First Summer School

Part A: Line-focus Solar Thermal Technologies

September 20-24, 2021

Lecture 4:

Energy Balance in a Parabolic trough Collector

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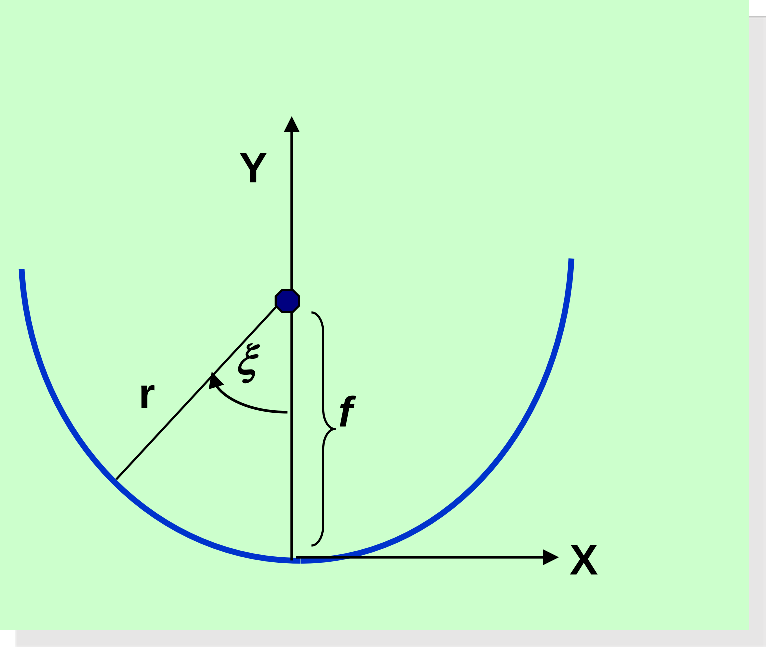
Basic Concepts

