EN671: Solar Energy Conversion Technology

Flat Plate Collectors

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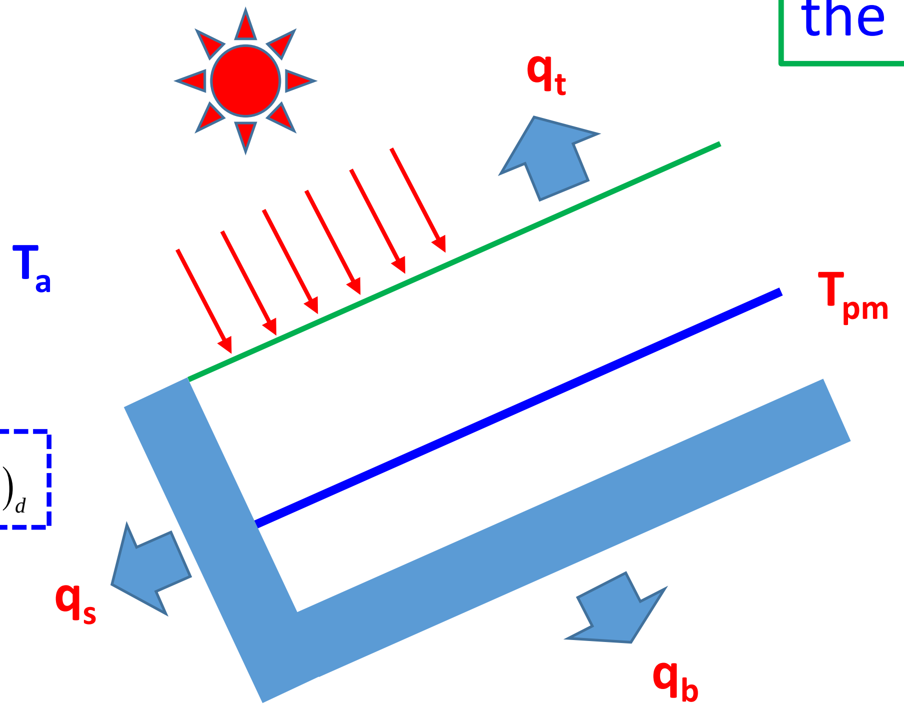
Collector Losses and loss estimation

Collector losses

Energy Balance on the absorber plate

$$q_u = A_p S - q_l$$

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



Heat lost from the collector

$$q_l = U_l A_p (T_{pm} - T_a)$$

U_l = Over all loss coefficient

A_p = Area of the absorber plate

T_{pm} = Average temperature of the absorber plate

T_a =Temperature of the surrounding air

Heat lost from the collector is the sum of heat lost from the top, the bottom and the sides

$$q_l = q_t + q_b + q_s$$

Loss coefficients

Each of the losses is also expressed in terms of coefficients

- ✓ Rate at which heat is lost from the top
- ✓ Rate at which heat is lost from the bottom
- ✓ Rate at which heat is lost from the side

