SOLAR THERMAL COLLECTORS

Wikipedia.org

Dr. Herena Torio

Learning outcomes on solar collectors

- Understand the physical principles governing solar thermal collectors

- Understand the main heat transfer mechanisms for solar thermal collectors

- Understand the relationship between the collector efficiency and main variables influencing it

- Get a critical understanding on equations describing collectors' performance

- Get familiar with parameters depicting collectors' performance

Outline

- **Collector types and system outline**

- **Main heat processes involved**

- **Collectors' performance: flat plate collectors**
  - Radiation
  - Mass flow
  - Geometry
  - Materials
  - Capacity effects (thermal inertia)

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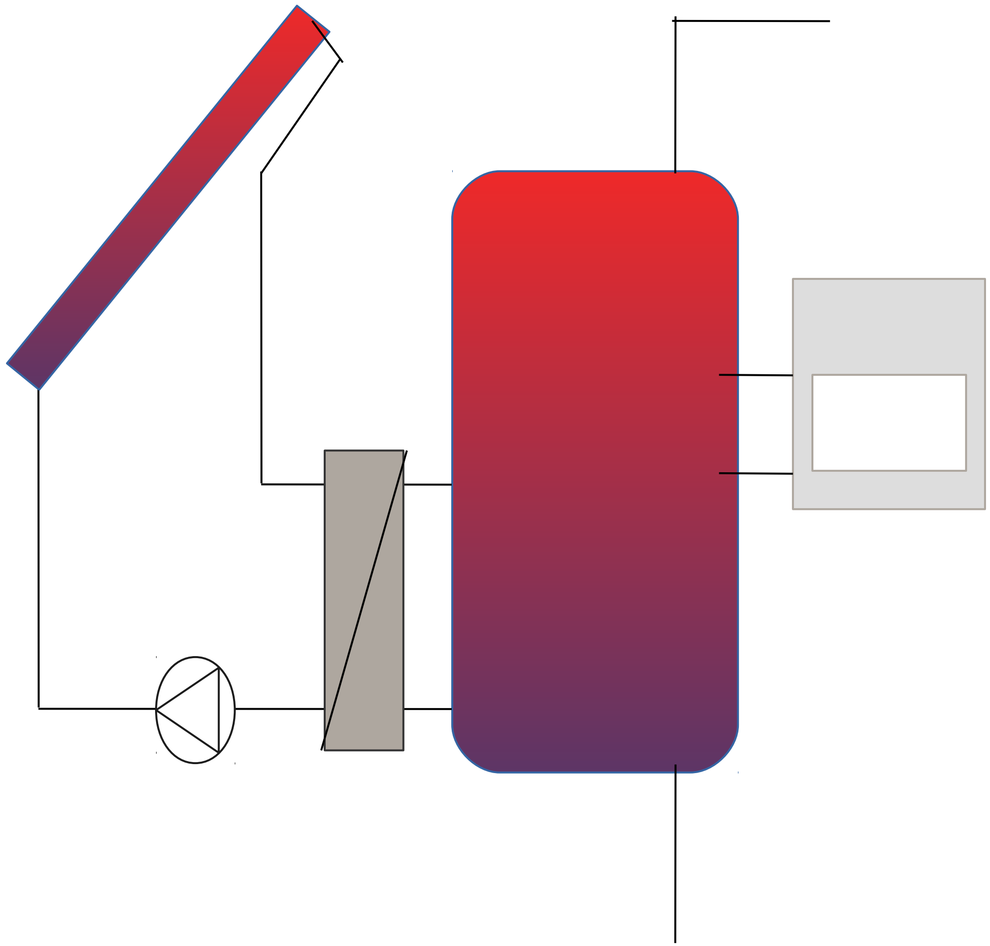
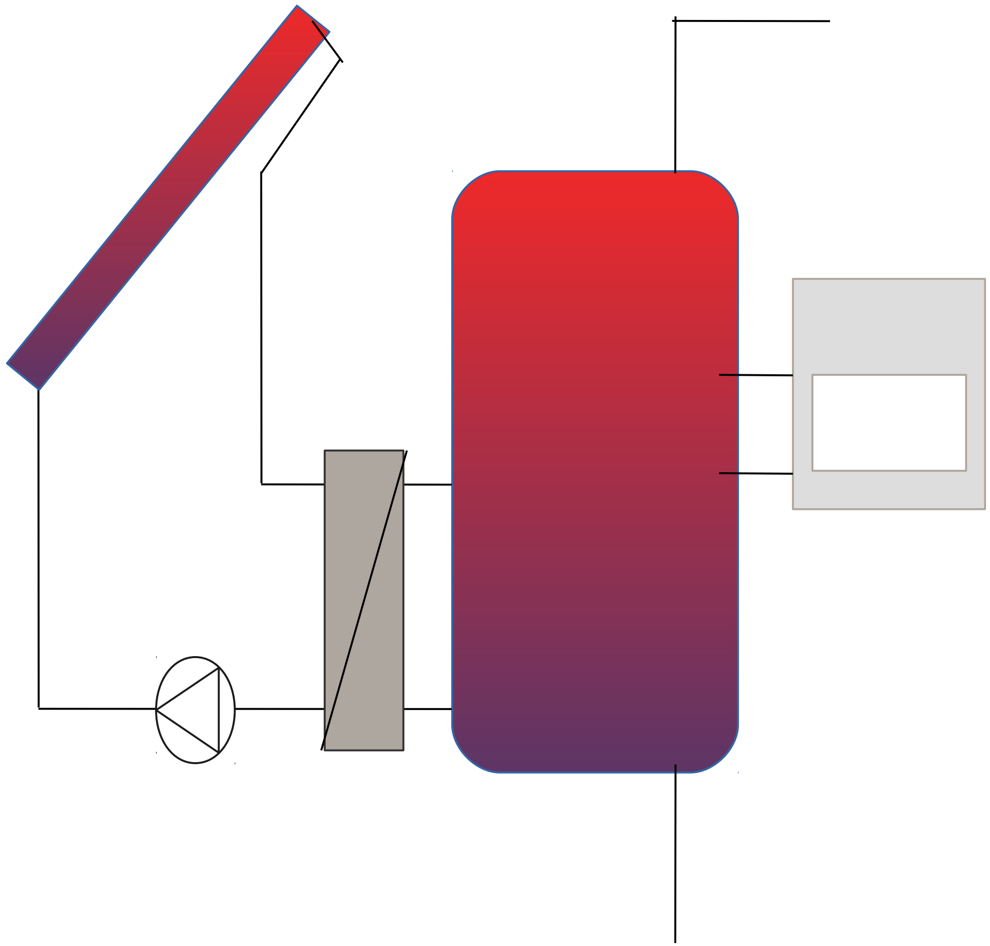
Solar thermal systems

