Module 3

Performance Analysis of Liquid Flat Plate Collectors: *General description, collector geometry, selective surface (qualitative discussion) basic energy-balance equation, stagnation temperature, transmissivity of the cover system, transmissivity – absorptivity product, numerical examples. The overall loss coefficient, correlation for the top loss coefficient, bottom and side loss coefficient, problems (all correlations to be provided). Temperature distribution between the collector tubes, collector heat removal factor, collector efficiency factor and collector flow factor, mean plate temperature, instantaneous efficiency (all expressions to be provided). Effect of various parameters on the collector performance; collector orientation, selective surface, fluid inlet temperature, number covers, dust.*

Photovoltaic Conversion*: Description, principle of working and characteristics, application.*

Contents

1 Thermal analysis of liquid flat plate collector 2

1.1 Solar radiation attenuation in cover system 4

1.1.1 Transmissivity of the cover system 4

1.2 Absorptivity of Absorber Plate (α) 7

1.3 Transmissivity - Absorptivity Product (τα) 7

1.4 Heat loss rate from absorber plate, q_L 8

1.5 Evaluation of loss coefficients 11

2 Effect of various parameters on performance 13

3 Solar Cell Principles. 14

1 Thermal analysis of liquid flat plate collector

Let us consider a flat plate solar collector shown in Fig. 5.3 for thermal analysis. The heat flow process is shown in Fig. 5.42.

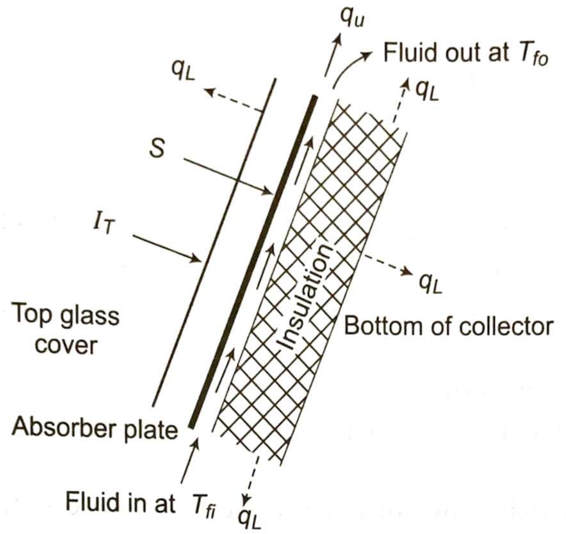

Figure 5.42 Heat transfer process in flat plate solar collector

Energy balance of the absorber plate, under steady state condition yields:

$$q_u = A_p S - q_L \tag{5.1}$$

where, q_u = useful heat gain (i.e. heat transfer rate to the working fluid), W
A_p = area of absorbing plate, m^2
S = incident solar flux absorbed in the collector plate, W/m^2
q_L = rate at which energy is lost by:
(i) convection and re-radiation from the top, and
(ii) conduction and convection from the bottom and sides of the collector

Also, the heat transfer rate to the working fluid is given by,

$$q_u = \dot{m}\, C_f (T_{fo} - T_{fi}) \tag{5.2}$$

where, $\dot{m}$ = mass flow rate of the fluid, kg/s
C_f = specific heat of the fluid, J/m^2-K
T_{fi} = fluid temperature at the input of collector, K
T_{fo} = fluid temperature at the output of collector, K

Solar flux incident on the top of the collector, is same as solar radiation received on inclined plane surface, as given in Chapter 4, Eq. (4.31), that is:

$$I_T = I_b r_b + I_d r_d + (I_b + I_d)\, r_r$$

where I_b and I_d are the beam and diffuse radiation components of solar radiation, r_b, r_d and r_r are "tilt factors" for beam, diffuse and reflected components respectively. Their expressions are given in Eq. (4.33), (4.34) and (4.35) respectively as follows:

$$r_b = \frac{\sin\delta \sin(\phi - \beta) + \cos\delta \cos\omega \cos(\phi - \beta)}{\sin\delta \sin\phi + \cos\delta \cos\omega \cos\phi}$$

$$r_d = \frac{1+\cos\beta}{2}$$

$$r_r = \rho\left(\frac{1-\cos\beta}{2}\right)$$

where ρ is reflection coefficient of the ground.

The flux S, absorbed in the absorber plate, can be given as,

$$S = I_b\, r_b\, (\tau\alpha)_b + \{I_d\, r_d + (I_b + I_d)\, r_r\}\, (\tau\alpha)_d \tag{5.3}$$

where,

τ = transmissivity of the glass cover system, defined as the ratio of the solar radiation coming through after reflection at the glass air interfaces and absorption in the glass to the radiation incident to the glass cover system.

α = absorptivity of the absorber plate.

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

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

The **instantaneous collection efficiency**, η_i of a flat plate solar collector is given by,

$$\eta_i = \frac{\text{useful heat gain}}{\text{solar radiation incident on the collector}} = \frac{q_u}{A_c\, I_T} \tag{5.4}$$

where, I_T = instantaneous radiation energy rate incident on collector face (W/m^2)

A_c = the collector gross area (area of the topmost cover including the frame). A_c is usually 15 to 20 per cent more than A_p.

