Thermal Analysis of Solar Collectors

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European Cooperation in the field of Scientific and Technical Research
Building Integration of Solar Thermal Systems – TU1205 – BISTS

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Types of solar collectors

Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (°C)
Stationary	Flat plate collector (FPC)	Flat	1	30-80
	Evacuated tube collector (ETC)	Flat	1	50-200
	Compound parabolic collector (CPC)	Tubular	1-5	60-240
Single-axis tracking			5-15	60-300
	Linear Fresnel reflector (LFR)	Tubular	10-40	60-250
	Parabolic trough collector (PTC)	Tubular	15-45	60-300
	Cylindrical trough collector (CTC)	Tubular	10-50	60-300
Two-axes tracking	Parabolic dish reflector (PDR)	Point	100-1000	100-500
	Heliostat field collector (HFC)	Point	100-1500	150-2000

Note: Concentration ratio is defined as the aperture area divided by the receiver/absorber area of the collector.

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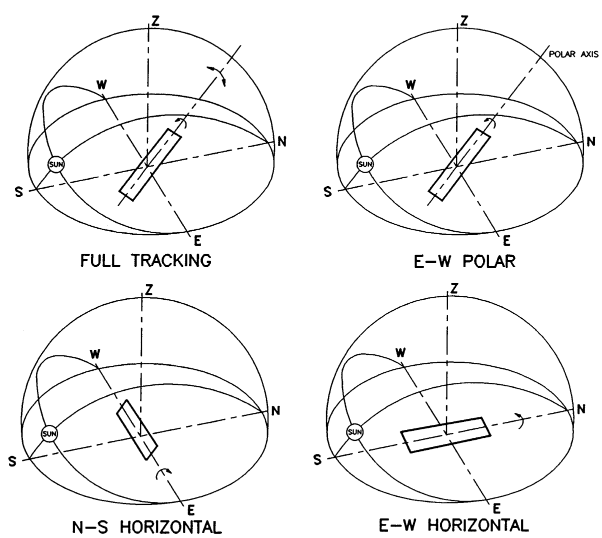

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Comparison of energy absorbed for various modes of tracking

Tracking mode	Solar energy (kWh/m²)			Percent to full tracking		
	E	SS	WS	E	SS	WS
Full tracking	8.43	10.60	5.70	100.0	100.0	100.0
E-W Polar	8.43	9.73	5.23	100.0	91.7	91.7
N-S Horizontal	6.22	7.85	4.91	73.8	74.0	86.2
E-W Horizontal	7.51	10.36	4.47	89.1	97.7	60.9

Note: E - Equinoxes, SS - Summer Solstice, WS - Winter Solstice

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Stationary collectors

No concentration

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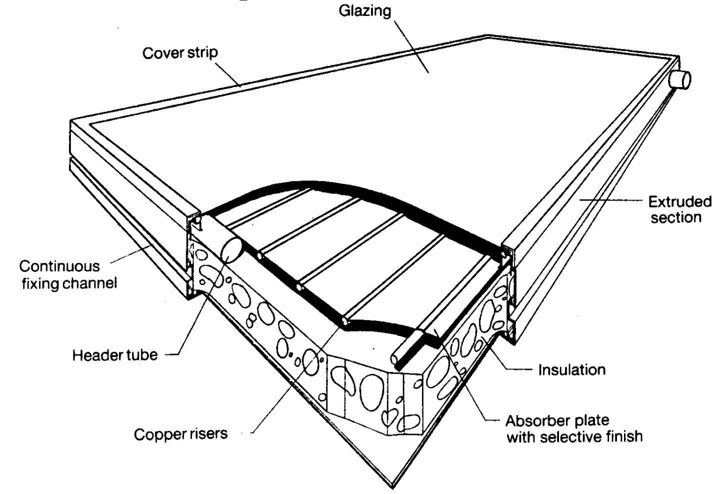
Flat-plate collector



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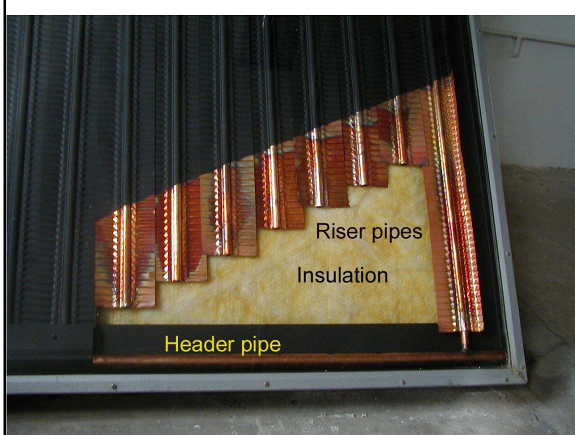
Flat-plate Collector