Basic parameters: Focal length



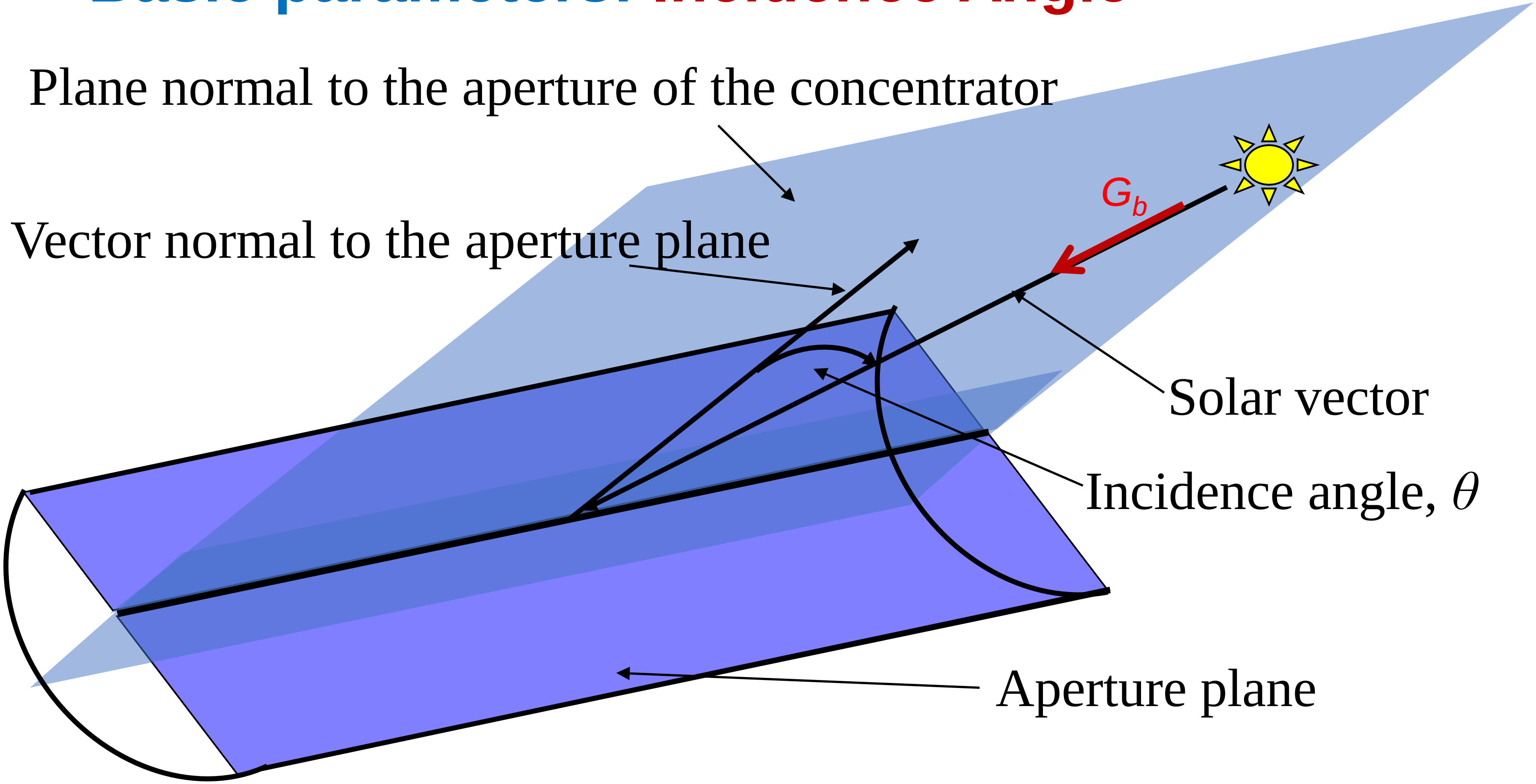
f = focal distance

Collector EuroTrough:
f = 1.71 m

$$y = \frac{x^2}{4 \cdot f} \qquad r = \frac{2 \cdot f}{1 + Cos\,(\xi)}$$

Basic Concepts

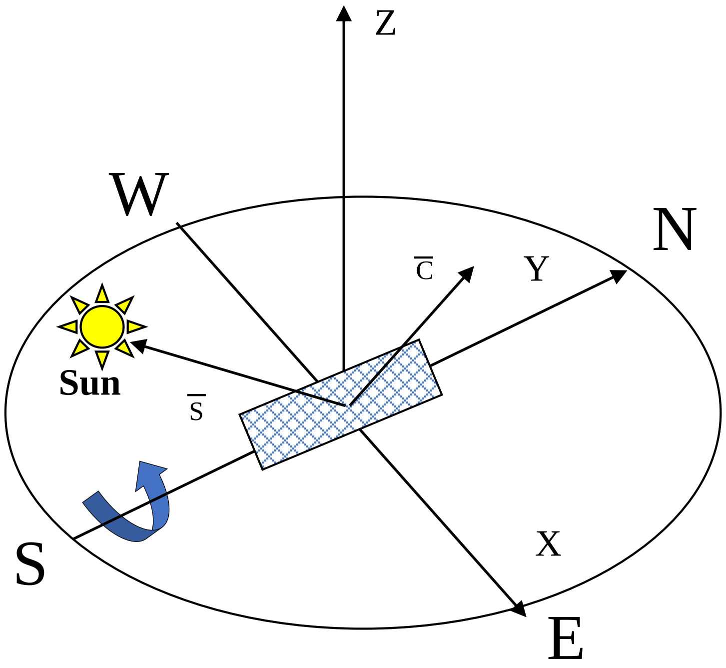
Basic parameters: Incidence Angle



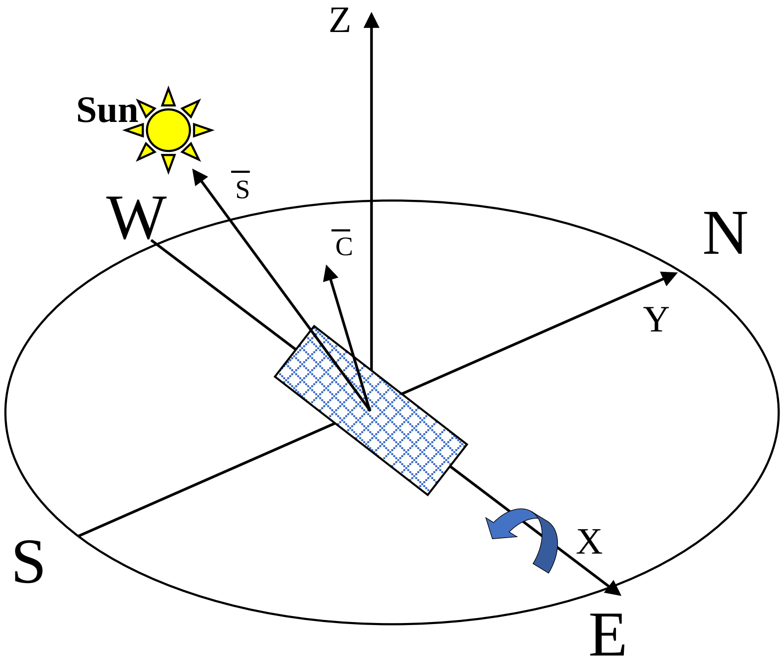
$$G_b \text{ useful } (W/m^2_{aperture}) = G_b \times \cos(\theta)$$

Basic Concepts

Basic collector orientations



a) North-South oriented



b) East-West oriented

Basic Concepts

Basic parameters: Incidence Angle

- East-West orientation

$$\cos(\theta) = \cos(\delta)\sqrt{cos^2(w) + tan^2(\delta)}$$

- North-South orientation

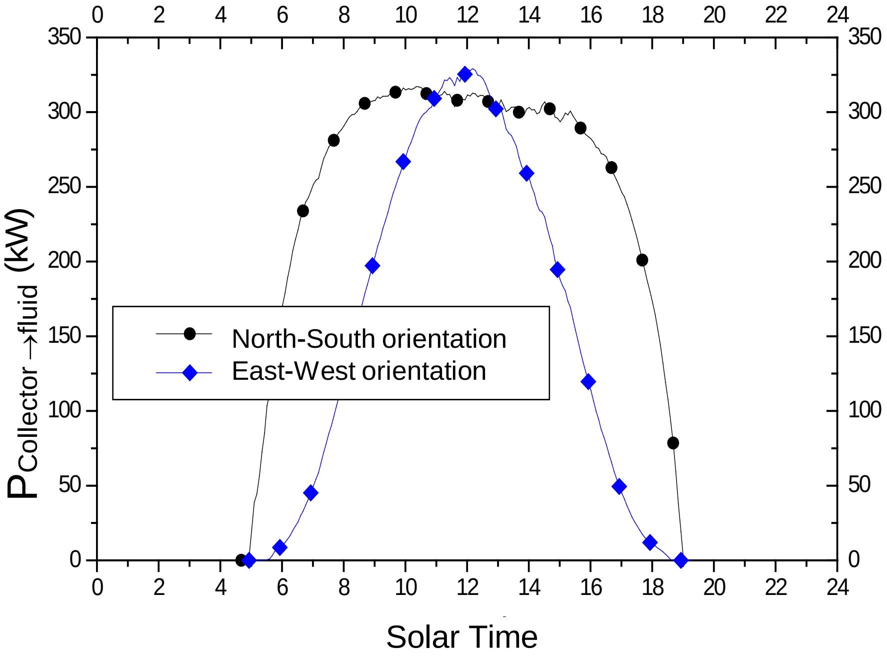
$$\cos(\theta) = \cos(\delta)\sqrt{sin^2(w) + \left(cos(Lat)\cdot cos(w) + tan(\delta)\cdot sin(Lat)\right)^2}$$