It is to be noted here, that the energy rate incident on the collector is $A_c I_T$. A fraction of this energy is lost in the cover system during transmission through it. The energy rate received on the absorber plate is $A_p S$. Out of this energy, q_u is the rate of heat (energy) transfer to working fluid while q_L is the energy loss rate from the absorber plate.

If the liquid flow rate through the collector is stopped, there is no useful heat gain and therefore, the efficiency is zero. In this case, total heat absorbed by plate is lost to ambient and the absorber plate attains a temperature according to $A_p S = q_L$. This is the highest temperature, the absorber plate can attain and is referred to as the **stagnation temperature**. Knowledge of the stagnation temperature is useful for comparing different collector designs. It also helps in proper material selection for the construction of collector.

To determine the efficiency of collector one needs to evaluate q_u, for which S and q_L are to be known. S can be evaluated using Eq. (5.3) provided the terms $(\tau\alpha)_b$ and $(\tau\alpha)_d$ are known. We shall now derive the expressions for evaluating theses quantities.

1.1 Solar radiation attenuation in cover system

1.1.1 Transmissivity of the cover system

When a beam radiation travelling through one medium strikes another medium it partly gets reflected, refracted and absorbed in the medium. Transmissivity, τ of the cover system may be obtained by considering transmissivity due to (i) reflection-refraction and (ii) absorption separately. Thus:

$$\tau = \tau_r \, \tau_a \tag{5.5}$$

where, τ_r = transmissivity obtained by considering only reflection and refraction, and

τ_a = transmissivity obtained by considering absorption only

(a) Transmissivity based on Reflection-Refraction, (τ_r)

As shown in Fig. 5.43, I_{bn} is the intensity of the incoming beam radiation striking the interface of two medium at an angle of incidence of θ_1. The reflected beam has reduced intensity of I_ρ making an angle of reflection which is equal to angle of incidence. The direction of incident and refracted beams are related to each other by Snell's law as follows:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} \tag{5.6}$$

where, θ_1 = angle of incidence,

θ_2 = angle of refraction, and

n_1, n_2 = refractive indices of the two media

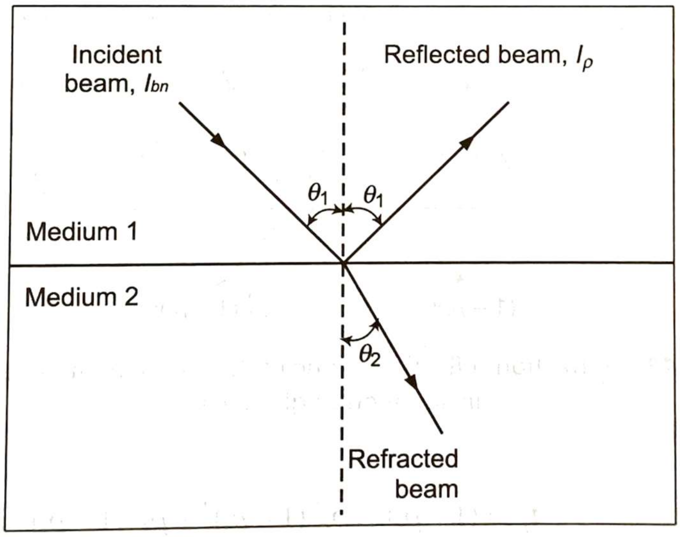

Figure 5.43 Reflection and refraction of the incident beam

The reflectivity ρ (= I_ρ/I_{bn}) is related to the angle of incidence and refraction as follows:

$$\rho = \frac{I_\rho}{I_{bn}} = \frac{1}{2}(\rho_I + \rho_{II}) \tag{5.7}$$

$$\rho_I = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} \tag{5.8}$$

$$\rho_{II} = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)} \tag{5.9}$$

where, ρ_I and ρ_{II} are the reflectivities of the two components of polarization.

For the special case of normal incidence ($\theta_1 = 0°$), it can be shown that,

$$\rho = \rho_I = \rho_{II} = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \tag{5.10}$$

The transmissivity τ_r is given by an expression,

$$\tau_r = \frac{1}{2}(\tau_{rI} + \tau_{rII}) \tag{5.11}$$

where, τ_{rI} and τ_{rII} are the transmissivities of the two components of polarization.

Let us now consider one of the components of polarization of beam radiation incident on single cover. As there are two interfaces in the cover, multiple reflections and refraction will occur as shown in Fig. 5.44.