$$q_t = U_t A_p \left(T_{pm} - T_a\right)$$

$$q_b = U_b A_p \left(T_{pm} - T_a\right)$$

$$q_s = U_s A_p \left(T_{pm} - T_a\right)$$

$$q_l = q_t + q_b + q_s$$

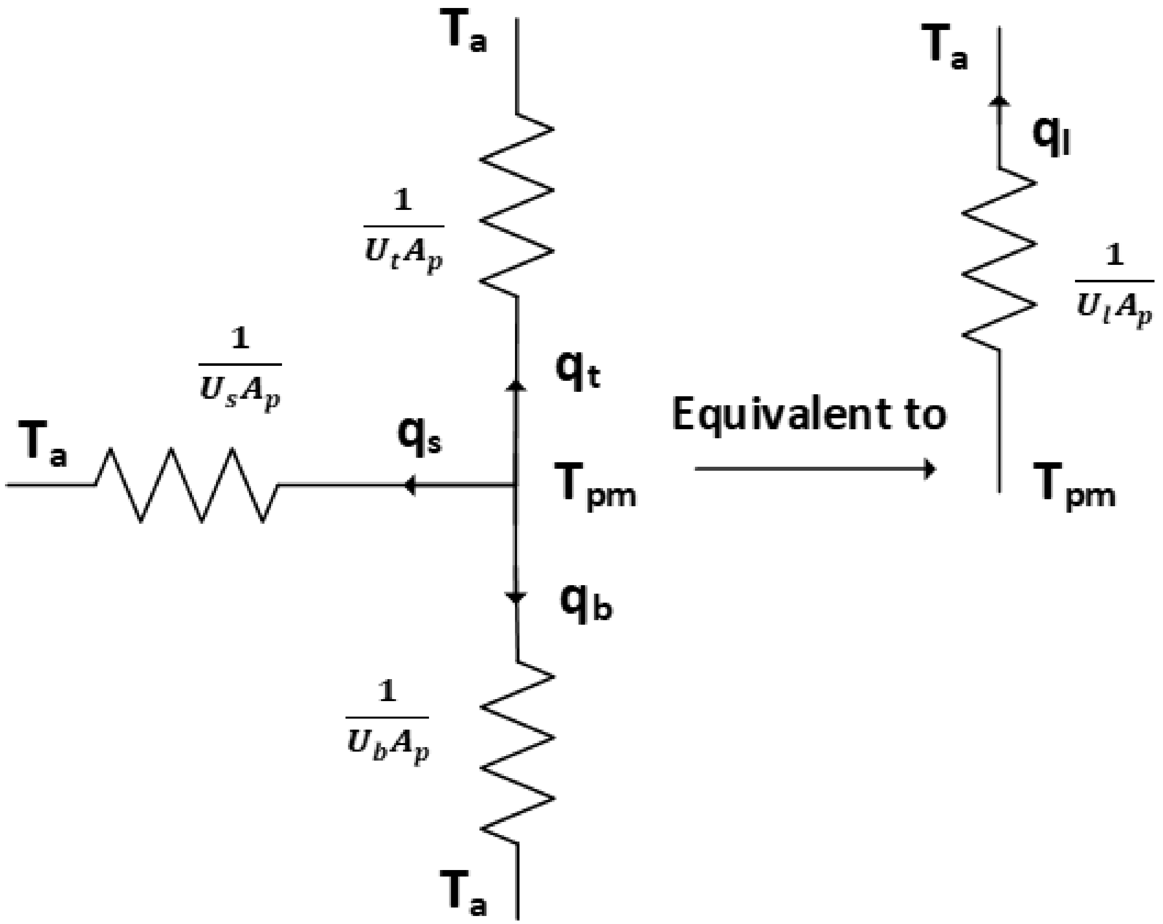
- U_t ✓ Top loss coefficient
- U_b ✓ Bottom loss coefficient
- U_s ✓ Side loss coefficient

Definition of each of the coefficients is based on the area A_p and the temperature difference (T_{pm}-T_a)

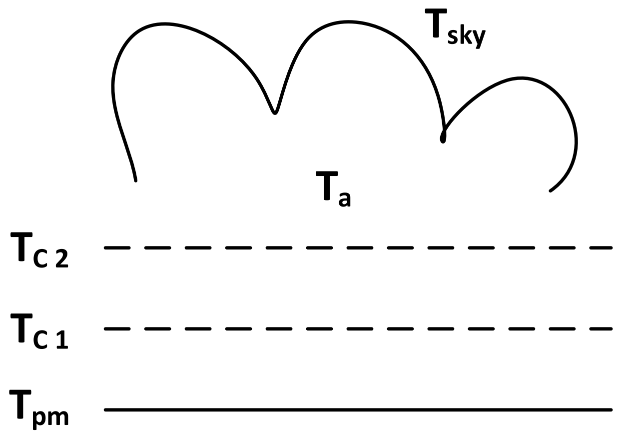
The overall loss coefficient : $U_l = U_t + U_b + U_s$

- ✓ The overall loss coefficient is a measure of all the losses.
- ✓ Its value should be in the range of 2 to 10 W/m^2-K

Thermal Resistance Network



Top loss coefficient



- **Evaluated by considering convection and re-radiation losses from the absorber plate in the upward direction.**

Assumption:

- The transparent covers and the absorber plate constitute a system of infinite parallel surfaces.
- The flow of heat is one dimensional and steady.
- Temperature drop across the thickness of the covers is negligible
- The interaction between the incoming solar radiation absorbed by the covers and the outgoing loss may be neglected.
- The transparent cover is assumed to be opaque.

