oC}$

5.6 Calculation of the overall heat loss coefficient U_L

This coefficient combines all thermal losses out of the collector in both convection and radiation modes. U_L is the sum of three loss coefficients: −

$$U_L = U_t + U_b + U_s \qquad 5.5$$

Where: U_t : Top heat loss coefficient (through the glass cover)

U_b : Back heat loss coefficient (through the back insulation)

U_s : Side heat loss coefficient (through the sidewise insulation)

The most important coefficient of the three above is the top coefficient U_t because the other two coefficients U_b and U_s can be minimized to a negligible values by increasing the insulation layers at back and sides of the collector. The top heat loss coefficient on the other hand cannot be freely decreased because of the presence of the glass cover and any heat decreasing part at the top side would shade the solar radiation and decrease collector efficiency.

5.6.1 Calculation of top heat loss coefficient U_t

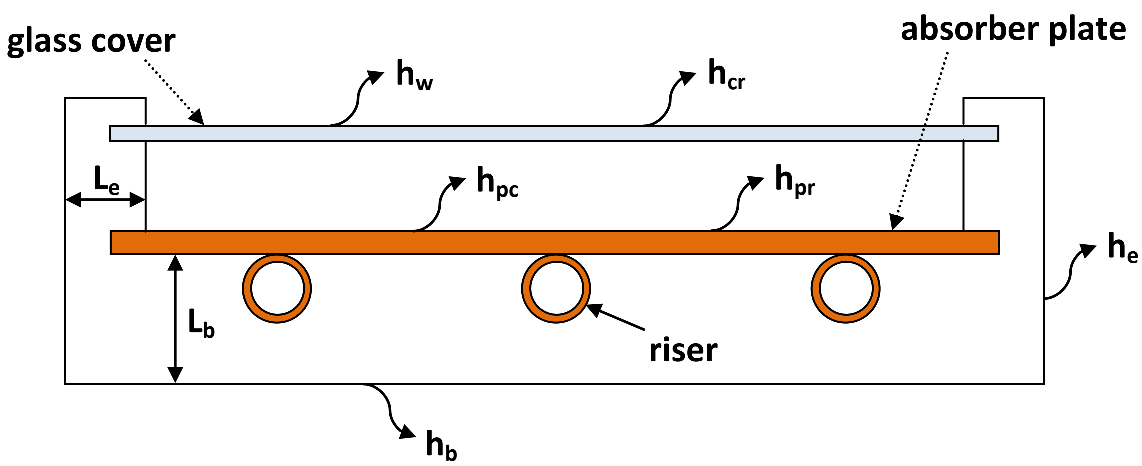

Fig. (5.3): Cross sectional view of a typical flat−plate solar collector showing various heat transfer coefficient.

Fig. (5.3) shows the various convection and radiation heat transfer coefficients out of the absorber plate and glass cover. The amount of heat lost by convection from the absorber plate per unit area is found as follows: −

$$q_{pc} = h_{pc}\left(T_{pm} - T_c\right) \qquad 5.6$$

Where h_{pc} is the convection heat transfer coefficient in the air gap between the absorber plate and the glass cover in (W/(m^2 ^{o}C) and T_c is the glass cover temperature.

The amount of heat lost by radiation from the absorber to the glass cover per unit area can be estimated as follows: –

$$q_{pr} = \frac{\sigma\left(T_{pm}^4 - T_c^4\right)}{\frac{1}{\epsilon_p}+\frac{1}{\epsilon_c}-1} \qquad 5.7$$

Where σ is the Stefan–Boltzmann coefficient = 5.67×10^{-8} W/(m^2 K^4) and ϵ_p and ϵ_c are the absorber plate and glass cover emissivities respectively.

The total heat loss from the absorber plate to the glass cover is the sum of q_{pc} and q_{pr} as follows: –

$$q_p = q_{pc} + q_{pr}$$

$$q_p = h_{pc}\left(T_{pm} - T_c\right) + \frac{\sigma\left(T_{pm}^4 - T_c^4\right)}{\frac{1}{\epsilon_p}+\frac{1}{\epsilon_c}-1} \qquad 5.8$$

$$q_p = h_{pc}\left(T_{pm} - T_c\right) + \frac{\sigma\left(T_{pm} - T_c\right)\left(T_{pm} + T_c\right)\left(T_{pm}^2 + T_c^2\right)}{\frac{1}{\epsilon_p}+\frac{1}{\epsilon_c}-1}$$

$$q_p = \left(T_{pm} - T_c\right)\left[h_{pc} + \frac{\sigma\left(T_{pm} + T_c\right)\left(T_{pm}^2 + T_c^2\right)}{\frac{1}{\epsilon_p}+\frac{1}{\epsilon_c}-1}\right]$$

$$q_p = \frac{\left(T_{pm} - T_c\right)}{R_{pc}} \qquad 5.9$$

Where R_{pc} is the thermal resistance between absorber plate and glass cover: –

$$R_{pc} = \left[h_{pc} + \frac{\sigma\left(T_{pm} + T_c\right)\left(T_{pm}^2 + T_c^2\right)}{\frac{1}{\epsilon_p}+\frac{1}{\epsilon_c}-1}\right]^{-1} \qquad 5.10$$