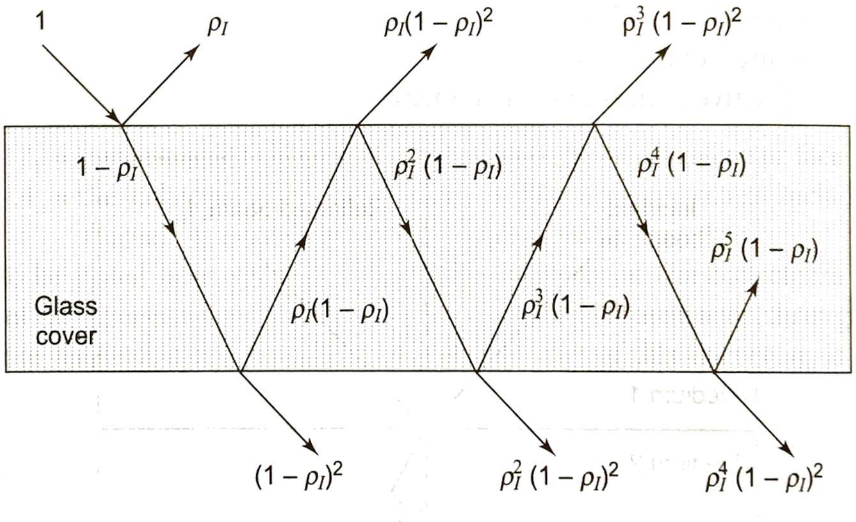

Figure 5.44 Refraction-reflection of one of the component of polarization incident on single cover

Hence,

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

$$= \frac{1 - \rho_I}{1 + \rho_I} \tag{5.12}$$

Similarly,

$$\tau_{rII} = \frac{1 - \rho_{II}}{1 + \rho_{II}} \tag{5.13}$$

Thus for a system with M number of covers, we can write,

$$\tau_{rI} = \frac{1-\rho_I}{1+(2M-1)\rho_I} \tag{5.14}$$

Similarly,

$$\tau_{rII} = \frac{1-\rho_{II}}{1+(2M-1)\rho_{II}} \tag{5.15}$$

(b) Transmissivity based on Absorption, (τ_α) Let us consider a transparent cover through which radiation is passing, as shown in Fig. 5.45. As per Bouger's law "the attenuation due to absorption is proportional to the local intensity". At depth 'x' from the top, the intensity is I_x. Now, on penetrating an elementary distance of dx, the attenuation ($-dI_x$) is given by:

$$-dI_x \;\alpha\; (I_x\, dx)$$

$$dIx = -K\, I_x\, dx \tag{5.16}$$

where, K is a constant of proportionality, known as **extinction coefficient**. Integrating over the thickness of cover, δ_c, we have

$$\tau_a = \frac{I_L}{I_{bn}} = e^{-k\delta_c} \tag{5.17}$$

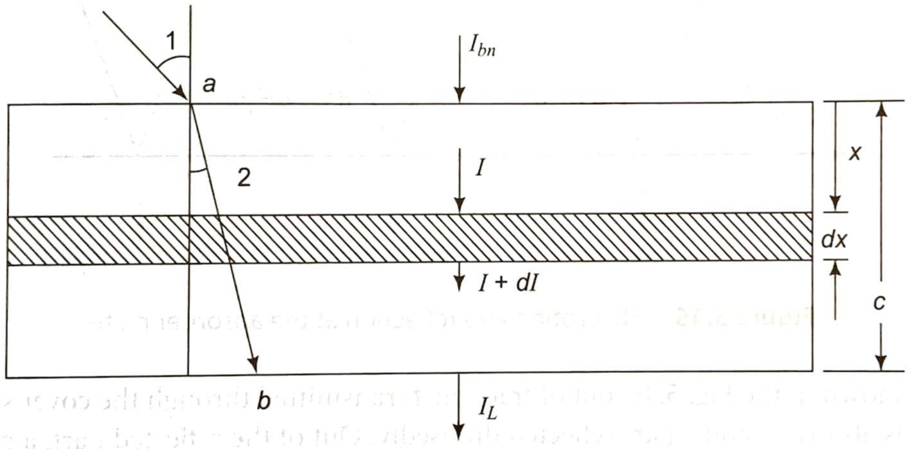

Figure 5.45 Absorption of the incident ray in a transparent cover

If the ray is incident at angle θ_1, as shown in Fig. 5.45, the path traversed through the cover would be 'ab' = $\delta_c/\cos\theta_2$, where θ_2 is angle of refraction.

$$\tau_a = e^{-k\delta_c/\cos\theta_2} \tag{5.18}$$

For M number of covers,

$$\tau_a = e^{-Mk\delta_c/\cos\theta_2} \tag{5.19}$$

The extinction coefficient K is the property of the material. For different qualities of glass its value varies from 4 to 25 per m.

Transmissivity for Diffuse Radiation As diffuse radiation, I_d come from many directions, it poses difficulty in the calculation of transmissivity for diffuse radiation.

The usual practice is to assume that diffuse radiation is equivalent to beam radiation coming at an angle of incidence of 60^0. In the case of diffuse radiation, since the rays come from many directions

1.2 Absorptivity of Absorber Plate (α)

The absorptivity, α, of the absorber plate is defined as the ratio of the solar radiation absorbed in the absorbing plate to the radiation incident to the absorber plate.