δ: declination
w: hourly angle
Lat: Geographical latitude

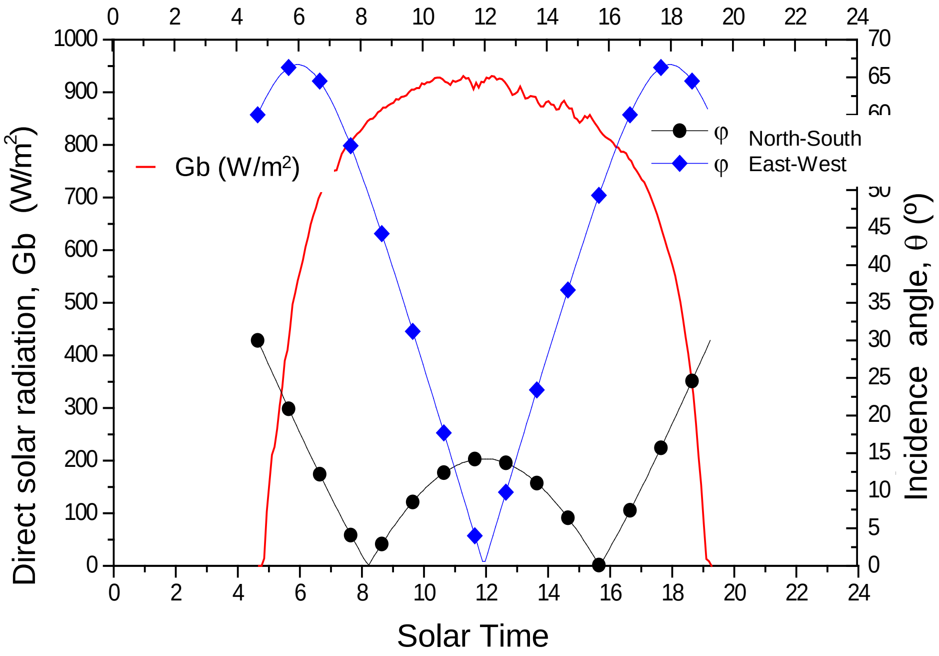
Basic Concepts

Basic parameters: Incidence Angle

ET-100, clear day in June in Almería



Useful thermal power

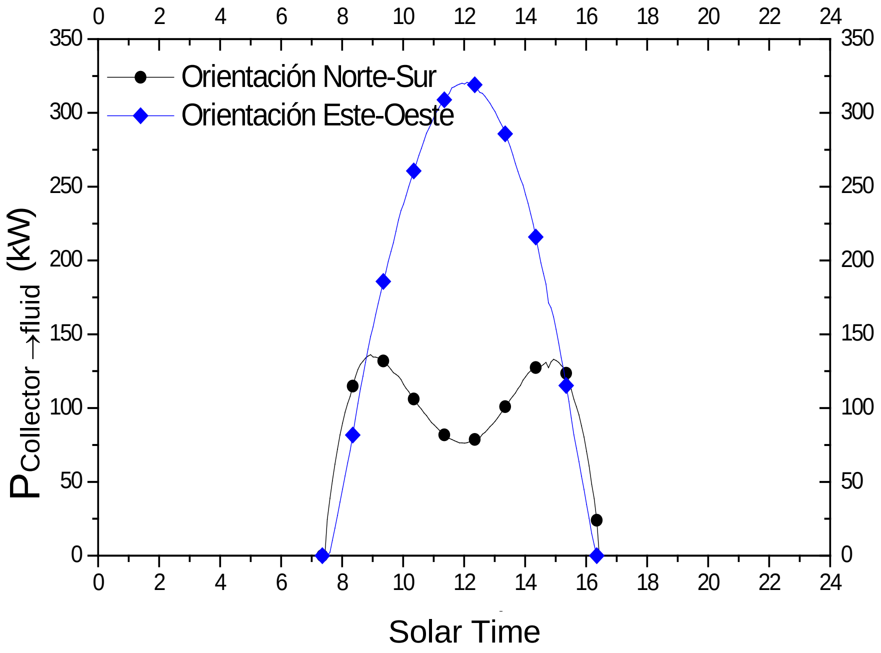


DNI and incidence angle

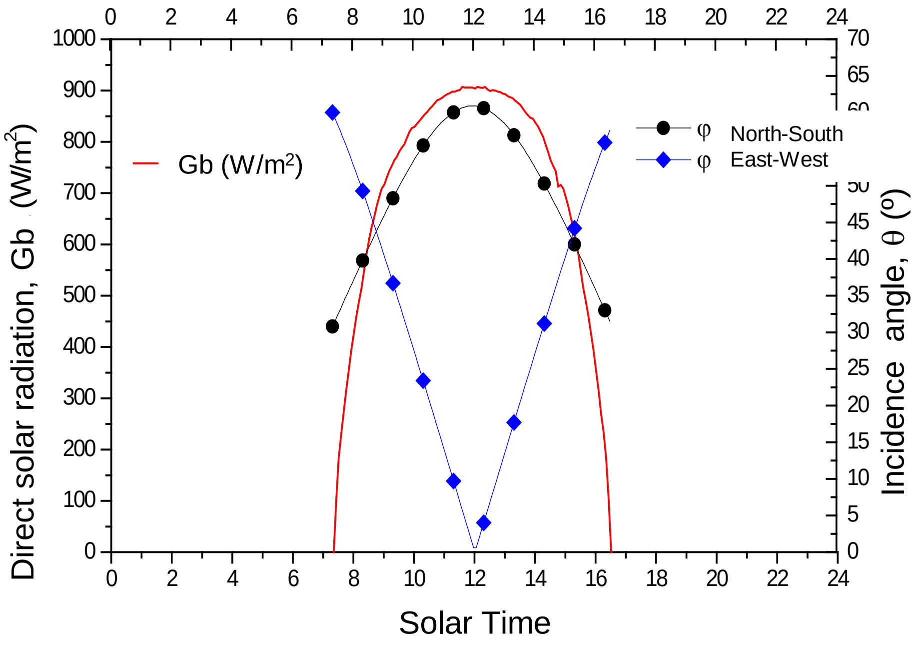
Basic Concepts

Basic parameters: Incidence Angle

ET-100, clear day in December in Almería



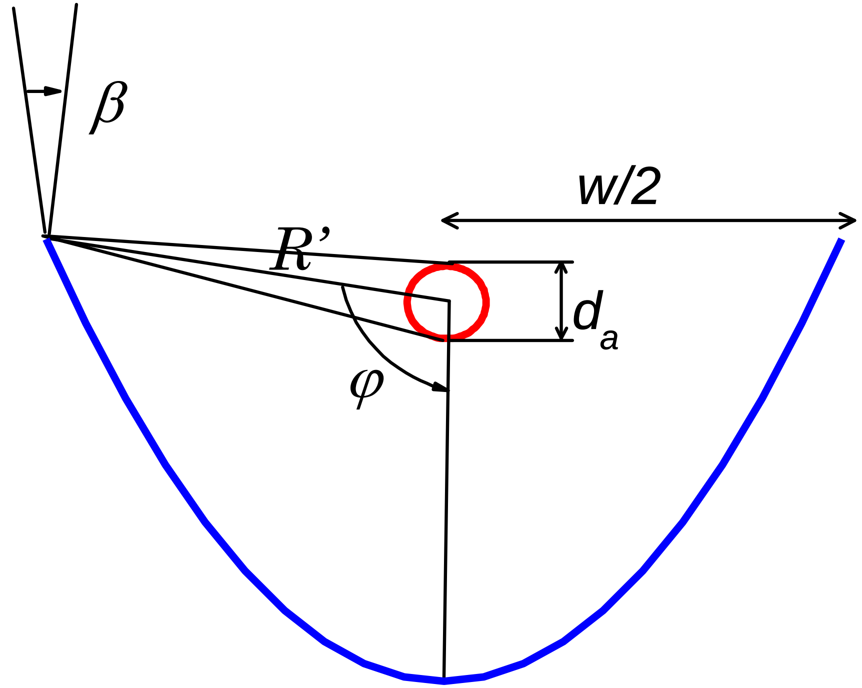
Useful thermal power



DNI and incidence angle

Basic Concepts

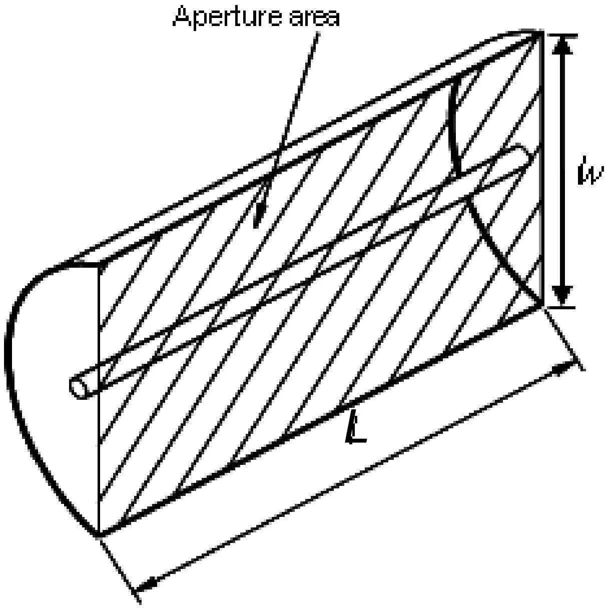
Acceptance, β, and Aperture, φ, angles



Collector EuroTrough:
w=5.76 m
φ=82º
β=1.37º≈24 mrad

Basic Concepts

Geometrical Concentration Ratio, C_{geo}



$$C_{geo} = \frac{A_c}{A_a} = \frac{w \cdot L}{\pi \cdot d_a \cdot L} = \frac{w}{\pi \cdot d_a}$$