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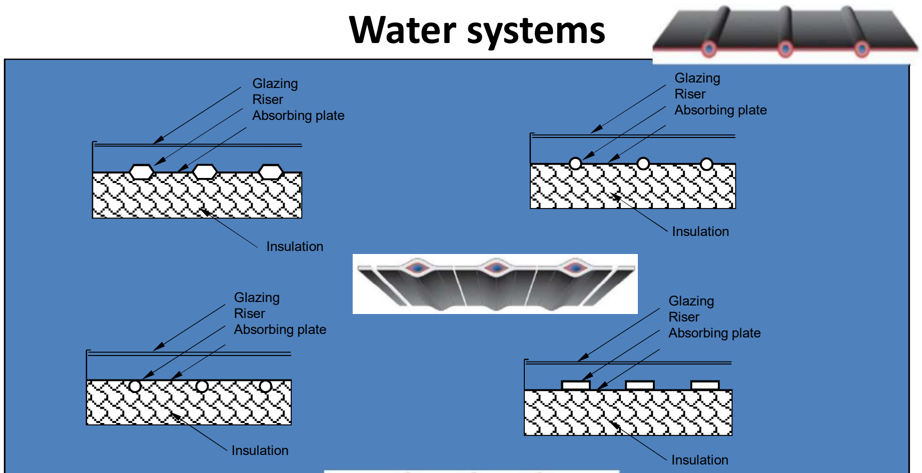
Types of flat-plate collectors
Water systems



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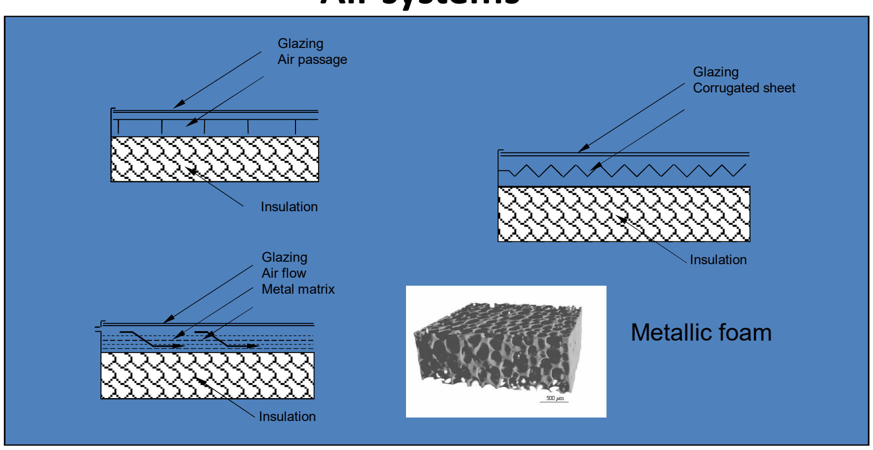
Types of flat-plate collectors
Air systems



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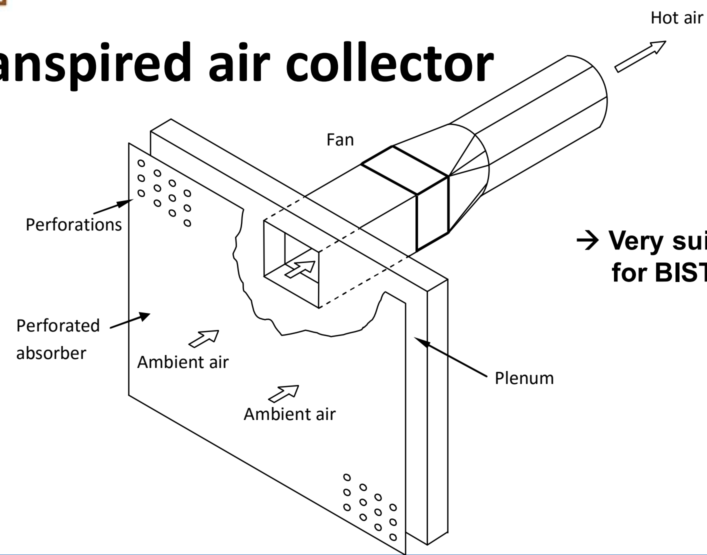
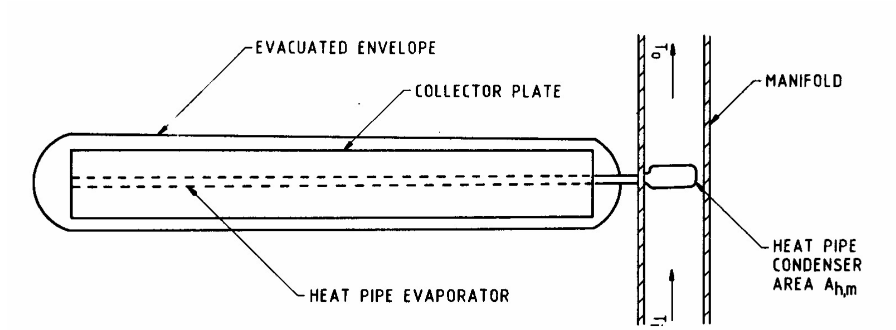
Transpired air collector