1.3 Transmissivity - Absorptivity Product (τα)

The transmissivity-absorptivity product is defined as the ratio of the flux absorbed in the absorber plate to the flux incident on the cover system and is denoted by the symbol ($\tau\alpha$), an appropriate (b or d) being added to indicate the type of incident radiation.

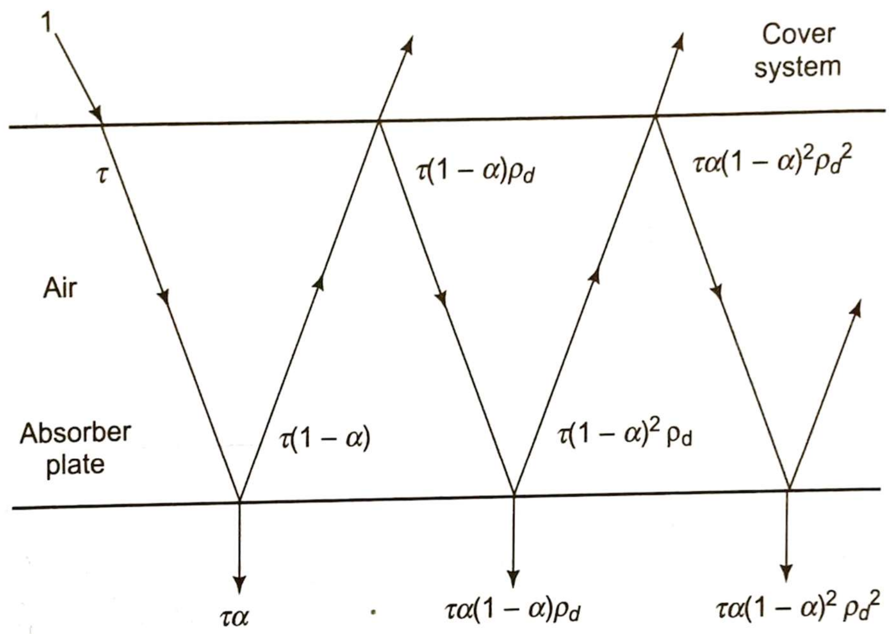

Figure 5.46 Absorption and reflection at the absorber plate

As shown in the Fig. 5.46, out of fraction τ transmitted through the cover system, a part is absorbed and a part reflected diffusedly. Out of the reflected part, a portion is transmitted out through the cover system and a portion reflected back to absorber plate. The process goes on indefinitely with successive attenuation. Thus net fraction absorbed is given by,

$$(\tau\alpha) = \tau\alpha\left[1 + (1-\alpha)\rho_d + (1-\alpha)^2\rho_d^2 + \ldots\right]$$

$$= \frac{\tau\alpha}{1-(1-\alpha)\rho_d} \tag{5.20}$$

where, ρ_d represents the diffuse reflectivity of the cover system. It can be shown that:

$$\rho_d = (\tau_a)_d \{1-(\tau_r)_d\} \tag{5.21}$$

where $(\tau_a)_d$ and $(\tau_r)_d$ are calculated for diffuse radiation considering an incidence angle of 60°. Eq. (5.20) may be applied separately to both, beam radiation and diffuse radiation. However, the values of cover system transmissivities are different for beam and diffuse radiations.

Thus for beam radiation,

$$(\tau\alpha)_b = \frac{(\tau)_b \times \alpha}{1-(1-\alpha)\rho_d} \tag{5.22}$$

And for diffuse radiation,

$$(\tau\alpha)_d = \frac{(\tau)_d \times \alpha}{1-(1-\alpha)\rho_d} \tag{5.23}$$

Same value of absorptivity α applies to both beam as well as diffuse radiations.

1.4 Heat loss rate from absorber plate, q_L

It is more convenient to express the heat lost from the collector in terms of an overall loss coefficient defined by the equation:

$$q_L = U_L A_p (T_{pm} - T_a) \tag{5.24}$$

where U_L = overall loss coefficient, W/m^2-K

A_p = area of absorber plate, m^2

T_{pm} = mean (or average) temperature of the absorber plate, K

and T_a = temperature of the surrounding air, K

The heat lost from the collector is the sum of the heat lost from the top, the bottom and the sides. Therefore, total heat loss rate of the collector is given by,

$$q_L = q_t + q_b + q_s \tag{5.25}$$

where q_t = rate at which heat is lost from the top

q_b = rate at which heat is lost from the bottom

q_s = rate at which heat is lost from the sides

Each of these loss components may also be expressed in terms of individual loss coefficients, that is, top loss coefficient, bottom loss coefficient and side loss coefficient respectively, defined by the following equation.

$$q_t = U_t A_p (T_{pm} - T_a) \tag{5.26}$$

$$q_b = U_b A_p (T_{pm} - T_a) \tag{5.27}$$

$$q_s = U_s A_p (T_{pm} - T_a) \tag{5.28}$$

It is to be noted here that in the above three equations the coefficients are defined on the basis of common area A_p and also common temperature difference. This simplifies the analysis and gives simple additive equation for overall loss component of the collector. Thus:

$$U_L = U_t + U_b + U_s \tag{5.29}$$

These losses can also be depicted in terms of thermal resistances as shown in Fig. 5.5. Typical value of overall loss coefficient is in range 2 to 10 kW/m^2-K.

