MODULE 12 Lecture No: 13

Solar Flat Plate Collectors

Lecture 13

12.4 THERMAL NETWORK FOR THE COLLECTOR

Thermal network diagram for a flat plate collector is shown in Fig. 12.3 (a). The flat plate collector is assumed to be having two glass covers. At some typical location on the plate where the temperature is T_P, solar energy absorbed is $S = I_T(\tau\alpha)$. This S is distributed to thermal losses from top and bottom and to useful energy gain. Assuming that the overall heat loss coefficient to be U_L , S the incident absorbed energy and Q_u to be the useful energy gain, thermal network shown in Fig. 12.3 (a) to the simplified form shown in Fig. 12.3 (b). The two networks will be equivalent subject to the relation between U_L and the other resistances shown in Fig. 12.3(a).

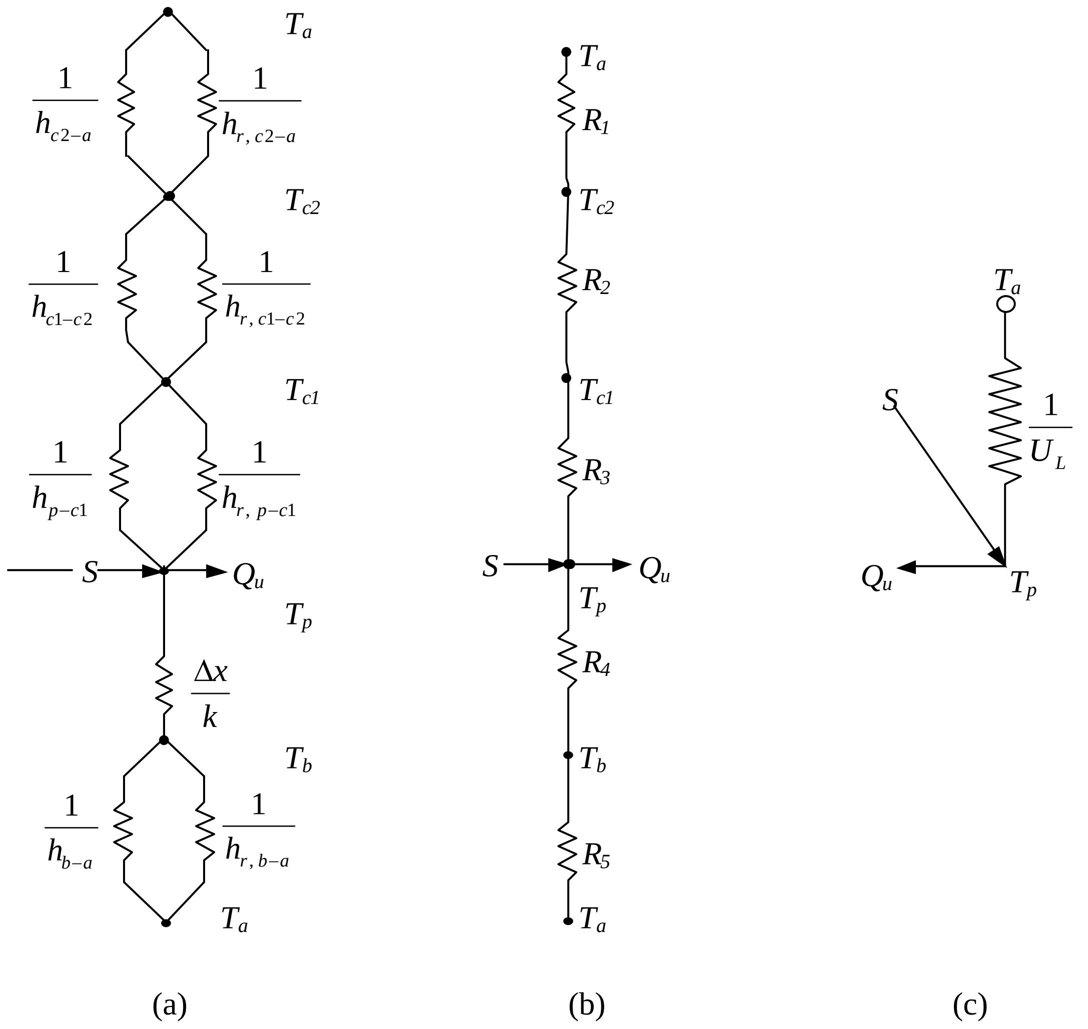

Fig. 12.3 Thermal network for a 2 cover flat plate collector a) in terms of conduction, convection and radiation b) in terms of equivalent resistances and c) simple equivalent circuit