A_C = net collector aperture area (m^2)

A_a = absorber area (m^2)

w = aperture width (m)

L = total length (m)

d_a = absorber diameter (m)

EuroTrough collector:
$C_{geo}=26.2$

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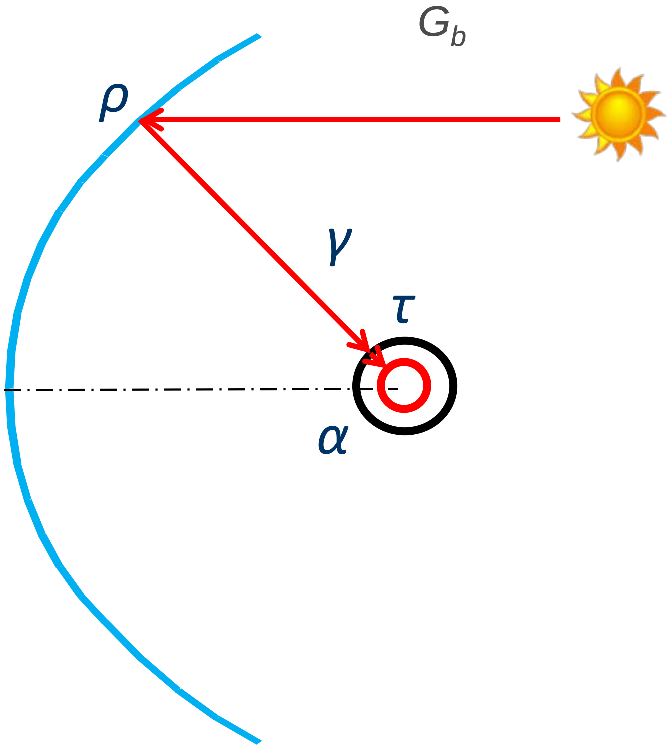
- Energy balance

Optical losses

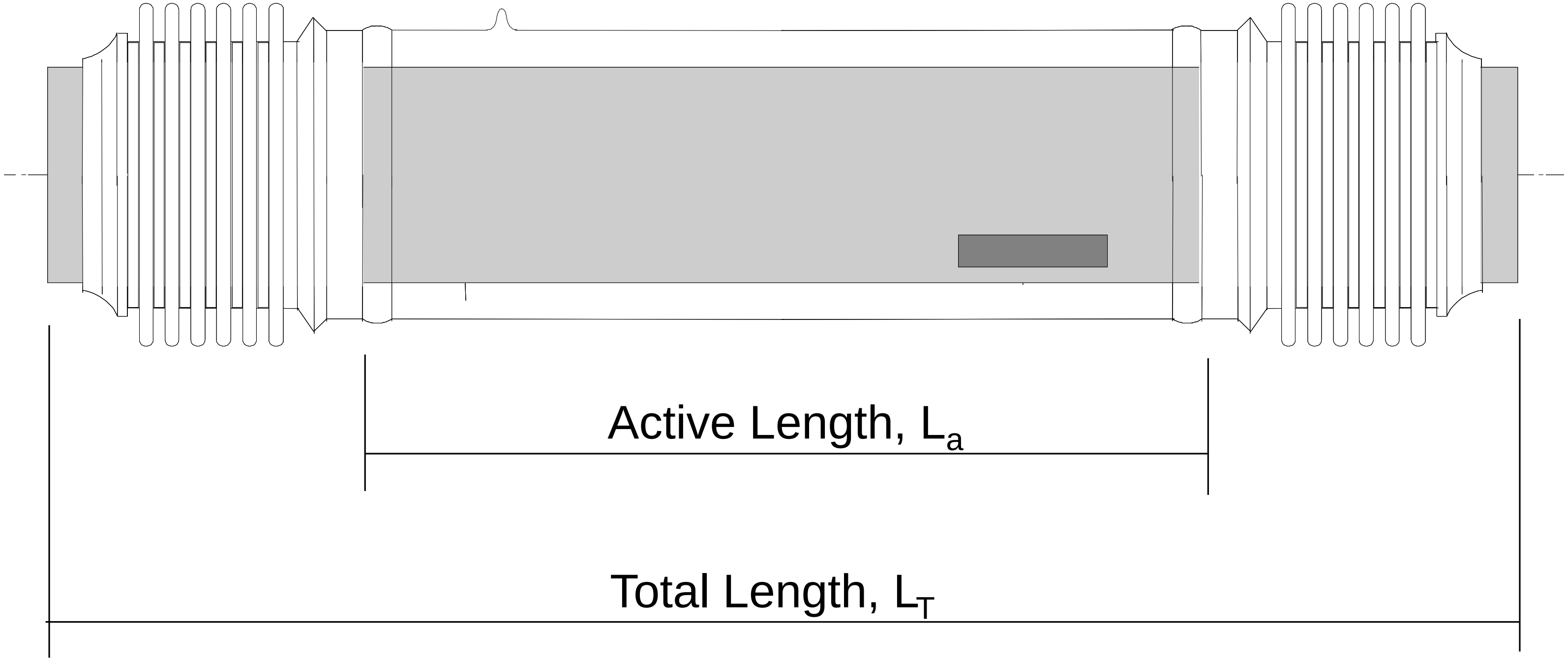


- The concentrator is not a perfect reflector (Reflectance, *ρ)*
- Not all the radiation reflected by the concentrator reaches the absorber tube (Intercept Factor, γ)
- The glass cover is not totally transparent (Transmittance, *τ)*
- The receiver is not a perfect absorber (Absorptance, *α)*

$$\eta_o = \rho \cdot \tau \cdot \alpha \cdot \gamma = \rho \cdot \tau \cdot \alpha \cdot \gamma_g \cdot \gamma_L$$