Heat transferred by convection and radiation absorber plate and first cover

$$\frac{q_t}{A_p} = h_{p-c_1}(T_{pm} - T_{c1}) + \frac{\sigma(T_{pm}^{\,4} - T_{c1}^{\,4})}{\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1\right)}$$

First cover and 2nd cover

$$\frac{q_t}{A_p} = h_{c1-c2}(T_{c1} - T_{c2}) + \frac{\sigma(T_{c1}^{\,4} - T_{c2}^{\,4})}{\left(\frac{1}{\varepsilon_c} + \frac{1}{\varepsilon_c} - 1\right)}$$

2nd cover and surroundings

$$\frac{q_t}{A_p} = h_w\left(T_{c2} - T_{sky}\right) + \sigma\varepsilon_c\left(T_{c2}^4 - T_{sky}^4\right)$$

Heat Transfer coefficient between inclined parallel surfaces

- Buchberg *et al.* developed the following correlations based on the experimental investigation of natural convection heat transfer coefficient for the enclosed space *(between the absorber plate to the first cover and the first cover to the second cover).*

$$Nu = 1; \text{ for } Ra\cos\beta < 1708$$

$$Nu = 1 + 1.446\left[1 - \frac{1708}{Ra\cos\beta}\right] \quad \text{for } 1708 < Ra\cos\beta < 5900$$

$$Nu = 0.229(Ra\cos\beta)^{0.252} \quad \text{for } 5900 < Ra\cos\beta < 9.23\times10^{4}$$

$$Nu = 0.157(Ra\cos\beta)^{0.285} \quad \text{for } 9.23\times10^{4} < Ra\cos\beta < 10^{6}$$

Properties are to be evaluated at the arithmetic mean of the surface temperatures

Heat Transfer coefficient at the top cover (wind heat transfer coefficient)

- McAdams correlations:

$$\boxed{h_w = 5.7 + 3.8V_{\propto}}$$

- Correlations developed by Test et al. :

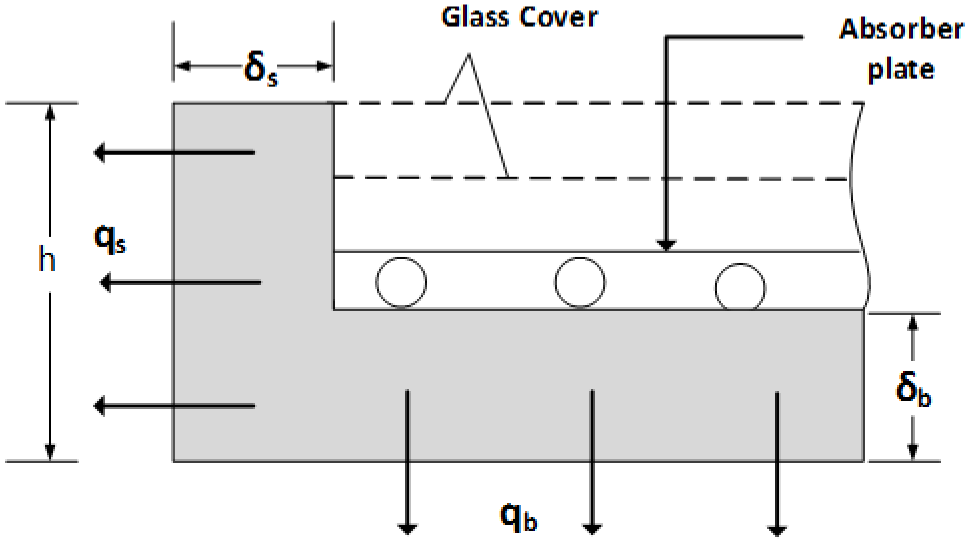
$$\boxed{h_w = 8.55 + 2.56V_{\propto}}$$