12.5 COLLECTOR OVERALL HEAT LOSS COEFFICIENT

The glass covers are at temperatures T_{C1} and T_{C2}. The emissivities of the plate, and the covers are ε_P and ε_{C1} and ε_{C2} respectively.

$$q_{loss,top} = h_{p-c1}\left(T_p - T_{c1}\right) + \frac{\sigma\left(T_p^4 - T_{c1}^4\right)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1} \qquad (12.4)$$

Eq.(12.4) can be rewritten as,

$$q_{loss,top} = \left(h_{p-c1} + h_{r,p-c1}\right)\left(T_p - T_{c1}\right) \tag{12.5}$$

where, $h_{r,p-c1}$ is the radiative heat transfer coefficient between the plate and the glass cover 1, defined by,

$$h_{r,p-c1} = \frac{\sigma\left(T_p + T_{c1}\right)\left(T_p^2 + T_{c1}^2\right)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1} \tag{12.6}$$

Thus the resistance R_3 can be expressed by,

$$R_3 = \frac{1}{h_{p-c1} + h_{r,p-c1}} \tag{12.7}$$

The resistance from the top cover to surroundings has the same form as Eq.(12.7), but the convection heat transfer coefficient is for wind blowing across the collector. The wind heat transfer coefficient can be calculated from,

$$h_w = 5.7 + 3.8V \tag{12.8}$$

(McAdams [30], Heat Transmission 3rd Ed., McGraw-Hill, 1954)

In Eq.(12.8) h_w is in W/m^2C and the wind velocity V, is in *m/s*. More recent relation is due to Watmuff et al [31],

$$h_w = 2.8 + 3.0V \tag{12.9}$$

In Eq. (12.9) also the units of h_w and V are W/m^2C and *m/s* respectively. The radiation loss from the top cover takes place to an effective sky temperature and hence the radiative heat transfer coefficient from cover 2 to the ambient, $h_{r,c2-a}$ is given by,

$$h_{r,c2-a} = \varepsilon_c \frac{\sigma\left(T_{c2} + T_s\right)\left(T_{c2}^2 + T_s^2\right)\left(T_{c2} - T_s\right)}{T_{c2} - T_a} \tag{12.10}$$

T_s in Eq.(12.10) is the effective sky temperature given by,

$$T_s = 0.0552 T_a^{1.5} \tag{12.11}$$

In Eq.(12.10) both T_s and T_a are expressed in Kelvin. The resistance R_1 can now be expressed as,

$$R_1 = \frac{1}{h_w + h_{r,c2-a}} \tag{12.12}$$

Similarly, R_2 is related by,

$$R_2 = \frac{1}{h_{c1-c2} + h_{r,c1-c2}} \tag{12.13}$$

where h_{c1-c2} is the convective heat transfer coefficient between the two covers and $h_{r,c1-c2}$ is the radiative heat transfer coefficient between the two covers, expressed in terms of the cover temperature T_{c1} and T_{c2} along with the emissivities as,

$$h_{r,c1-c2} = \frac{\sigma (T_{c1} + T_{c2})(T_{c1}^2 + T_{c2}^2)}{\frac{1}{\varepsilon_{c1}} + \frac{1}{\varepsilon_{c2}} - 1} \tag{12.14}$$

For this two cover system, the top loss coefficient, U_t can be calculated from,

$$U_t = \frac{1}{R_1 + R_2 + R_3} \tag{12.15}$$

The resistances R_4 and R_5 represent the two resistances in series for heat loss from the bottom. The bottom loss coefficient U_b is given by,

$$U_b = \frac{1}{R_4 + R_5} \tag{12.16}$$

R_4, the resistance to conduction through the bottom insulation is given by,

$$R_4 = \frac{L}{k} \tag{12.17}$$

L is the thickness of the insulation and *k* is the thermal conductivity. Usually R_5 the resistance to convection from the bottom of the collector is small and is negligible compared to R_4 and is often considered as zero. Thus, U_b is simply given by,

$$U_b = \frac{1}{R_4} = \frac{k}{L} \tag{12.17}$$

As can be seen from the expressions, U_t and U_b can be calculated by calculating the various resistances which are expressed in terms of the temperatures. The calculation of the overall heat transfer coefficient thus involves an iterative procedure. The calculation will be demonstrated through an example in the lecture class. The overall heat transfer coefficient U_L is related to the top and bottom loss coefficients by,

$$U_L = U_t + U_b \tag{12.19}$$

There will be exceptions to Eq. (12.19) for certain collector configurations, when the working fluid itself comes in contact with the collector covers which are losing heat.