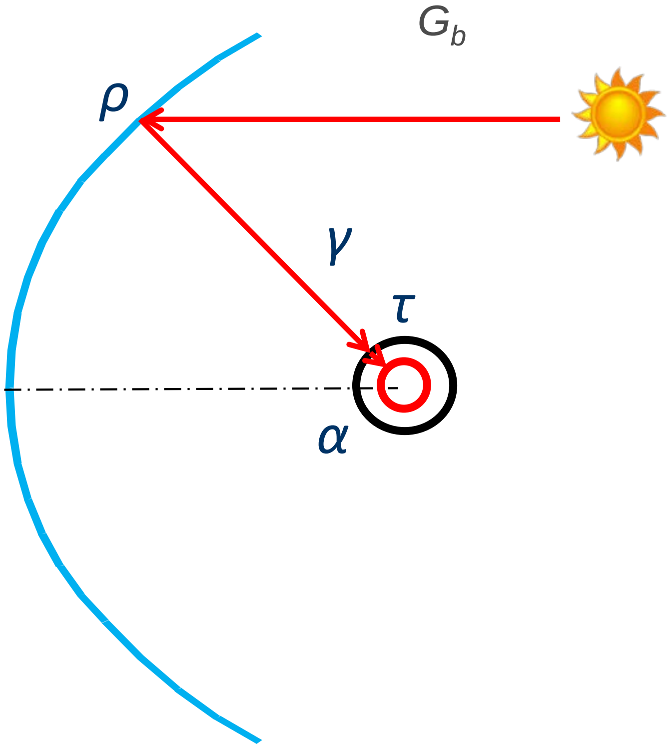
Optical efficiency

Typical evacuated receiver tube



$$\gamma_L = L_a / L_T$$

Optical losses



- The concentrator is not a perfect reflector (Reflectance, *ρ)*
- Not all the radiation reflected by the concentrator reaches the absorber (Intercept Factor, γ)
- The glass cover is not totally transparent (Transmittance, *τ)*
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$$\eta_o = \rho\cdot\tau\cdot\alpha\cdot\gamma = \rho\cdot\tau\cdot\alpha\cdot\gamma_g\cdot\gamma_L$$

$$\rightarrow \eta_{o,\theta=0^o} = \eta_{o,peak} = \rho\cdot\tau\cdot\alpha\cdot\gamma\Big|_{\theta=0^o}$$

Optical Efficiency = Power absorbed at the receiver / Available solar power

Optical losses

Dependence of optical properties with the incidence angle: the *incidence angle modifier, K(θ)*

$$\boxed{\eta_{opt,\varphi=\theta} = \eta_{opt,0º} \cdot K(\theta) = \rho_{0º} \cdot \gamma_{0º} \cdot \tau_{0º} \cdot \alpha_{0º} \cdot K(\theta)}$$

$$K(\theta) = \frac{\eta_{opt}(\theta)}{\eta_{\mathrm{opt},\theta=0º}}$$

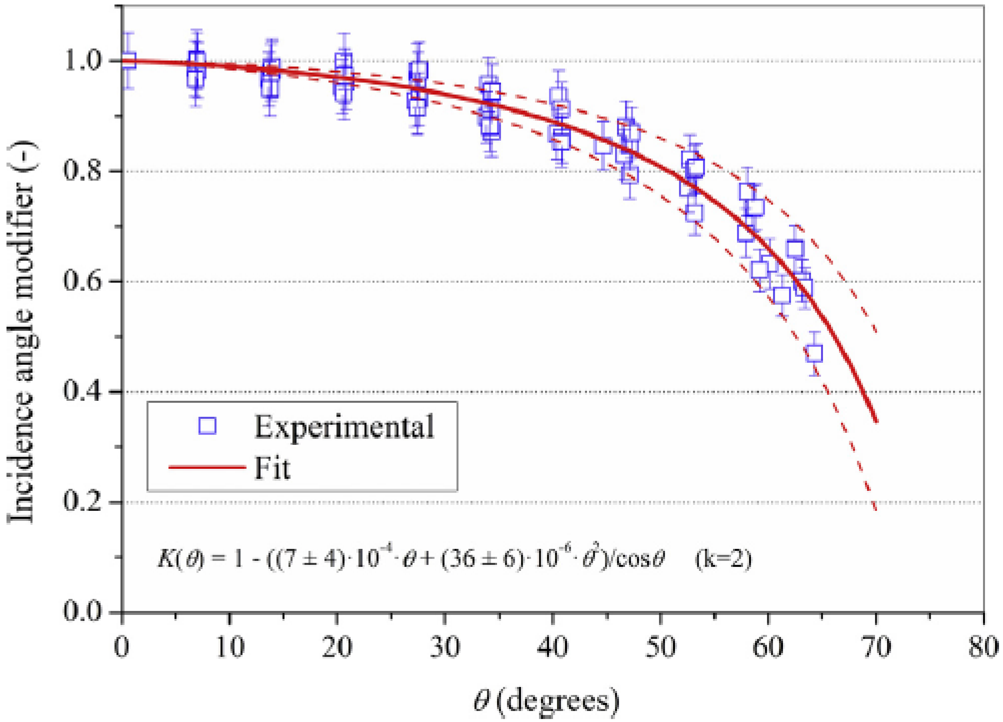
$$K(\theta) = 1 - \frac{b_1 \cdot \theta + b_2 \cdot \theta^2}{\cos(\theta)}$$

Optical efficiency

Example of $K(\theta)$: URSSATrough collector

$\eta_{opt,0^{o}} = 0.768$

$$K(\theta) = 1 - \frac{7 \cdot 10^{-4} \cdot \theta + 36 \cdot 10 - 6 \cdot \theta^{2}}{\cos(\theta)}$$