- Sky temperature:

$$\boxed{T_{sky} = T_a - 6}$$

Bottom Loss coefficient

- Evaluated by considering conduction convection losses from the absorber plate towards downward
- Assumptions: (1)Flow of heat is one dimensional and steady, (2)Thermal resistance associated with conduction dominates



$$\boxed{U_b = \frac{k_i}{\delta_b} = \frac{\text{Thermal conductivity of the insulation}}{\text{Thickness of insulation}}}$$

k_i = Thermal conductivity of the insulation

δ_b = Thickness of Insulation

Side loss coefficient

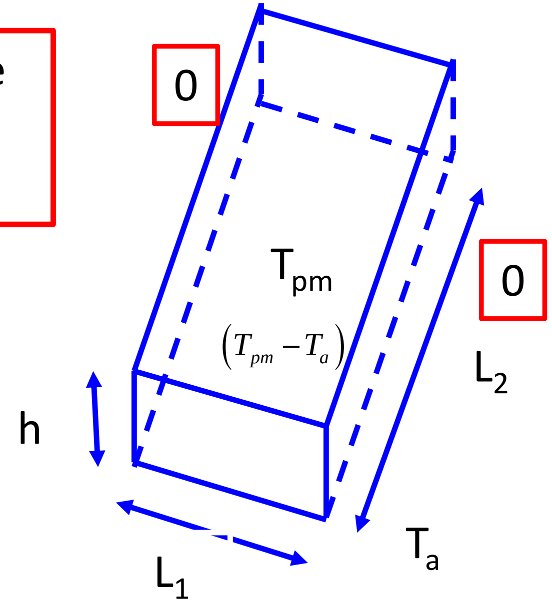
$$\boxed{q_s = U_s A_p \left(T_{pm} - T_a\right)}$$

Average temperature drop across the side insulation

- ✓ Conduction resistance dominates
- ✓ Flow of heat is one dimensional and steady

$$q_s = 2 \times h \times \left(L_1 + L_2\right) \times k_i \frac{\left(T_{pm} - T_a\right)}{2\delta_s}$$

$$A_p = L_1 \times L_2$$



$$U_s = \frac{q_s}{A_p\left(T_{pm} - T_a\right)} = \frac{2h\left(L_1 + L_2\right)k_i \dfrac{\left(T_{pm} - T_a\right)}{2\delta_s}}{L_1 \times L_2 \left(T_{pm} - T_a\right)}$$

$$\Rightarrow U_s = \frac{(L_1 + L_2)hk_i}{L_1 L_2 \delta_s}$$

$A = 2L_2*h+2L_1*h = 2(L_2*h+L_1*h)$

Ex.1: For a FPC with a top-loss coefficient of 6.6 W/m² °C, determine the overall loss coefficient by using following data:

- Back insulation thickness = 0.045 m
- Thermal conductivity of insulation = 0.04 W/m² °C
- Collector bank length = 8 m
- Collector bank width = 2.5 m
- Collector thickness = 0.08 m
- Edge insulation thickness = 0.02 m

$$\boxed{U_b = \frac{k_i}{\delta_b} = \frac{0.04}{0.045} = 0.889 \text{ W/m}^2.^{\text{o}}\text{C}}$$

$$\boxed{U_s = \frac{(L_1 + L_2)hk_i}{L_1 L_2 \delta_s} = \frac{(8+2.5)0.08\times 0.04}{8\times 2.5\times 0.02} = 0.084 \text{ W/m}^2 \, ^{\text{o}}\text{C}}$$

$$\boxed{U_l = U_t + U_b + U_s = 6.6 + 0.889 + 0.084 = 7.573 \text{ W/m}^2.^{\text{o}}\text{C}}$$

Ex.1: Calculate the overall loss coefficient for a flat-plate collector with two glass covers. The following data is given: (a) size of the absorber plate: 1.90 m x 0.90 m, (b) spacing between plate and first glass cover: 5 cm, (c) spacing between first and second glass cover: 5 cm, (d) plate emissivity : 0.90, (e) glass cover emissivity: 0.85, (f) collector tilt: 23 ^{o}, (g) Mean plate temperature: 73 ^{o}C, (h) Ambient air temperature: 25 ^{o}C, (i) wind speed : 2.7 m/s, (j) Back insulation thickness: 10 cm, (k) side insulation thickness: 5 cm, (l) thermal conductivity of insulation: 0.07 W/m-K. Use the appropriate correlation from the correlation Table-1. The properties of air is given in Table-2.