Equation (5.2) can now be written as:

$$q_u = A_p S - U_L A_p (T_{pm} - T_a) \tag{5.30}$$

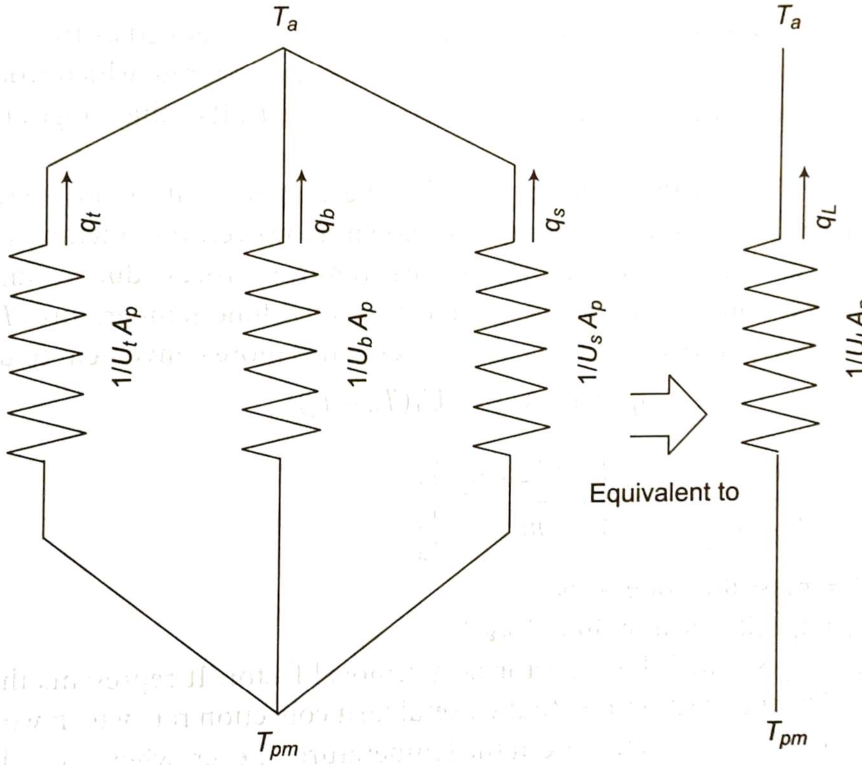

Figure 5.47 Thermal resistance network showing collector losses

A modified equation in which the term, plate temperature, T_{pm} is replaced by local fluid temperature; T_f (temperature of fluid flowing in the tubes) can also be obtained as follows:

$$q_u = F'[A_p S - U_L A_p (T_f - T_a)] \tag{5.31}$$

where, $$F' = \frac{1/U_L}{W\left[\dfrac{1}{U_L\{E_f(W-D_o)+D_o\}} + \dfrac{\delta_a}{k_a D_o} + \dfrac{1}{\pi D_i h_f}\right]} \tag{5.32}$$

D_i, D_o = inside and outside diameters of tubes, m

k_a = thermal conductivity of adhesive material, W/m-K
W = pitch of tubes (spacing between adjacent tubes), m
h_f = heat transfer coefficient on the inside surface of the tube (tube to fluid heat transfer coefficient), W/m^2-K

$$a = (U_L/k_p\delta_p)^{1/2} \tag{5.33}$$

k_p = thermal conductivity of plate, W/m-K
δ_p = thickness of absorber plate, m

$$E_f = \frac{\tanh\{a(W - D_o)/2\}}{\{a(W - D_o)/2\}} \tag{5.34}$$

E_f is known as plate effectiveness, which is defined as the ratio of the heat conducted through the plate to the fluid tube, to the heat which would have been conducted if the thermal conductivity of the plate material was infinite.

The term F' is known as collector efficiency factor and defined as the ratio of the actual useful heat collection rate to the useful heat collection rate which would occur if the collector absorber plate were at the temperature T_f. Its value ranges from 0.90 to 0.95.

The heat loss from the collector can thus be calculated if either average plate temperature or local fluid temperature is known. However, these temperatures are generally not known. By considering the heat removal process due to fluid flow, a modified expression can be obtained in terms of inlet fluid temperature, T_{fi}. This is usually a known quantity and hence the expression is more convenient to use. Thus:

$$q_u = F_R A_p [S - U_L(T_{fi} - T_a)] \tag{5.35}$$

where $$F_R = \frac{\dot{m}\, C_f}{U_L\, A_p}\left[1 - \exp\left(-\frac{F' U_L A_p}{\dot{m}\, C_f}\right)\right] \tag{5.36}$$

$\dot{m}$ = mass flow rate, kg/s
C_f = specific heat of fluid, J/kg-K

The term F_R is called the collector heat removal factor. It represents the ratio of actual useful heat collection rate to the useful heat collection rate which would occur if the collector absorber plate were at the temperature T_{fi} everywhere. Its value ranges from 0 to 1. Equation (5.36) is often referred to as Hottel-Whillier-Bliss equation.