Valenzuela et al.,
Energy 70 (2014) 456-464

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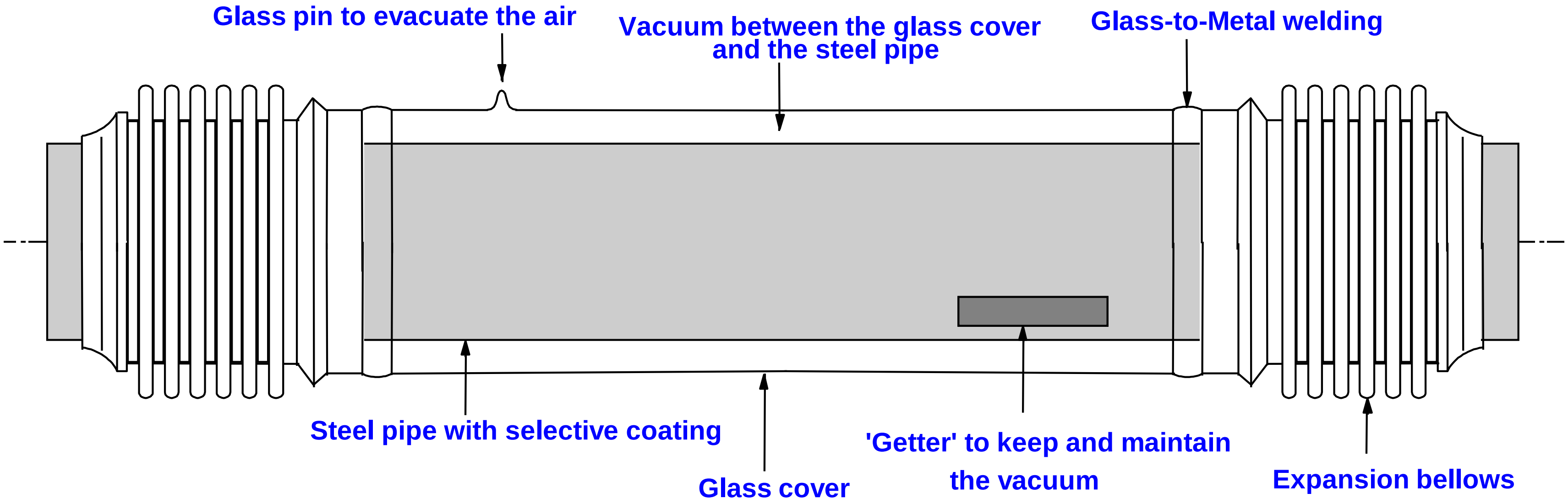
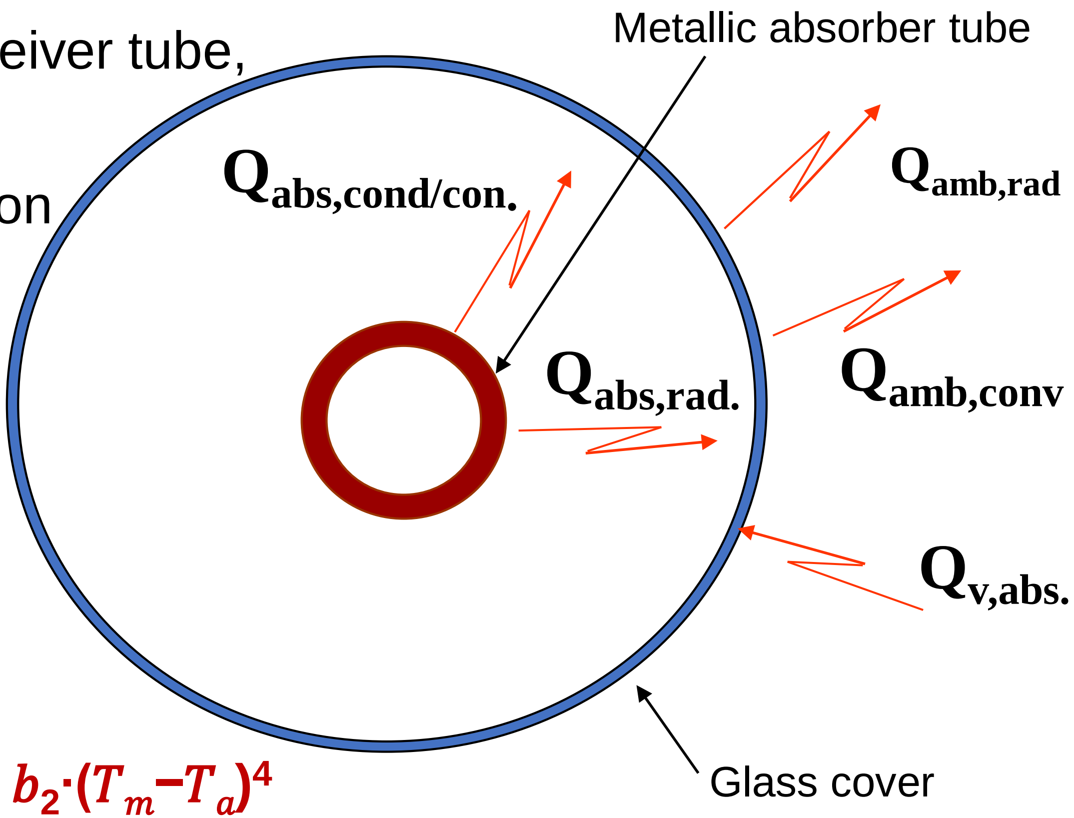
Thermal losses



Thermal losses

The overall thermal losses in a receiver tube, $P_{Q,\text{captador}\rightarrow\text{ambiente}}$, are due to convection, radiation and conduction

They can be calculated altogether using experimental correlations:



$$P_{Q,\text{collector}\rightarrow\text{ambient}}\ \text{(W/m)} = b_1 \cdot (T_m - T_a) + b_2 \cdot (T_m - T_a)^4$$

b_1 , b_2 : experimental coefficients

T_a : ambient temperature

T_m : Fluid mean temperature in the receiver tube

Thermal losses

Sometimes the manufacturers of receiver tubes give a different correlation to calculate the thermal losses in their tubes. An example of this is the correlation to calculate the thermal losses in the receiver tubes PTR70 (developed by SCHOTT and manufactured by RIOGLASS nowadays):

$$P_{Q,\text{collector}\rightarrow\text{ambient}}\ [\text{W/m}] = 0.00154{*}\Delta T^2 + 0.2021{*}\Delta \text{T} - 24.899 + [(0.00036{*}\Delta T^2 + 0.2029{*}\Delta T + 24.899){*}(G_b/900){*}\cos(\theta)]$$

being:

ΔT = temperature difference between the working fluid and ambient air
G_b = Direct solar irradiance, W/m^2
θ = Incidence angle

Be aware that the above equation gives the thermal loss in W/m. The total thermal loss is calculated multiplying this value by the total length of the collector

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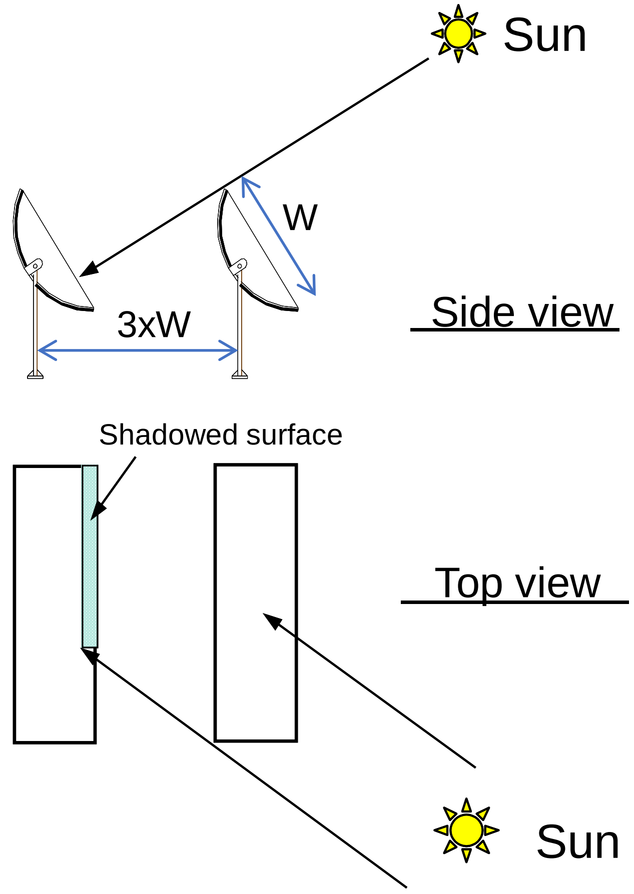
Geometrical losses