First system overview



Solar thermal systems
First system overview



Main solar thermal
collector types:

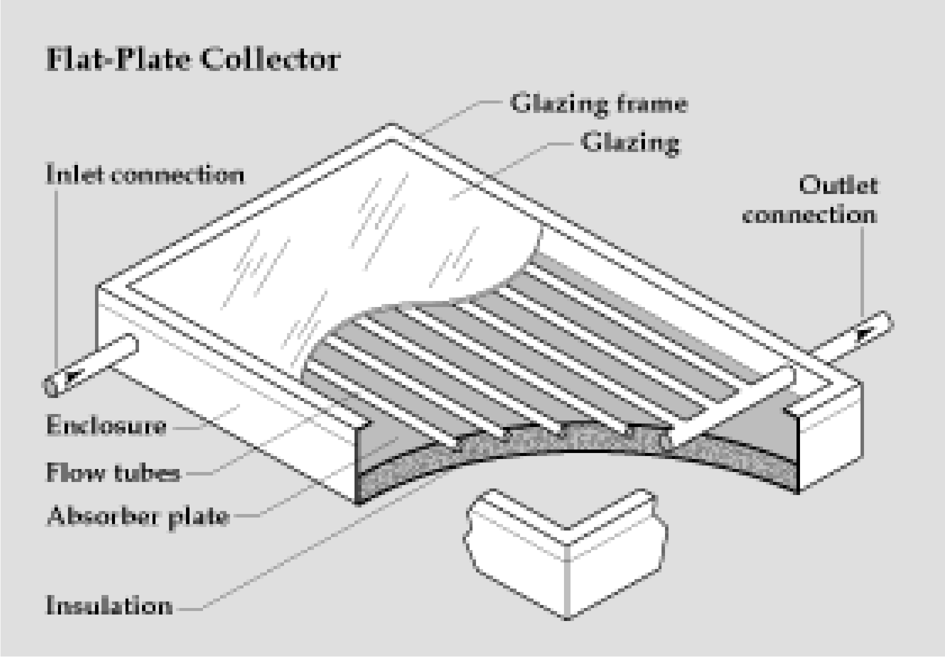
- flat plate

- vacuum tube

- concentrating collectors:
concentrating parabolic
compound (CPC)

Main collector types

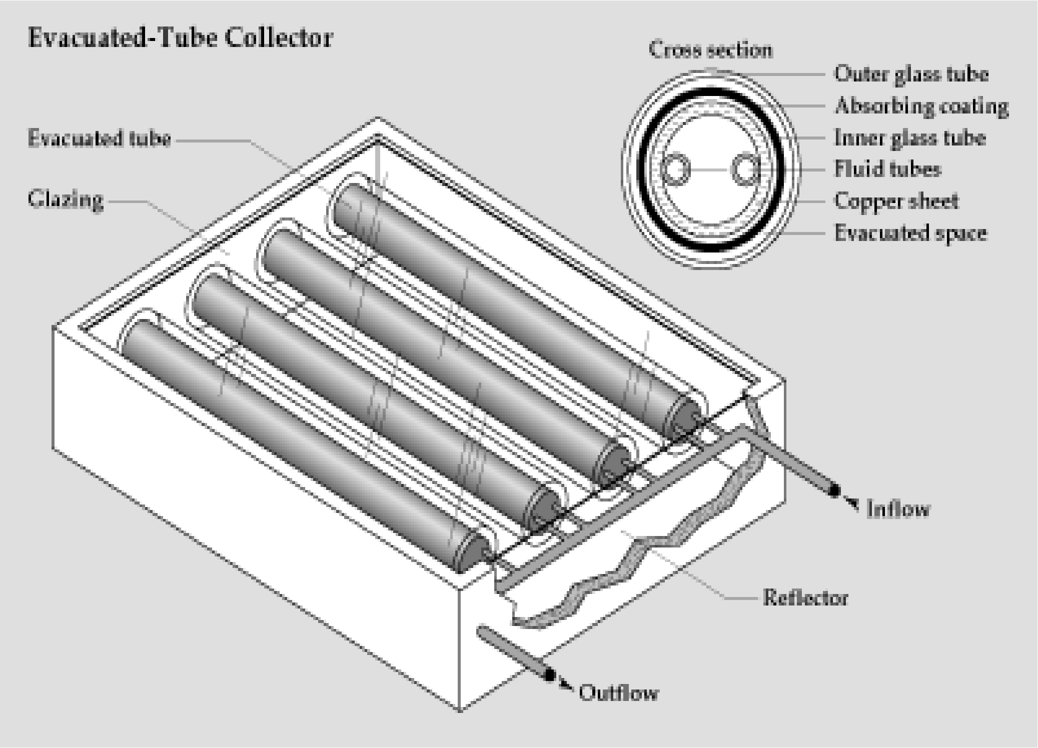
Flat plate collectors



Source: wikimedia.org

Main collector types

Vacuum tube collectors



Source: wikimedia.org

Main collector types

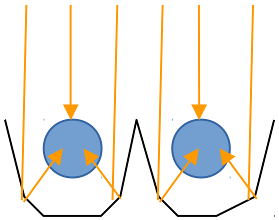
Concentrating collectors

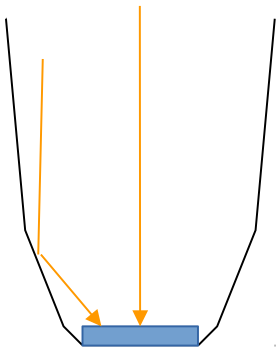
Non imaging: CPC

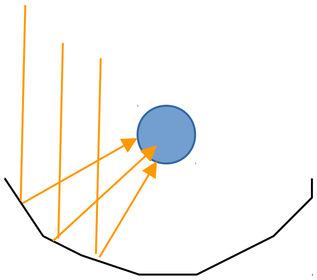
- lower concentration rates
- lower temperatures
- better use of diffuse radiation