The same procedure can be repeated for the glass cover. The convection heat loss rate per unit area from the glass cover to the ambient air at T_a is: –

$$q_{cc} = h_w\left(T_c - T_a\right) \qquad 5.11$$

Where h_w is the wind heat transfer coefficient that can be calculated from the following temperature as a function of wind velocity V_w: –

$$h_w = 2.8 + 3V_w \qquad 5.12$$

The radiation heat loss rate per unit area from the glass cover to an effective sky temperature T_s is: –

$$q_{cr} = \epsilon_c \sigma (T_c^4 - T_s^4) \qquad 5.13$$

Where T_s can be estimated from the following equation as a function of ambient temperature T_a: –

$$T_s = 0.0559 T_a^{1.5} \qquad 5.14$$

Accordingly, the total heat loss from the glass cover is the sum of q_{cc} and q_{cr}: –

$$q_c = q_{cc} + q_{cr}$$

$$q_c = h_w (T_c - T_a) + \epsilon_c \sigma (T_c^4 - T_s^4) \qquad 5.15$$

$$q_c = (T_c - T_a)\left[h_w + \frac{\epsilon_c \sigma (T_c^4 - T_s^4)}{T_c - T_a}\right]$$

$$q_c = \frac{T_c - T_a}{R_{ca}} \qquad 5.16$$

Where R_{ca} is the thermal resistance between the glass cover and the surroundings: –

$$R_{ca} = \left[h_w + \frac{\epsilon_c \sigma \left(T_c^4 - T_s^4\right)}{T_c - T_a}\right]^{-1} \qquad 5.17$$

When the collector reaches steady state operation the heat received by the glass cover q_p equals the heat lost to the surroundings q_c which in turn equals the total heat lost by the collector from the top side q_t: –

$$q_t = q_p = q_c \qquad 5.18$$

Combining equations 5.9, 5.16 and 5.18 it follows that: –

$$q_t = \frac{T_{pm} - T_a}{R_{pc} + R_{ca}} = U_t \left(T_{pm} - T_a\right) \qquad 5.19$$

Where U_t is the collector top heat loss coefficient: –

$$U_t = \frac{1}{R_{pc} + R_{ca}} \qquad 5.20$$

The top heat loss coefficient U_t and glass cover temperature T_c are both unknowns in the previous equations. A trial and error solution is therefore necessary to solve the problem. Initial guess value of T_c is assumed and used to evaluate U_t which in turn can be used to find a new value of T_c from eqs. 5.16, 5.18 and 5.19 as follows: –

$$T_{c,new} = U_t R_{ca}\left(T_{pm} - T_a\right) + T_a \qquad 5.21$$

Ex. 5.2 A flat–plate solar collector operates with a mean plate temperature of 50 ^oC when the ambient temperature is 10 ^oC . Find the top heat loss coefficient if the convection heat transfer coefficient in the air gap is 3 W/(m^2 ^oC) and the speed of the wind is 5 m/s. Take the absorber plate and glass cover emissivities to be 0.3 and 0.8 respectively.

Sol.

T_{pm} = 50 + 273 = 323 K T_a = 10 + 273 = 283 K

$T_s = 0.0559\ T_a^{1.5} = 0.0559 \times 283^{1.5}$ T_s = 266.12 K

$h_w = 2.8 + 3\ V_w = 2.8 + 3 \times 5 = 17.8$ W/(m^2 ^oC)

first assumption of the cover temperature is: T_c = 30 ^oC = 303 K

$$R_{pc} = \left[h_{pc} + \frac{\sigma\left(T_{pm} + T_c\right)\left(T_{pm}^2 + T_c^2\right)}{\frac{1}{\epsilon_p} + \frac{1}{\epsilon_c} - 1}\right]^{-1}$$

$$R_{pc} = \left[3 + \frac{5.67 \times 10^{-8}(323 + 303)(323^2 + 303^2)}{\frac{1}{0.3} + \frac{1}{0.8} - 1}\right]^{-1}$$

R_{pc} = 0.2023

$$R_{ca} = \left[h_w + \frac{\epsilon_c \sigma(T_c^4 - T_s^4)}{T_c - T_a}\right]^{-1}$$

$$R_{ca} = \left[17.8 + \frac{0.8 \times 5.67 \times 10^{-8}(303^4 - 266.12^4)}{303 - 283}\right]^{-1}$$

R_{ca} = 0.0391

$$U_t = \frac{1}{R_{pc} + R_{ca}} = \frac{1}{0.2023 + 0.0391} = 4.142\ \mathrm{W/(m^2\ °C)}$$

$T_{c,new} = U_t\, R_{ca}\,(T_{pm} - T_a) + T_a = 4.142 \times 0.0391\,(323 - 283) + 283 = 289.4$ K

The process is repeated using the new value of T_c = 289.4 K

$$R_{pc} = \left[3 + \frac{5.67 \times 10^{-8}(323 + 289.4)(323^2 + 289.4^2)}{\frac{1}{0.3} + \frac{1}{0.8} - 1}\right]^{-1} = 0.2073$$

$$R_{ca} = \left[17.8 + \frac{0.8 \times 5.67 \times 10^{-8}(289.4^4 - 266.12^4)}{289.4 - 283}\right]^{-1} = 0.0312$$

$$U_t = \frac{1}{R_{pc} + R_{ca}} = \frac{1}{0.2073 + 0.0312} = 4.192\ \mathrm{W/(m^2\ °C)}$$

$T_{c,new} = U_t\, R_{ca}\,(T_{pm} - T_a) + T_a = 4.192 \times 0.0312\,(323 - 283) + 283 = 288.23$ K

The process can be repeated for further accuracy

So: $U_t = 4.192\ \mathrm{W/(m^2\ °C)}$