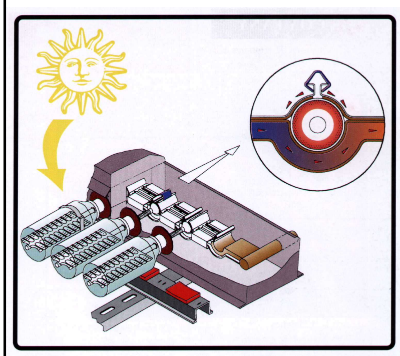


→ **Very suitable for BISTS**

Schematic diagram of an evacuated tube collector



Evacuated tube collectors



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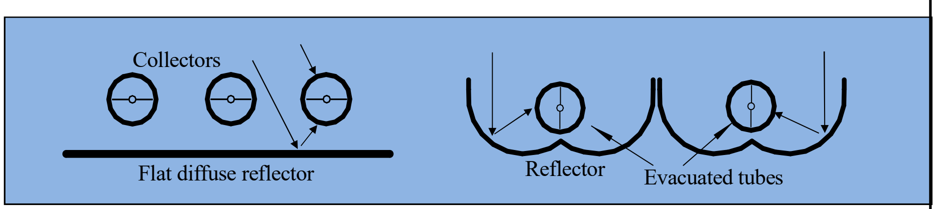
Enhancent of collectors



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Stationary collectors

Concentrating

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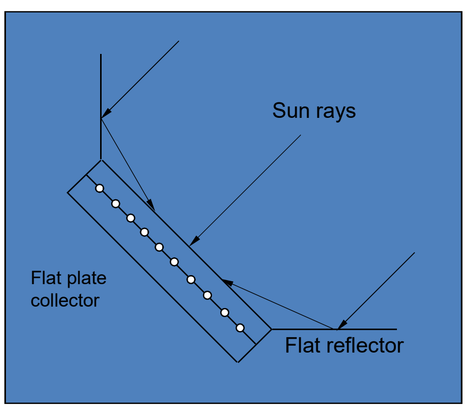
Flat plate collector with flat reflectors



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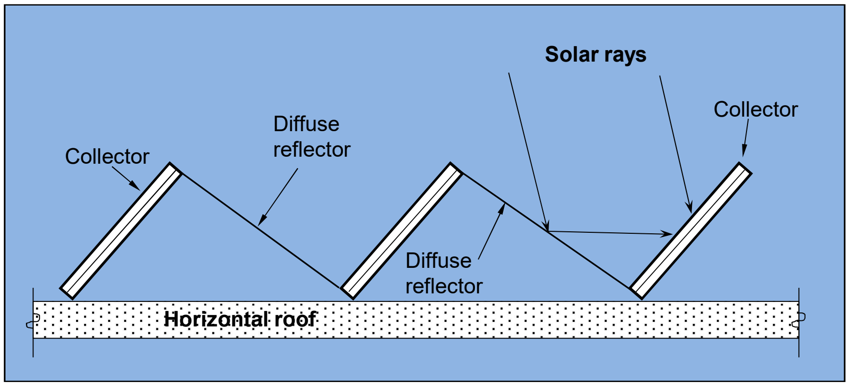
Saw-tooth arrangement