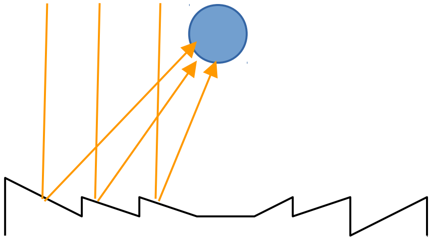
Imaging:

- parabolic through
- solar tower
- parabolic dish
- Fresnel collectors









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- **Collector types and system outline**
- **Main heat processes involved**
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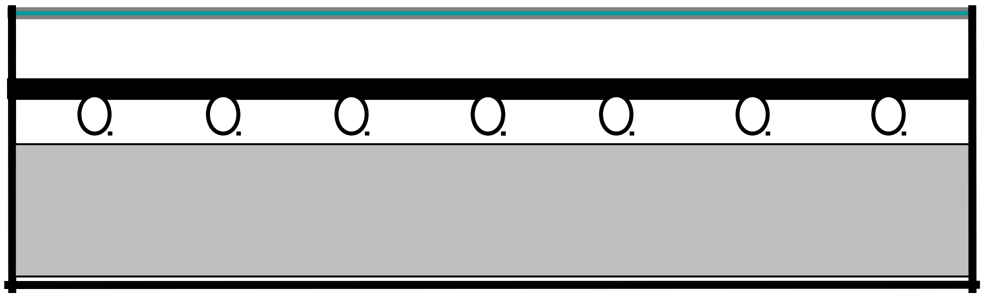
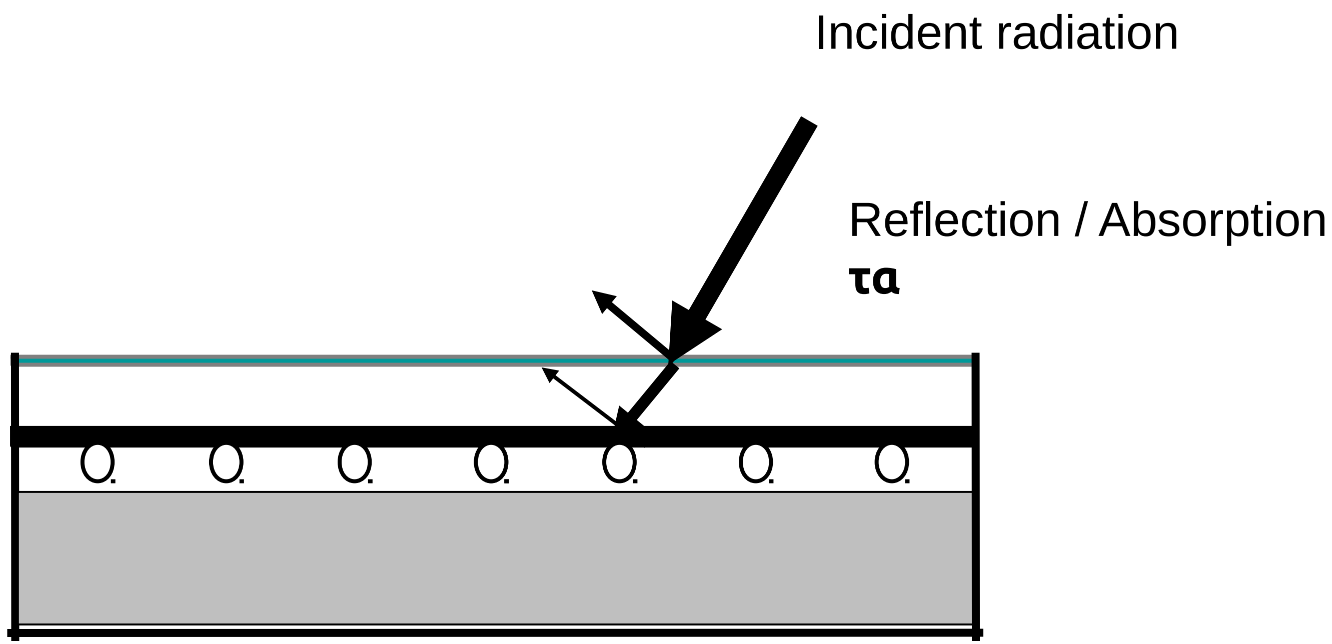
Main heat processes involved