There are two types of geometrical losses:



a) Losses due to shadowing

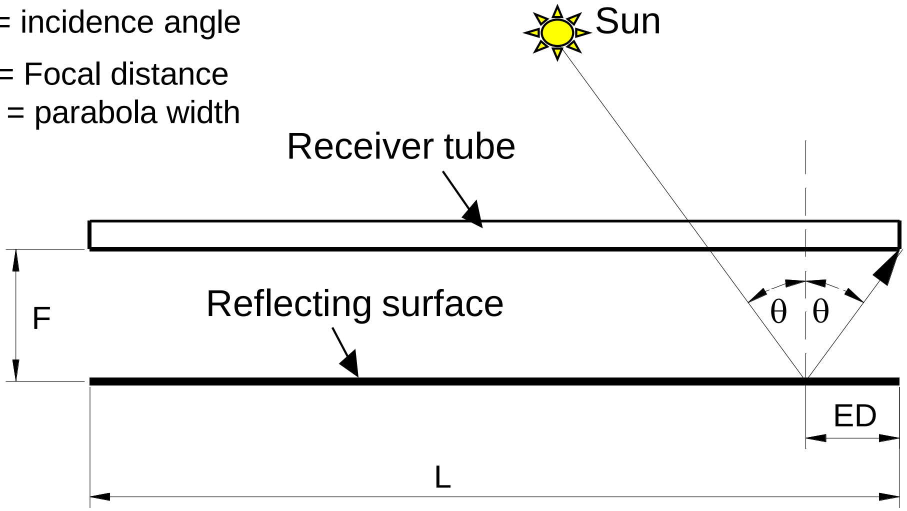
A_f= useless collecting area

L = length of the parabolic trough concentrator

θ = incidence angle

F = Focal distance

W = parabola width



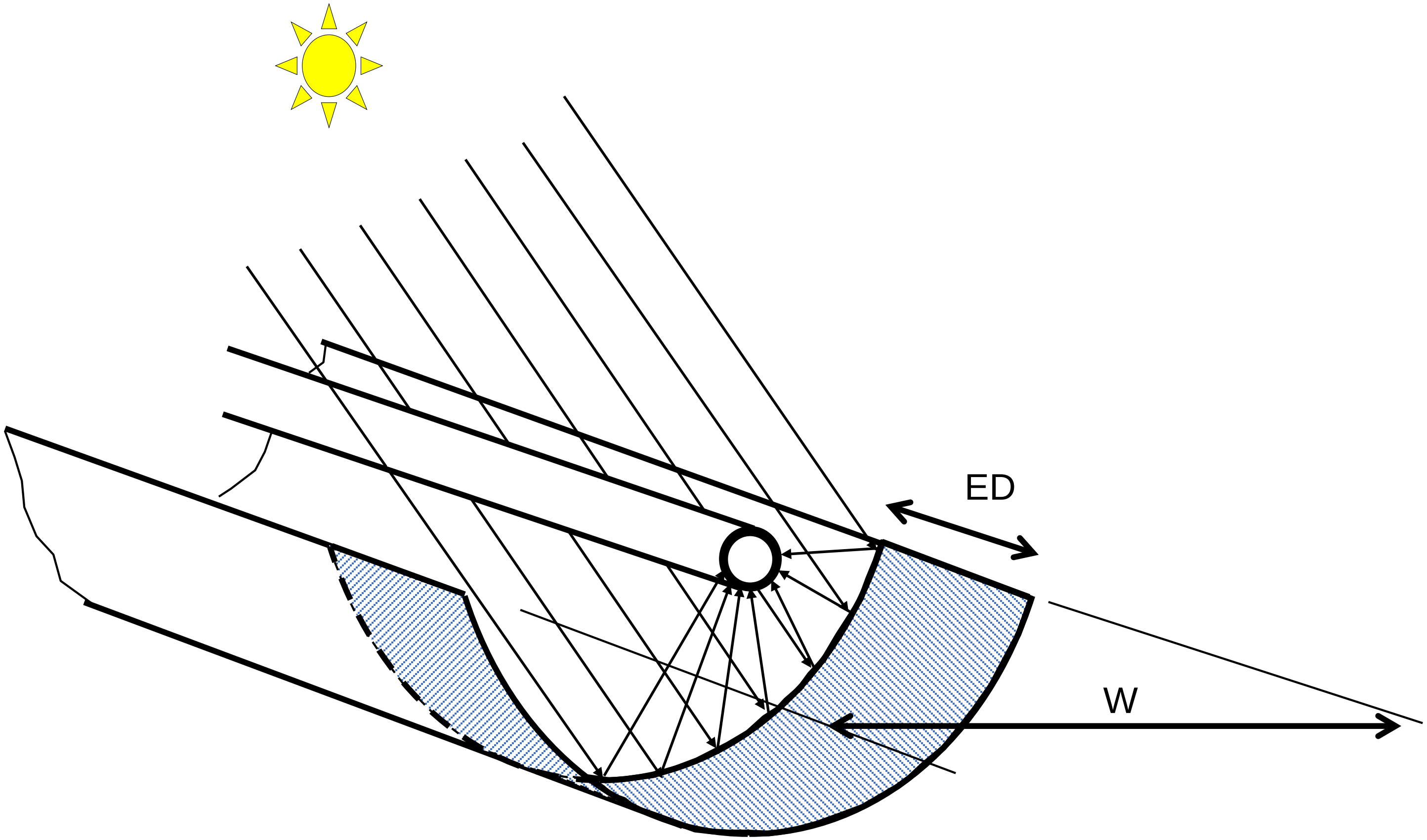
$$A_f = W \times ED = W \times Fm \times \tan(\theta)$$