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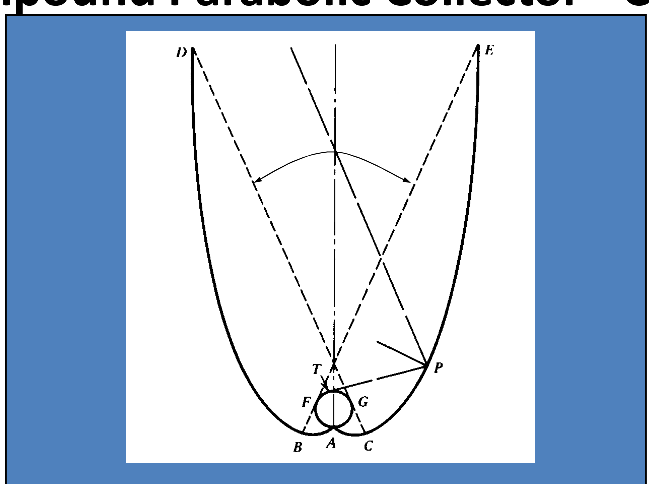
Compound Parabolic Collector - CPC



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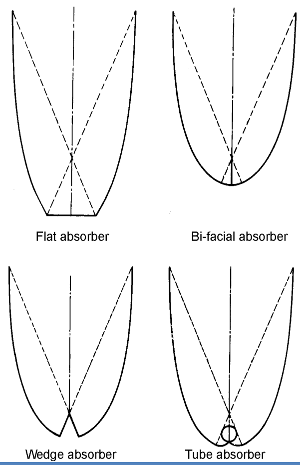
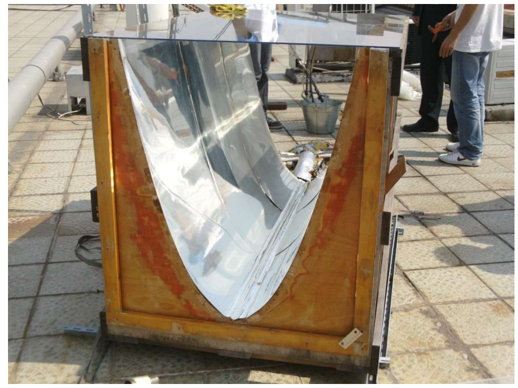
CPC types





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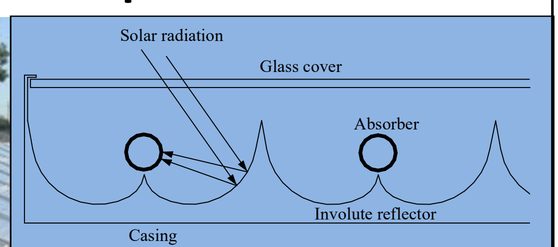
Application as flat plate collector



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Sun tracking collectors

Concentrating

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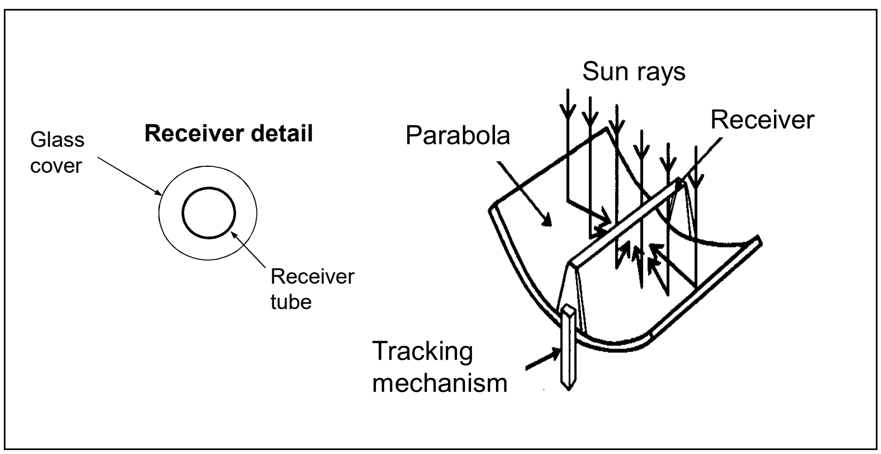
Schematic of a parabolic trough collector



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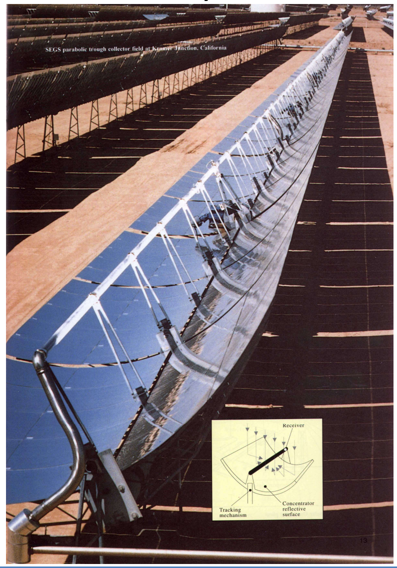
Parabolic trough collectors