12.6 ITERATIVE PROCEDURE FOR CALCULATING U_t

It is straight forward to calculate U_b as per Eq. (12.17). In order to estimate U_t, given the operating temperature of the absorber (plate) T_p, the temperatures T_{c1} and T_{c2},which, are a priori unknown, are required to estimate radiative and covective heat transfer coefficients. Thus, it becomes necessary to guess say, T_{c1} and correct according to certain criterion. Of course, the ambient temperature T_a is known meteorological information.

It is presumed that the relations needed to estimate the convective heat transfer coefficients, h_{p-c1}, h_{c1-c2} and h_{rc2-a} are known. The information, basically, the heat transfer coefficient between parallel plates, is available in any standard text book on Heat Transfer or Hand Book compilations. Of course, the relations for the wind heat heat loss coefficient h_w are given by Eqs. (12.8) or Eq. (12.9).

The Radiative heat transfer coefficients $h_{r,c1-c2}$ and $h_{r,c2-a}$ can be estimated only if the temperatures T_{c1} *and* T_{c2} are known. T_{c1} *and* T_{c2} depend on the Radiative and convective heat transfer. But, unless $h_{r,c1-c2}$ and $h_{r,c2-a}$ are known T_{c1} *and* T_{c2} can not be estimated and vice versa.

In other words the calculation of U_t is iterative. Even if T_p is assumed as a known operating condition.

The Iterative Procedure

1. Guess T_{c1}

Let it be, T_{c1}^{1}

2. Calculate

$$q_{loss,top}^{1} = \left(h_{p-c1} + h_{r,p-c1}^{1}\right)\left(T_p - T_{c1}^{1}\right)$$

3. Estimate T_{c2}^{1} by equating

$$q_{loss,top}^{1} = \left(h_{p-c1} + h_{r,p-c1}^{1}\right)\left(T_p - T_{c1}^{1}\right) = \left(h_{c1-c2} + h^{1}_{r,c1-c2}\right)\left(T_{c1}^{1} - T_{c2}^{1}\right)$$

4) Estimate $q_{loss,top}^{11}$ from,

$$q_{loss,top}^{11} = \left(h_w + h_{r,c2-a}\right)\left(T_{c2}^{1} - T_a\right)$$

In general $q_{loss,top}^{1} \neq q_{loss,top}^{11}$

5) If $$\frac{|\, q_{loss,top}^{1} - q_{loss,top}^{11} \,|}{q_{loss,top}^{1}} < 0.05,\ say,$$

$$T_{c1}^{1}\ and\ T_{c2}^{1}$$ are acceptable.

6) If $$\frac{|\,q_{loss,top}^{1}-q_{loss,top}^{11}\,|}{q_{loss,top}^{1}}>0.05,\ say,$$

Change

$$T_{c1}^{1}\ to\ T_{c1}^{2}\ where\ T_{c1}^{2}=T_{c1}^{1}\pm\Delta T$$

The choice of $\pm$ can be made depending on

$$\left(q_{loss,top}^{1}-q_{loss,top}^{11}\right)>0\ or\ \left(q_{loss,top}^{1}-q_{loss,top}^{11}\right)<0$$

7) REPEAT UNTIL

$$\frac{|\,q_{loss,top}^{1}-q_{loss,top}^{11}\,|}{q_{loss,top}^{1}}<0.05,$$

12.7 CORRELATION FOR U_t

Since the procedure to evaluate U_t is cumbersome involving an iterative procedure, Klein (Solar Energy, Vol.17, p.79, 1975) developed a correlation for U_t as,

$$U_t=\left\{\frac{N}{\frac{C}{T_{p,m}}\left[\frac{\left(T_{p,m}-T_a\right)}{\left(N+f\right)}\right]^{e}}+\frac{1}{h_w}\right\}^{-1}+\frac{\sigma\left(T_{p,m}+T_a\right)\left(T_{p,m}^{2}+T_a^{2}\right)}{\left(\varepsilon_p+0.00591Nh_w\right)^{-1}+\frac{2N+f-1+0.133\varepsilon_p}{\varepsilon_g}-N}$$

(12.20)

where

N = Number of glass covers

$$f = \left(1 + 0.089h_w - 0.1166h_w\varepsilon_p\right)\left(1 + 0.07866N\right) \quad (12.20\ a)$$

$$C = 520\left(1 - 0.000051\beta^2\right) \quad for\ \ 0^0 < \beta < 70^0.$$

$$For\ 70 < \beta < 90,\ Use\ \ \beta = 70^0 \quad (12.20\ b)$$

$$e = 0.43\left(1 - 100/T_{p,m}\right) \quad (12.20\ c)$$

β = collector tilt, degrees

T_a = ambient temperature (K)

$T_{p,m}$ = mean plate temperature (K)

h_w = wind heat transfer coefficient, W/m^2C