Using the procedure described above the efficiency of a flat plate collector may be calculated. For a properly designed flat plate collector an instantaneous efficiency of the order of 50–60 per cent may be achieved.

1.5 Evaluation of loss coefficients

1. Top Loss Coefficient, U_t

The top loss coefficient is evaluated by considering convection and re-radiation losses from the absorber plate in the upward direction. Evaluation through normal procedure requires tedious iterative calculations. Based on calculations for a large number of cases covering the entire range of conditions normally expected for flat plate collectors, Malhotra et al. [28] suggested following empirical equation for calculation of U_t.

$$U_t = \left[\frac{M}{\left(\frac{C}{T_{pm}}\right)\left(\frac{T_{pm}-T_a}{M+f}\right)^{0.252}} + \frac{1}{h_w}\right]^{-1} + \left[\frac{\sigma(T_{pm}^2+T_a^2)(T_{pm}+T_a)}{\frac{1}{\varepsilon_p+0.0425M(1-\varepsilon_p)} + \frac{2M+f-1}{\varepsilon_c} - M}\right] \tag{5.37}$$

where, $$f = \left(\frac{9}{h_w} - \frac{30}{h_w^2}\right)\left(\frac{T_a}{316.9}\right)(1+0.091M) \tag{5.38}$$

$$C = 204.429(\cos\beta)^{0.252}/L^{0.24} \tag{5.39}$$

$$h_w = 8.55 + 2.56\,V_\infty \tag{5.40}$$

= convective heat transfer coefficient at the cover (often referred to as wind heat transfer coefficient, W/m^2-k)

V_∞ = wind speed, m/s

M = Number of glass covers

σ = Stefan-Boltzmann constant, W/m^2-K^4

ε_p = Emissivity of absorber surface for long wavelength radiation

ε_c = Emissivity of cover for long wavelength radiation

L = Spacing between absorber plate and 1st glass cover (which is also equal to spacing between the two adjacent glass covers)

2. Bottom Loss Coefficient, U_b

The bottom loss component U_b is evaluated by considering conduction and convection losses from the absorber plate in the downward direction through the bottom of the collector as shown in Fig. 5.48.

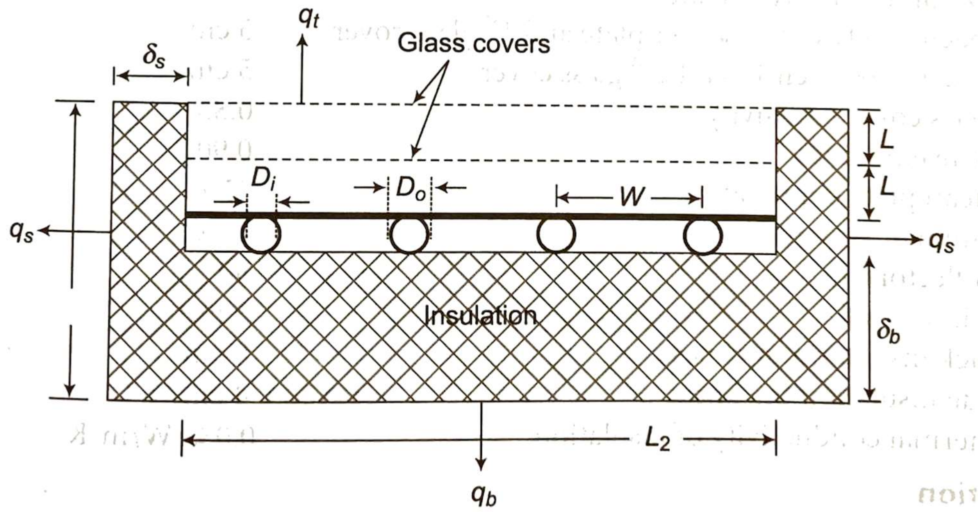

Figure 5.48 Bottom and side losses from a flat plate collector

It is assumed that the flow of heat is one dimensional and steady. In most cases, the thickness of insulation provided is such that the convection is negligible and heat loss takes place predominantly by conduction. Thus, the bottom heat loss is given by,

$$U_b = \frac{k_i}{\delta_b} \tag{5.41}$$

where, k_i = Thermal conductivity of insulation, W/m-K
δ_b = Thickness of the insulation, m

3. Side Loss Coefficient, U_s

In this case also, it is assumed that the convection is negligible, conduction losses dominate and the flow is one dimensional and steady. If the dimensions of absorber plate are $L_1 \times L_2$ and the height of collector casing is L_3, the area across which the heat flows sideways is $2(L_1 + L_2)\,L_3$. The temperature drop across which the heat flow takes place varies from $(T_{pm} - T_a)$ at the absorber level to zero, both at the top and at the bottom. Therefore, average temperature drop across the side insulation may be considered as, $(T_{pm} - T_a)/2$. The heat flow may be given as,

$$q_s = 2L_3(L_1 + L_2)k_i \frac{T_{pm} - T_a}{2\delta_s} \tag{5.42}$$

Therefore,

$$U_s = \frac{L_3(L_1 + L_2)k_i}{L_1 L_2 \delta_s} \tag{5.43}$$

where, δ_s = Thickness of the insulation, m

2 Effect of various parameters on performance

(a) Selective Surface Absorber plate surfaces which exhibit the characteristics of high value of absorptivity for incoming solar radiation and low value of emissivity for outgoing re-radiation are called selective surfaces. Such surfaces are desirable because they maximize the net energy collection. Some examples of selective surface layers are copper oxide, nickel black, and black chrome.