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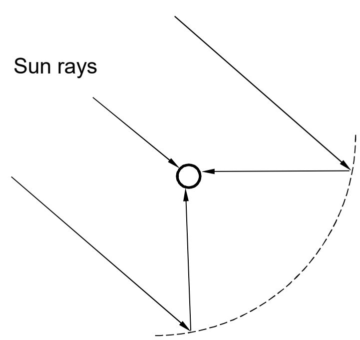
Fresnel type parabolic trough collector



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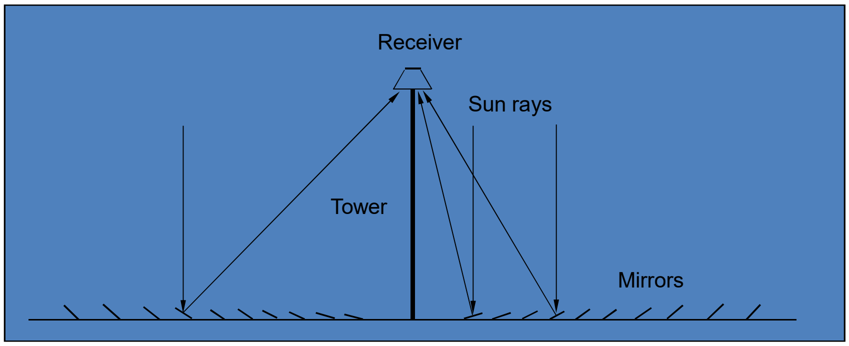
Schematic diagram of a downward facing receiver illuminated from a Linear Fresnel Reflector (LFR) field



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Schematic diagram showing interleaving of mirrors in a CLFR with reduced shading between mirrors

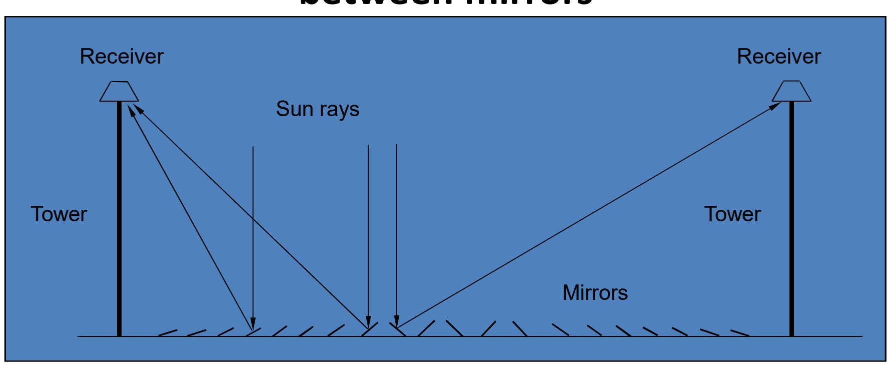

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Photo of Fresnel system

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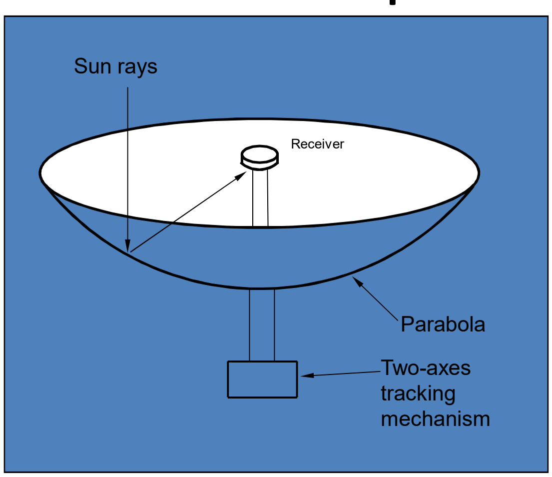
Schematic of a parabolic dish collector