Cross section flat plate collector



Main heat processes involved

Cross section flat plate collector



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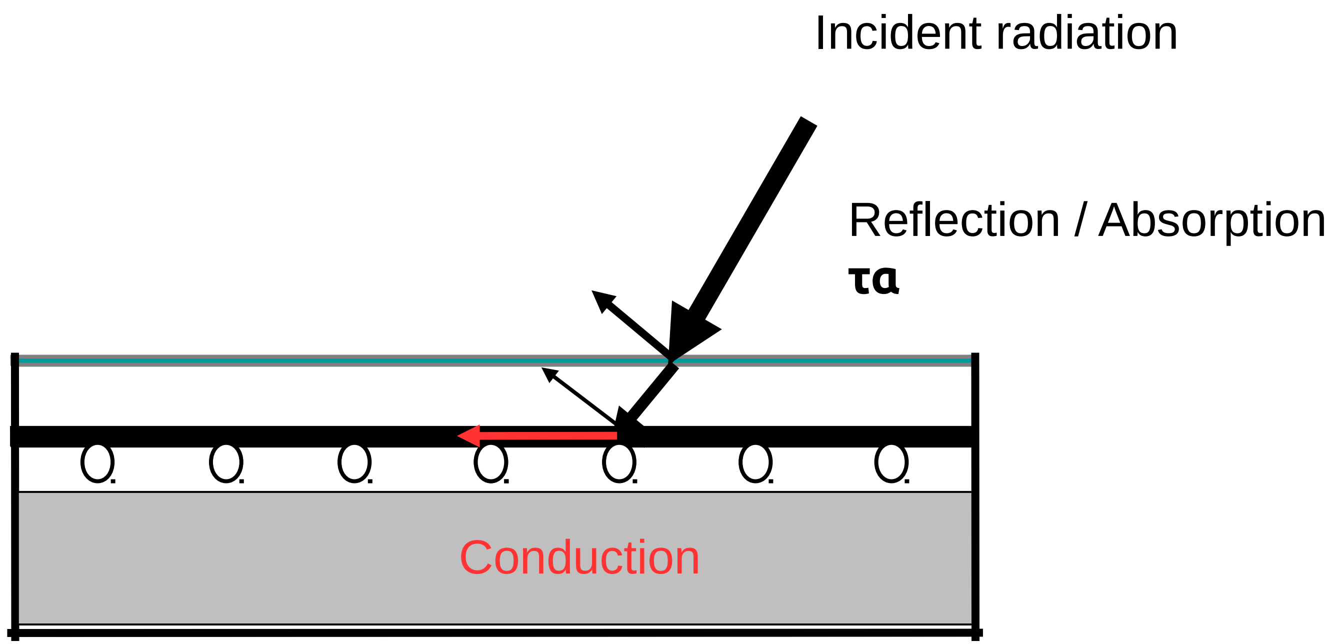
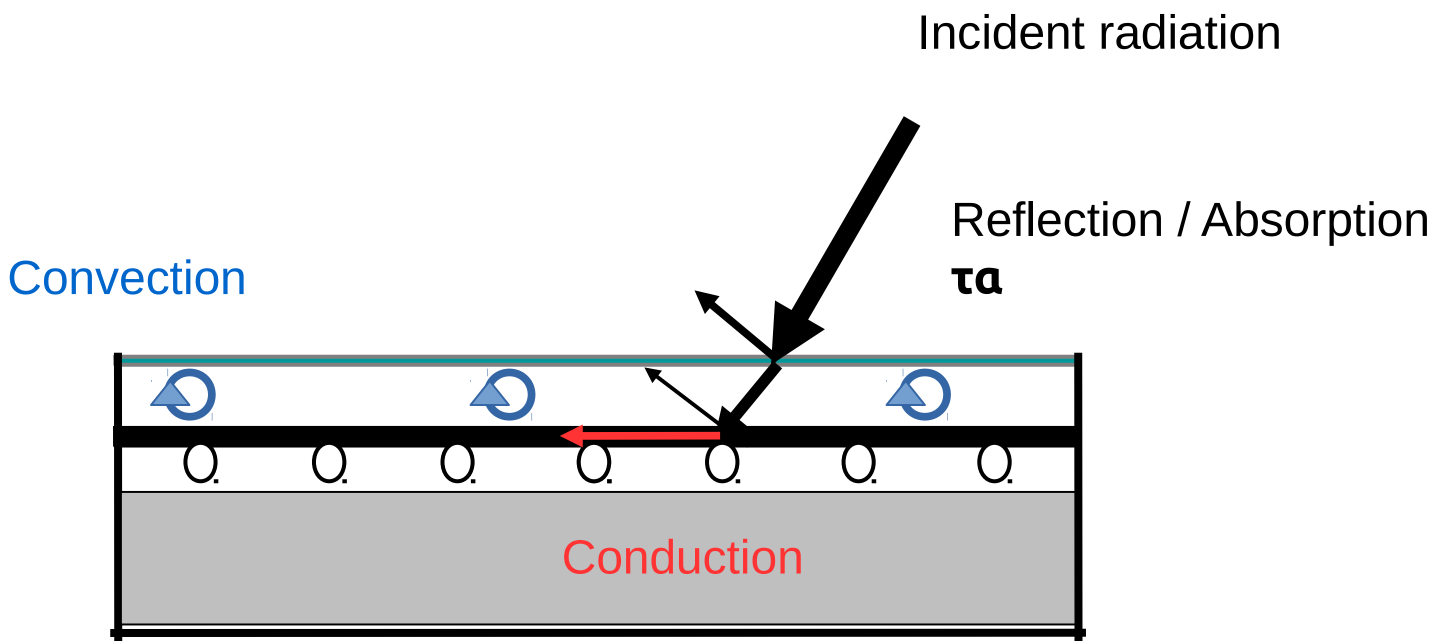