(b) Number of Covers With the increase in the number of covers, the values of both $(\tau\alpha)_b$ and $(\tau\alpha)_d$ decrease, and thus the flux absorbed by the absorber plate decreases. The value of heat loss from the absorber plate also decreases. However, the amount of decrease is not the same for each cover. Maximum efficiency is obtained with one or two covers.

(c) Spacing Heat loss also varies with spacing between two covers and that between temperature and also varies with tilt. Since collectors are designed to operate at different locations with varying tilts and under varying service conditions, an optimum value of spacing is difficult to specify. Spacing in the range from 4 to 8 cm is normally suggested.

(d) Collector Tilt Flat plate collectors are normally used in a fixed position and do not track the sun. Therefore, the tilt angle at which they are fixed is very important. The optimum tilt depends on the nature of the application. The usual practice is to recommend a value of $(\varphi + 10°)$ or $(\varphi + 15°)$ for winter applications (e.g. water heating, space heating, etc.) and $(\varphi - 10°)$ or $(\varphi - 15°)$ for summer applications (e.g. absorption refrigeration plant, etc.).

(e) Dust on the Top of the Cover When a collector is deployed in a practical system, the dust gets accumulated over it, reducing transmitted flux through the cover. This requires continuous cleaning of the cover, which is not possible in a practical situation. Cleaning is generally done once in a few days. For this reason, it is recommended that the incident flux be multiplied by a correction factor which accounts for the reduction in intensity because of the accumulation of dust. In general, a correction factor from 0.92 to 0.99 seems to be indicated.

3 Solar Cell Principles.

The photo-voltaic effect can be observed in nature in a variety of materials, but the materials that have shown the best performance in sunlight are the semi-conductors. When photons from the sun are absorbed in a semiconductor, they create free electrons with higher energies than the electrons which provide the bonding in the base crystal. Once these electrons are created, there must be an electric field to induce these higher energy electrons to flow out of the semi-conductor to do useful work. The electric field in most solar cells is provided by a junction of materials which have different electrical properties.

What is a solar cell?

Solid state device that converts incident solar energy directly into electrical energy

Advantages:

1. Efficiencies from a few percent up to 20-30%
2. No moving parts
3. No noise
4. Lifetimes of 20-30 years or more

To obtain a useful power output from photon interaction in a semi-conductor three processes are required.

1. The photons have to be absorbed in the active part of the material and result in electrons being excited to a higher energy potential.
2. The electron-hole charge carrier created by the absorption must be physically separated and moved to the edge of the cell.
3. The charge carriers must be removed from the cell and delivered to a useful load before they loose their extra potential.

For completing the above processes, a solar cell consists of:

a. Semi-conductor in which electron hole pairs are created by absorption of incident solar radiation.
b. Region containing a drift field for charge separation, and
c. Charge collecting front and back electrodes.

The photo-voltaic effect can be described easily for p-n junction in a semi-conductor. In an intrinsic semi-conductor such as silicon, each one of the four valence electrons of the material atom is tied in a chemical bond, and there are no free electrons at absolute zero. If a piece of such a material is doped on one side by a five-valence electron material, such as arsenic or phosphorus, there will be an excess electrons in that side, becomes an n-type semiconductor. The excess electrons will be practically free to move in the semiconductor lattice. When the other side of the same piece is dopped by a three-valence electron material, such as boron, there will be deficiency of electrons leading to a p-type semiconductor. This deficiency is expressed in terms of excess of holes free to move in the lattice. Such a piece of semi-conductor with one side of the p-type and the other of the n-type is called a p-n junction. In this junction after the photons are absorbed, the free electrons of the n-side will tend to flow to the p-side, and the holes of the p-side will tend to flow to the n region to compensate for their respective deficiencies. This diffusion will create an electric field E_F from the n region to the p-region. This field will increase until it reaches equilibrium for V_e, the sum of the diffusion potentials for holes and electrons. If electrical contacts are made with the two semiconductor materials and the contacts are connected through an external electrical conductor, the free electrons will flow from the n-type material through the conductor to the p-type material. Here the free electrons will enter the holes and become bound electrons; thus, both free electrons and holes will be removed. The flow of electrons through the external conductor constitutes an electric current which will continue as long as more free electrons and holes are being formed by the solar radiation. This is the basis of photovoltaic conversion, that is, the conversion of solar energy into electrical energy. The combination of n-type and p-type semiconductors thus constitutes a photovoltaic (PV) cell or solar cell. All such cells generate direct current which can be converted into alternating current if desired.