Table-1 Correlation table

$$Nu = 1 + 1.446\left[1 - \frac{1708}{Ra\cos\beta}\right] \quad \text{for } 1708 < Ra\cos\beta < 5900$$

$$Nu = 0.229(Ra\cos\beta)^{0.252} \quad \text{for } 5900 < Ra\cos\beta < 9.23\times10^4$$

$$Nu = 0.157(Ra\cos\beta)^{0.285} \quad \text{for } 9.23\times10^4 < Ra\cos\beta < 10^6$$

$$T_{sky} = T_a - 6$$

$$h_w = 5.7 + 3.8V_\infty$$

Table 2 Properties of air

Properties of air at 1 atm pressure

Temp. T, °C	Density ρ, kg/m³	Specific Heat c_p J/kg·K	Thermal Conductivity k, W/m·K	Thermal Diffusivity α, m²/s	Dynamic Viscosity μ, kg/m·s	Kinematic Viscosity ν, m²/s	Prandtl Number Pr
−150	2.866	983	0.01171	4.158×10^{-6}	8.636×10^{-6}	3.013×10^{-6}	0.7246
−100	2.038	966	0.01582	8.036×10^{-6}	1.189×10^{-6}	5.837×10^{-6}	0.7263
−50	1.582	999	0.01979	1.252×10^{-5}	1.474×10^{-5}	9.319×10^{-6}	0.7440
−40	1.514	1002	0.02057	1.356×10^{-5}	1.527×10^{-5}	1.008×10^{-5}	0.7436
−30	1.451	1004	0.02134	1.465×10^{-5}	1.579×10^{-5}	1.087×10^{-5}	0.7425
−20	1.394	1005	0.02211	1.578×10^{-5}	1.630×10^{-5}	1.169×10^{-5}	0.7408
−10	1.341	1006	0.02288	1.696×10^{-5}	1.680×10^{-5}	1.252×10^{-5}	0.7387
0	1.292	1006	0.02364	1.818×10^{-5}	1.729×10^{-5}	1.338×10^{-5}	0.7362
5	1.269	1006	0.02401	1.880×10^{-5}	1.754×10^{-5}	1.382×10^{-5}	0.7350
10	1.246	1006	0.02439	1.944×10^{-5}	1.778×10^{-5}	1.426×10^{-5}	0.7336
15	1.225	1007	0.02476	2.009×10^{-5}	1.802×10^{-5}	1.470×10^{-5}	0.7323
20	1.204	1007	0.02514	2.074×10^{-5}	1.825×10^{-5}	1.516×10^{-5}	0.7309
25	1.184	1007	0.02551	2.141×10^{-5}	1.849×10^{-5}	1.562×10^{-5}	0.7296
30	1.164	1007	0.02588	2.208×10^{-5}	1.872×10^{-5}	1.608×10^{-5}	0.7282
35	1.145	1007	0.02625	2.277×10^{-5}	1.895×10^{-5}	1.655×10^{-5}	0.7268
40	1.127	1007	0.02662	2.346×10^{-5}	1.918×10^{-5}	1.702×10^{-5}	0.7255
45	1.109	1007	0.02699	2.416×10^{-5}	1.941×10^{-5}	1.750×10^{-5}	0.7241
50	1.092	1007	0.02735	2.487×10^{-5}	1.963×10^{-5}	1.798×10^{-5}	0.7228
60	1.059	1007	0.02808	2.632×10^{-5}	2.008×10^{-5}	1.896×10^{-5}	0.7202
70	1.028	1007	0.02881	2.780×10^{-5}	2.052×10^{-5}	1.995×10^{-5}	0.7177
80	0.9994	1008	0.02953	2.931×10^{-5}	2.096×10^{-5}	2.097×10^{-5}	0.7154
90	0.9718	1008	0.03024	3.086×10^{-5}	2.139×10^{-5}	2.201×10^{-5}	0.7132
100	0.9458	1009	0.03095	3.243×10^{-5}	2.181×10^{-5}	2.306×10^{-5}	0.7111
120	0.8977	1011	0.03235	3.565×10^{-5}	2.264×10^{-5}	2.522×10^{-5}	0.7073
140	0.8542	1013	0.03374	3.898×10^{-5}	2.345×10^{-5}	2.745×10^{-5}	0.7041
160	0.8148	1016	0.03511	4.241×10^{-5}	2.420×10^{-5}	2.975×10^{-5}	0.7014
180	0.7788	1019	0.03646	4.593×10^{-5}	2.504×10^{-5}	3.212×10^{-5}	0.6992
200	0.7459	1023	0.03779	4.954×10^{-5}	2.577×10^{-5}	3.455×10^{-5}	0.6974
250	0.6746	1033	0.04104	5.890×10^{-5}	2.760×10^{-5}	4.091×10^{-5}	0.6946
300	0.6158	1044	0.04418	6.871×10^{-5}	2.934×10^{-5}	4.765×10^{-5}	0.6935
350	0.5664	1056	0.04721	7.892×10^{-5}	3.101×10^{-5}	5.475×10^{-5}	0.6937
400	0.5243	1069	0.05015	8.951×10^{-5}	3.261×10^{-5}	6.219×10^{-5}	0.6948
450	0.4880	1081	0.05298	1.004×10^{-4}	3.415×10^{-5}	6.997×10^{-5}	0.6965
500	0.4565	1093	0.05572	1.117×10^{-4}	3.563×10^{-5}	7.806×10^{-5}	0.6986
600	0.4042	1115	0.06093	1.352×10^{-4}	3.846×10^{-5}	9.515×10^{-5}	0.7037