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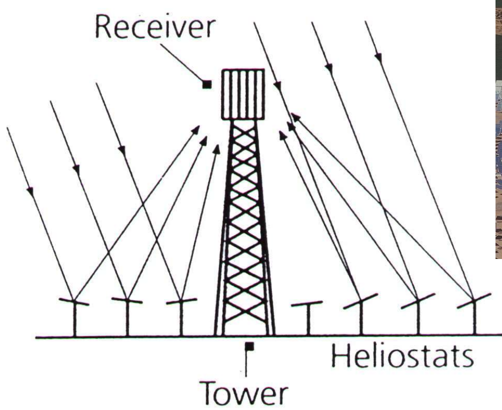
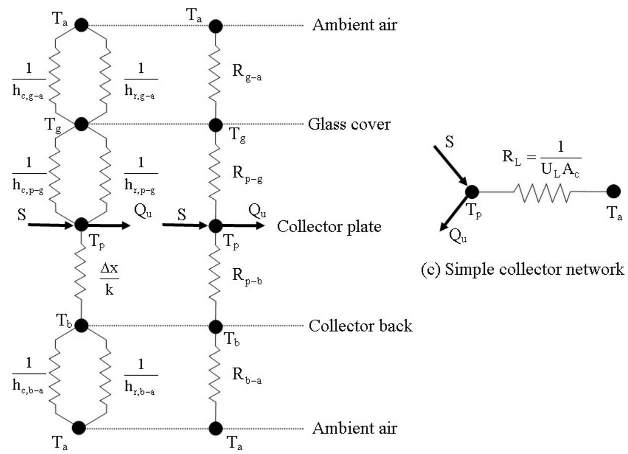
Schematic of central receiver system



Thermal analysis of collectors

Flat-plate collector thermal losses



(a) Heat transfer network (b) Resistance network

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Flat-plate collector thermal losses

- From the simple thermal network the collector thermal losses are:

$$Q_{loss} = \frac{T_p - T_a}{R_L} = U_L A_c (T_p - T_a)$$

- The total heat loss coefficient U_L is given by:

  $U_L = U_t + U_b + U_e$ (top, back, edges)

- The various relations can be obtained from basic heat transfer analysis

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Empirical relation

- This relation gives adequate accuracy:

$$U_t = \frac{1}{\dfrac{N_g}{\dfrac{C}{T_p}\left[\dfrac{T_p - T_a}{N_g + f}\right]^{0.33} + \dfrac{1}{h_w}}} + \frac{\sigma\left(T_p^2 + T_a^2\right)\left(T_p + T_a\right)}{\dfrac{1}{\varepsilon_p + 0.05N_g\left(1-\varepsilon_p\right)} + \dfrac{2N_g + f - 1}{\varepsilon_g} - N_g}$$

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- Where:

$$f = \left(1 - 0.04h_w + 0.0005h_w^2\right)\left(1 + 0.091N_g\right)$$

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

$$h_w = \frac{8.6V^{0.6}}{L^{0.4}}$$

- The minimum value of wind heat loss coefficient, h_w for still air is 5 W/m²K, so if above equation gives a lower value we use this value as a minimum.

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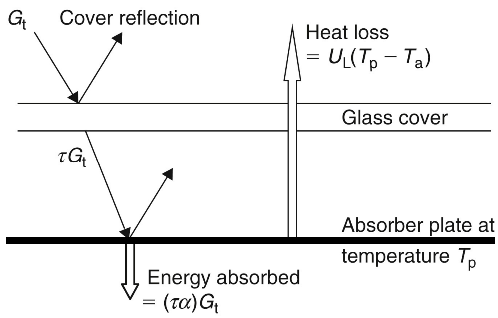
Useful energy collected from a flat plate collector



- In the form of equation this is given by:

$$Q_u = A_c\left[G_t(\tau\alpha) - U_L\left(T_p - T_a\right)\right] = \dot{m}c_p\left[T_o - T_i\right]$$

Useful energy collected from a collector-Flat plate

- General formula:

$$Q_u = A_c\left[G_t(\tau\alpha) - U_L\left(T_p - T_a\right)\right] = mc_p\left[T_o - T_i\right]$$

- by substituting inlet fluid temperature (T_i) for the average plate temperature (T_p):

$$Q_u = A_c F_R\left[G_t(\tau\alpha) - U_L\left(T_i - T_a\right)\right]$$

  – Where F_R is the heat removal factor

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Heat removal factor

- Heat removal factor represents the ratio of the actual useful energy gain that would result if the collector-absorbing surface had been at the local fluid temperature.
- Equation:

$$F_R = \frac{\dot{m}c_p}{A_c U_L}\left(1 - \mathrm{Exp}\left[-\frac{U_L F' A_c}{\dot{m}c_p}\right]\right)$$

F′=collector efficiency factor

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Collector efficiency

- Finally, the collector efficiency can be obtained by dividing Q_u by (G_t A_c). Therefore:

$$\eta = F_R\left[(\tau\alpha) - \frac{U_L(T_i - T_a)}{G_t}\right]$$

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Concentration ratio

- The concentration ratio (C) is defined as the ratio of the aperture area to the receiver/absorber area, i.e.:

$$C = \frac{A_a}{A_r}$$

- For flat-plate collectors with no reflectors, C=1. For concentrators C is always greater than 1. For a single axis tracking collector the maximum possible concentration is given by:

$$C_{\max} = \frac{1}{\sin(\theta_m)}$$

- and for two-axes tracking collector:

$$C_{\max} = \frac{1}{\sin^2(\theta_m)}$$

where θ_m is the half acceptance angle limited by the size of the sun's disk, small scale errors and irregularities of the reflector surface and tracking errors.