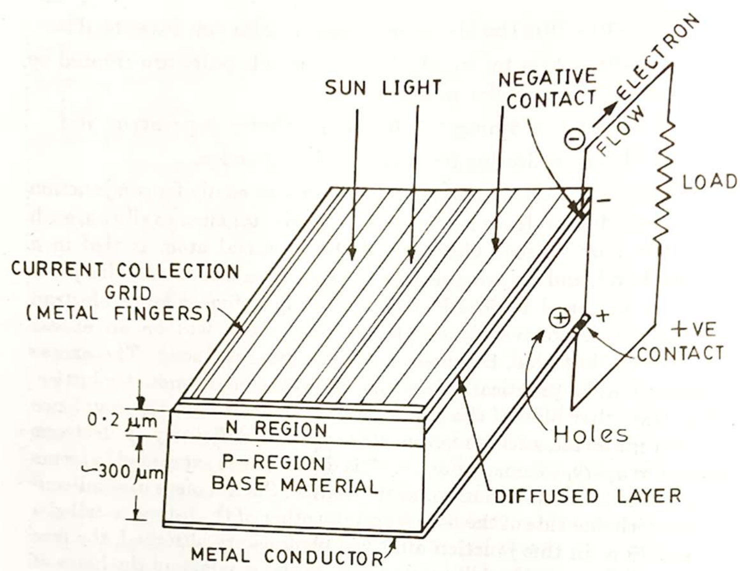

Figure 1: Schematic view of a typical solar cell

The most normal configuration for a solar cell to make a p-n junction semiconductor is as shown schematically in Fig. The junction of the 'p type' and 'n type' materials provides an inherent electric field which separates the charge created by the absorption of sunlight. This p-n junction is usually obtained by putting a p-type base material into, a diffusion furnace containing a gaseous n-type dopant such as phosphorus and allowing the n-dopant to diffuse into the surface about 0.2 um. The junction is thus formed slightly below the planar surface of the cell and the light impinges perpendicular to the junction. The positive and negative charges created by the absorption of photons are thus encouraged to drift to the front and back of the solar cell. The back is completely covered by a metallic contact to remove the charges to the electric load. The collection of charges from the front of the cell is aided by a fine grid of narrow metallic fingers. The surface coverage of the conducting collectors is typically about 5 per cent in order to allow as much light as possible to reach active junction area. An antireflective coating is applied on the top of the cell. Fig. demonstrates how this p-n junction provides an electrical field that sweeps the electrons in one direction and the positive holes in the other. If the junction is in thermodynamic equilibrium, then the Fermi energy, must be uniform throughout. Since the Fermi level is near the top of the gap of an n-doped material and near the bottom of the p-doped side, an electric field must exist at the junction providing the charge separation function of the cell. Important characteristic of the Fermi level is that, in thermodynamic equilibrium, it is always continuous across the contact between the two materials.

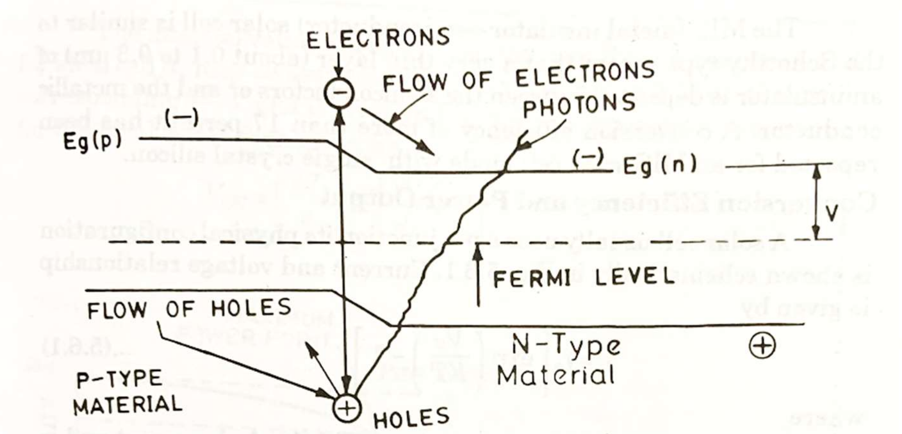

Figure 2: p-n Junction electric fields

Each of the individual solar cells will produce power at about 0.5 V with the current directly proportional to the cell's area. The individual cells are connected in series-parallel combination to meet the voltage, power and reliability requirements of the particular application. Space cells are covered with transparent 'cover slips' to absorb the high energy particles in space that could cause damage in the cell and result in a degradation of output. For terrestrial applications, the solar cell panels have to be encapsulated to protect them from atmospheric degradation due to oxidation of the metal contacts, which would cause peeling and open circuits materials such as glass, acrylics or silicon epoxies are used to provide a clear, weather fight front covering for the panels.