Top loss coefficient:

$$\frac{q_t}{A_p} = h_{p-c_1}(T_{pm} - T_{c1}) + \frac{\sigma(T_{pm}{}^4 - T_{c1}{}^4)}{\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_c} - 1\right)}$$

$$\frac{q_t}{A_p} = h_{c1-c2}(T_{c1} - T_{c2}) + \frac{\sigma(T_{c1}{}^4 - T_{c2}{}^4)}{\left(\frac{1}{\varepsilon_c} + \frac{1}{\varepsilon_c} - 1\right)}$$

$$\frac{q_t}{A_p} = h_w\left(T_{c2} - T_{sky}\right) + \sigma\varepsilon_c\left(T_{c2}^4 - T_{sky}^4\right)$$

T_{c1} (K)	T_{c2} (K)	q_t/A_p Eq.(1)	q_t/A_p Eq.(2)	q_t/A_p Eq.(3)	Average W/m^2
328	306	167.498	176.803	196.749	180.350
327	305	176.925	175.391	175.293	175.869

Empirical equation for top loss coefficient

Klein

$$U_t = \left[\frac{M}{\left(\frac{C}{T_{pm}}\right)\left(\frac{T_{pm}-T_a}{M+f}\right)^{0.33}} + \frac{1}{h_w} \right]^{-1} + \left[\frac{\sigma(T^2_{pm} - T^2_{a})(T_{pm} - T_a)}{\frac{1}{\varepsilon_p + 0.005M(1-\varepsilon_p)} + \frac{(2M+f-1)}{\varepsilon_c} - M} \right]$$

$320 \le T_{pm} \le 420\text{K}$

$260 \le T_a \le 310\text{K}$

$0.1 \le \varepsilon_p \le 0.95$

$0 \le V_\infty \le 10 \text{ m/s}$

$1 \le M \le 3$

$0 \le \beta \le 90^\circ$

$$\text{where } f = (1 - 0.04h_w + 0.0005h^2_w)(1 + 0.091M)$$

$$C = 365.9(1 - 0.00883\beta + 0.0001298\beta^2)$$

$$M = \text{number of glass covers}$$

Malhotra et al.

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

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

$$C = 204.429\cos\beta)^{0.25} / L^{0.24}$$

$$L = \text{Spacing (m)}$$

Summary

- Heat lost from the collector
- Loss coefficients
  - Top loss
  - Bottom loss
  - Side loss
  - Overall loss coefficient
- Solved problems how to calculate losses associated with FPC
  - Iterative technique
  - Use of correlations

Thank you