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Maximum concentration

- For a perfect collector and tracking system C_{max} depends only on the sun's disk which has a width of 0.53° (32′). Therefore:
- For single axis tracking:

  C_{max} = 1/sin(16′) = 216
- For full tracking:

  C_{max} = 1/sin^2(16′) = 46,747

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Concentrating collectors

- The useful energy delivered from a concentrator is:

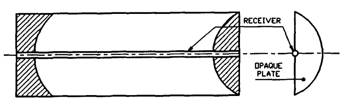
$$Q_u = G_b \eta_o A_a - A_r U_L \left(T_r - T_a\right)$$

- Where n_o is the optical efficiency given by:

$$\eta_o = \rho\tau\alpha\gamma\left[\left(1 - A_f \tan(\theta)\right)\cos(\theta)\right]$$

- And A_f is the geometric factor given by:

$$A_f = \frac{2}{3}W_a h_p + fW_a\left[1 + \frac{W_a^2}{48f^2}\right]$$



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Concentrating collectors efficiency

- Similarly as for the flat-plate collector the heat removal factor can be used:

$$Q_u = F_R\left[G_b \eta_o A_a - A_r U_L \left(T_i - T_a\right)\right]$$

- And the collector efficiency can be obtained by dividing Q_u by ($G_b A_a$):

$$n = F_R\left[\eta_o - U_L\left(\frac{T_i - T_a}{G_b C}\right)\right]$$

Note C in the denominator

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PERFORMANCE OF SOLAR COLLECTORS

- The thermal performance of the solar collector is determined by obtaining:
  - Values of instantaneous efficiency for different combinations of incident radiation, ambient temperature, and inlet fluid temperature.
  - The variation of steady-state thermal efficiency with incident angles between the direct beam and the normal to collector aperture area at various sun and collector positions (incidence angle modifier).
  - The transient thermal response characteristics of the collector (time constant).

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Collector efficiency

- For flat-plate collectors:

$$\eta = F_R(\tau\alpha) - F_R U_L \left(\frac{T_i - T_a}{G_t} \right)$$

- For concentrating collectors:

$$\eta = F_R \eta_o - \frac{F_R U_L}{C} \frac{(T_i - T_a)}{G_b}$$

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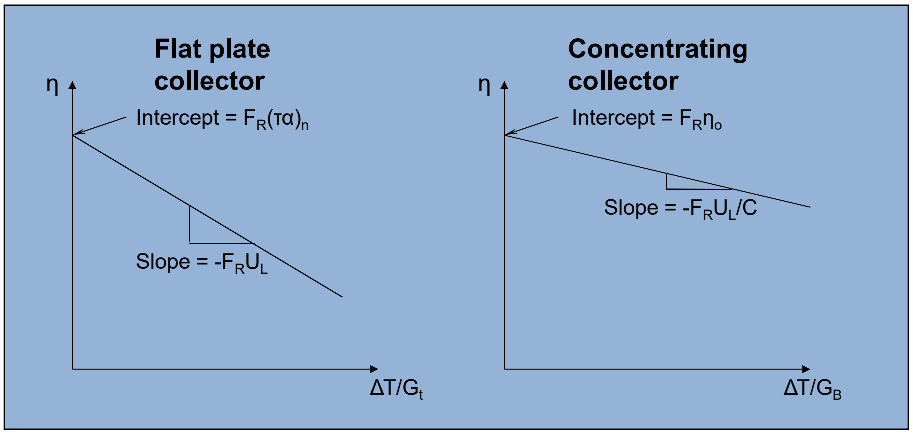
Efficiency plots



Incidence Angle Modifier
Flat plate collectors

- The above performance equations assume that the sun is perpendicular to the plane of the collector, which rarely occurs.
- For the glass cover plates of a flat-plate collector, specular reflection of radiation occurs on the collector glazing thereby reducing the (τα) product.
- The incident angle modifier is defined as the ratio of τα at some incident angle θ to (τα) at normal radiation $(\tau\alpha)_n$:

$$K_\theta = \frac{(\tau\alpha)}{(\tau\alpha)_n} = 1 - b_o\left(\frac{1}{\cos(\theta)} - 1\right)$$

Efficiency equation by considering incidence angle modifier

- With the incidence angle modifier the collector efficiency equation can be modified as:

$$\eta = F_R \left[(\tau\alpha)_n K_\theta - U_L \frac{(T_i - T_a)}{G_t} \right]$$

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Collector Time Constant

- A last aspect of collector testing is the determination of the heat capacity of a collector in terms of the time constant.
- Whenever transient conditions exist, the performance equations given before do not govern the thermal performance of the collector since part of the absorbed solar energy is used for heating up the collector and its components.