$$Fm = F + (F \times W^2 / 48 \times F^2)$$

b) End losses

Geometrical losses

End losses in a parabolic trough concentrator



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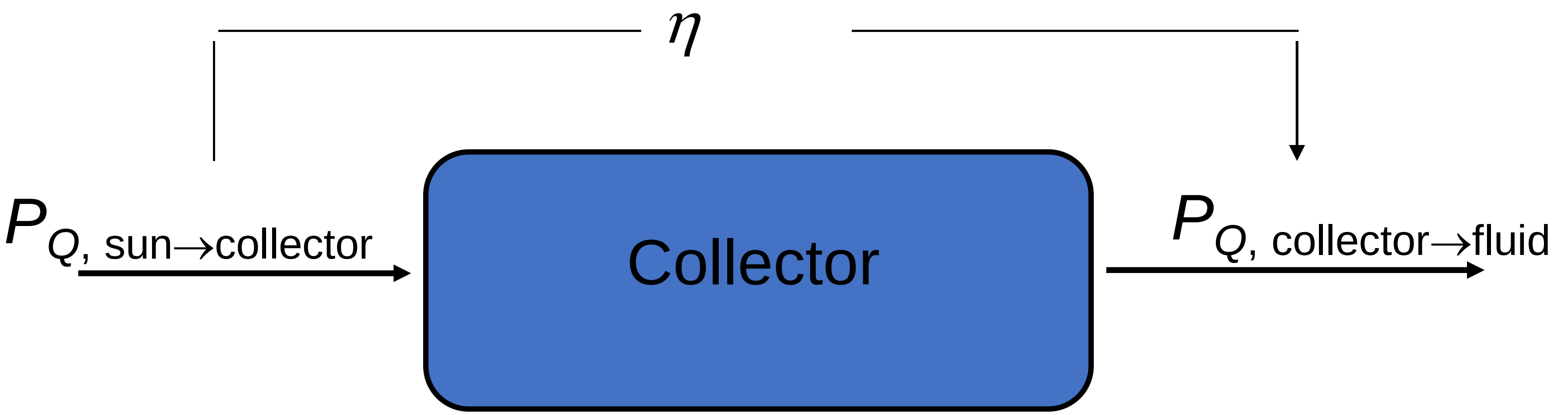
Energy balance

Collector overall efficiency



η

$P_{Q,\,\text{sun}\rightarrow\text{collector}}$

Collector

$P_{Q,\,\text{collector}\rightarrow\text{fluid}}$

$P_{Q,\,\text{sun}\rightarrow\text{collector}}$ = useful radiant solar power in the aperture area of the collector, W

$P_{Q,\,\text{collector}\rightarrow\text{fluid}}$ = net thermal power transferred to the fluid in the receiver, W

$$\boxed{\eta = P_{Q,\,\text{collector}\rightarrow\text{fluid}} \;/\; P_{Q,\,\text{sun}\rightarrow\text{collector}}}$$

Energy balance

Useful Radiant Solar Power and Net Thermal Power

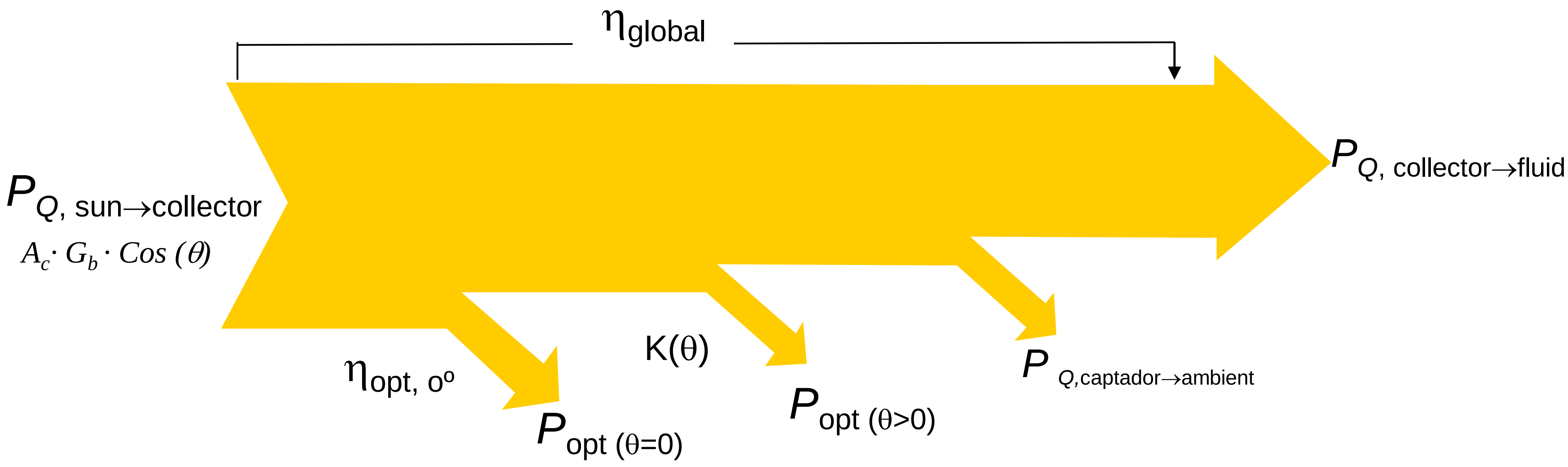
- Useful radiant solar power on the collector: $P_{Q,sun\rightarrow collector} = A_c \cdot G_b \cdot Cos\ (\theta)$

A_c = Aperture area of the reflecting surface of the collector, (m^2)
G_b = Direct solar irradiance, (W/m^2)
θ = Incidence angle, (º)

- Net thermal power delivered by the collector: $P_{Q,collector\rightarrow fluid} = q_m \cdot (h_{out} - h_{in})$

q_m = working fluid mas flow, (kg/s)
h_{in} = working fluid specific enthalpy at the collector inlet, (J/kg)
h_{out} = working fluid specific enthalpy at the collector outlet, (J/kg)

Energy balance



η_{global}

$P_{Q,\ sun \rightarrow collector}$

$A_c \cdot G_b \cdot Cos\ (\theta)$

$P_{Q,\ collector \rightarrow fluid}$

$\eta_{opt,\ o^o}$

$K(\theta)$

$P_{opt\ (\theta=0)}$

$P_{opt\ (\theta>0)}$

$P_{Q,captador \rightarrow ambient}$

$$\boxed{P_{Q,\ collector \rightarrow fluid} = A_c \cdot G_b \cdot Cos\ (\theta) \cdot \eta_{opt,0^o} \cdot K(\theta) \cdot F_e - P_{Q,collector \rightarrow ambient}}$$

$$\begin{cases} P_{Q,collector \rightarrow ambient} = b_1 \cdot (T_m - T_a) + b_2 \cdot (T_m - T_a)^4 \qquad \text{ór} \\ P_{Q,collector \rightarrow ambient}\ [W/m] = 0{,}00154 * \Delta T^2 + 0{,}2021 * \Delta T - 24{,}899 + \\ \qquad [(0{,}00036 * \Delta T^2 + 0{,}2029 * \Delta T + 24{,}899) * (G_b / 900) * \cos(\theta)] \end{cases}$$

Optical efficiency

Dependence of optical properties with the soiling: soiling/cleanliness factor

The soiling factor, *Fe*, takes into account the reduction of reflectivity and absorptivity of the mirrors and glass tubes respectively due to the progressive accumulation of dust along the time after washing the mirrors and glass tubes

$$F_e = \frac{\rho}{\rho_{nom}} \cdot \frac{\tau}{\tau_{nom}}$$

F_e is usually within the range: 0.9 - 1

$$\eta_{opt} = \rho_{nom} \cdot \gamma_{0º} \cdot \tau_{nom} \cdot \alpha_{0º} \cdot K(\theta) \cdot F_e$$

$$\boxed{\left.\eta_{opt}\right|_{\theta \neq 0º} = \eta_{opt,0º} \cdot K(\theta) \cdot F_e}$$

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- **Thank you very much for your attention**
- **Questions?**

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