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Collector time constant

- The time constant of a collector is the time required for the fluid leaving the collector to reach 63% of its ultimate steady value after a step change in incident radiation. The collector time constant is a measure of the time required for the following relationship to apply:

$$\frac{T_{ot} - T_i}{T_{oi} - T_i} = \frac{1}{e} = 0.368$$

  - T_{ot} = Collector outlet water temperature after time t (° C)
  - T_{oi} = Collector outlet initial water temperature (° C)
  - T_i = Collector inlet water temperature (° C)
- The procedure for performing this test is to operate the collector with the fluid inlet temperature maintained at the ambient temperature.
- The incident solar energy is then abruptly reduced to zero by shielding a flat-plate collector.
- The temperatures of the transfer fluid are continuously monitored as a function of time until above equation is satisfied.

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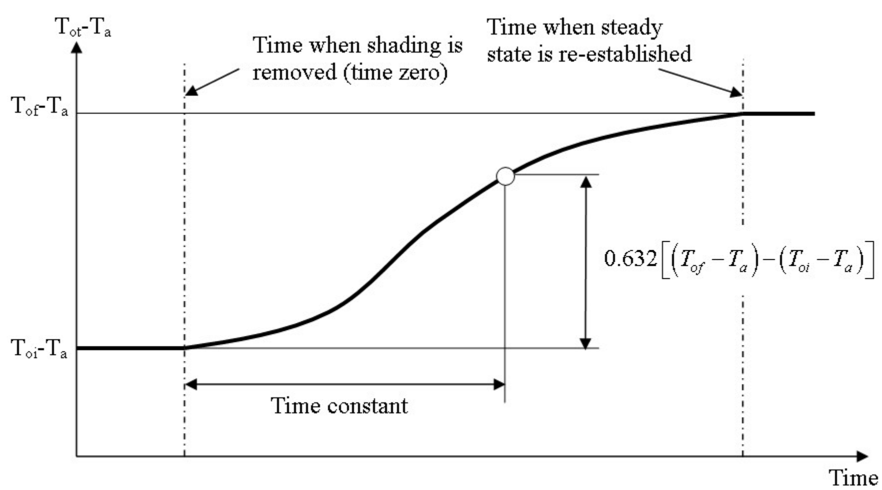
Time constant as specified in ISO 9806-1:1994



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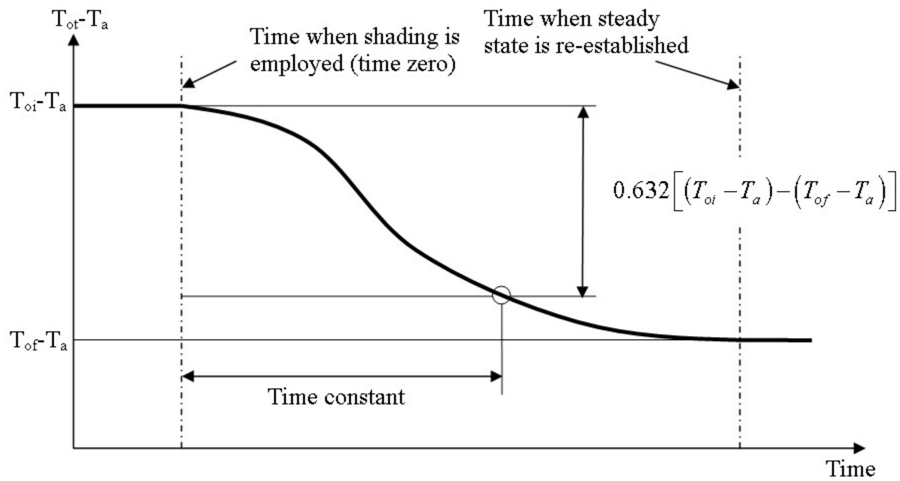
Time constant as specified in ASHRAE 93:2003



Thank you for your attention,

any questions please….