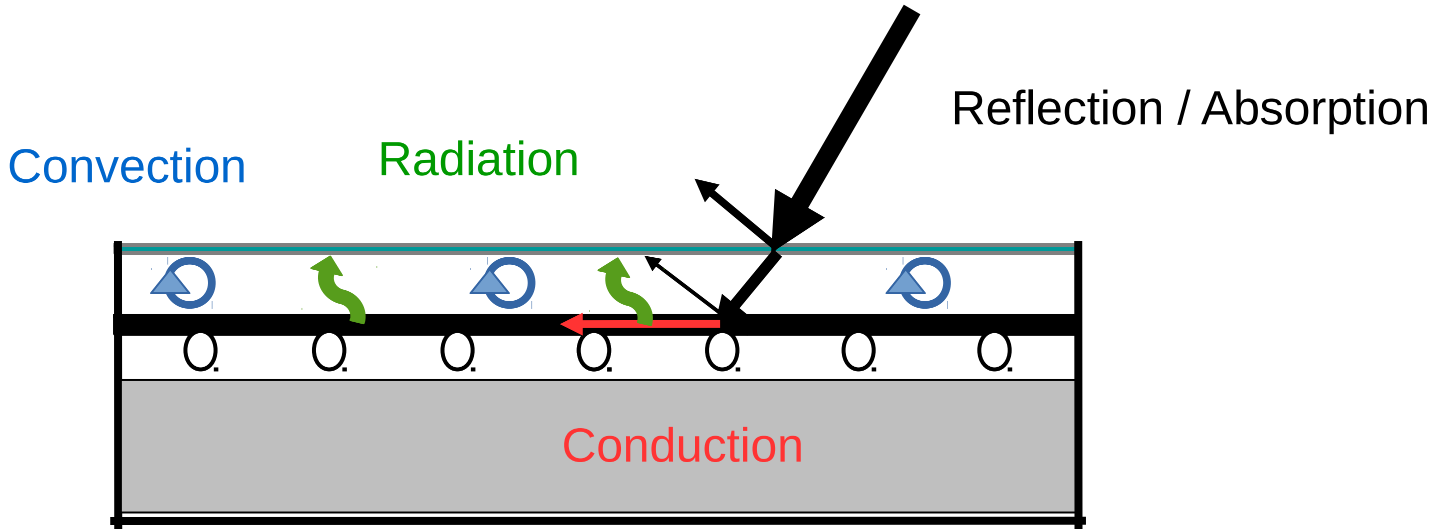
Main heat processes involved

Cross section flat plate collector



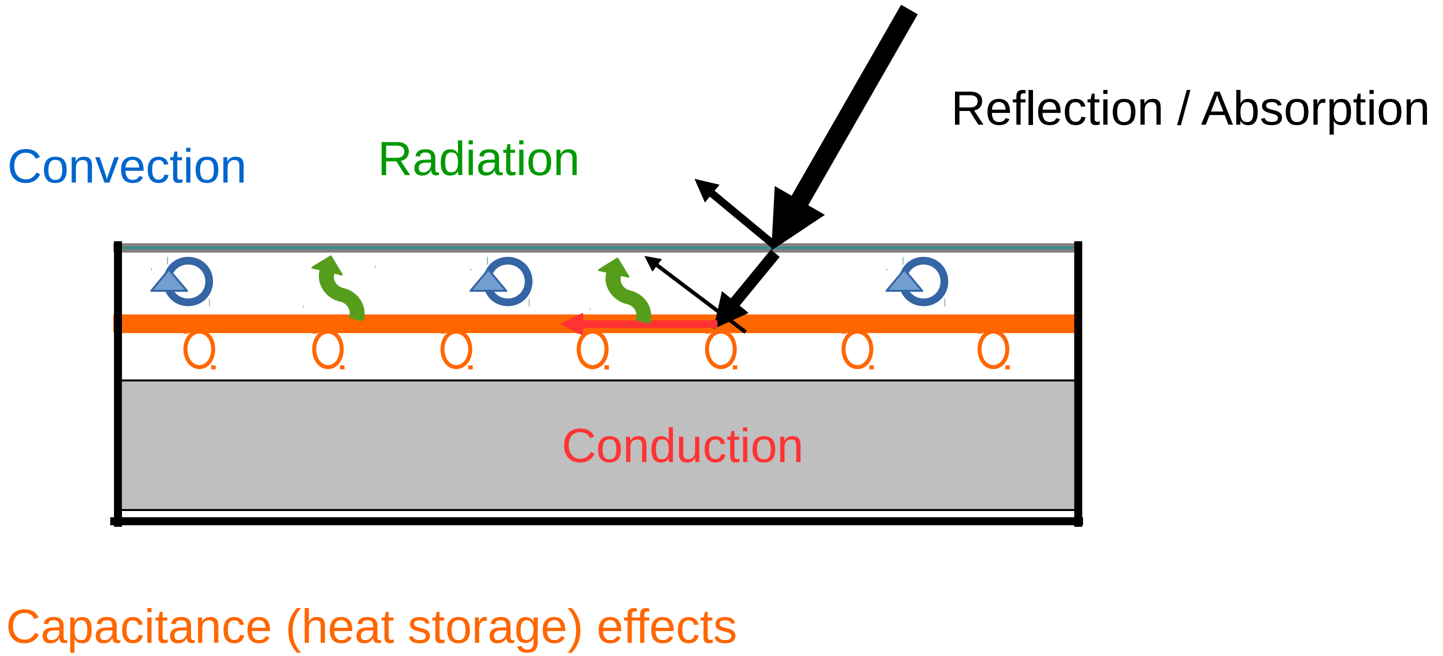
Main heat processes involved

Cross section flat plate collector



Main heat processes involved

Cross section flat plate collector



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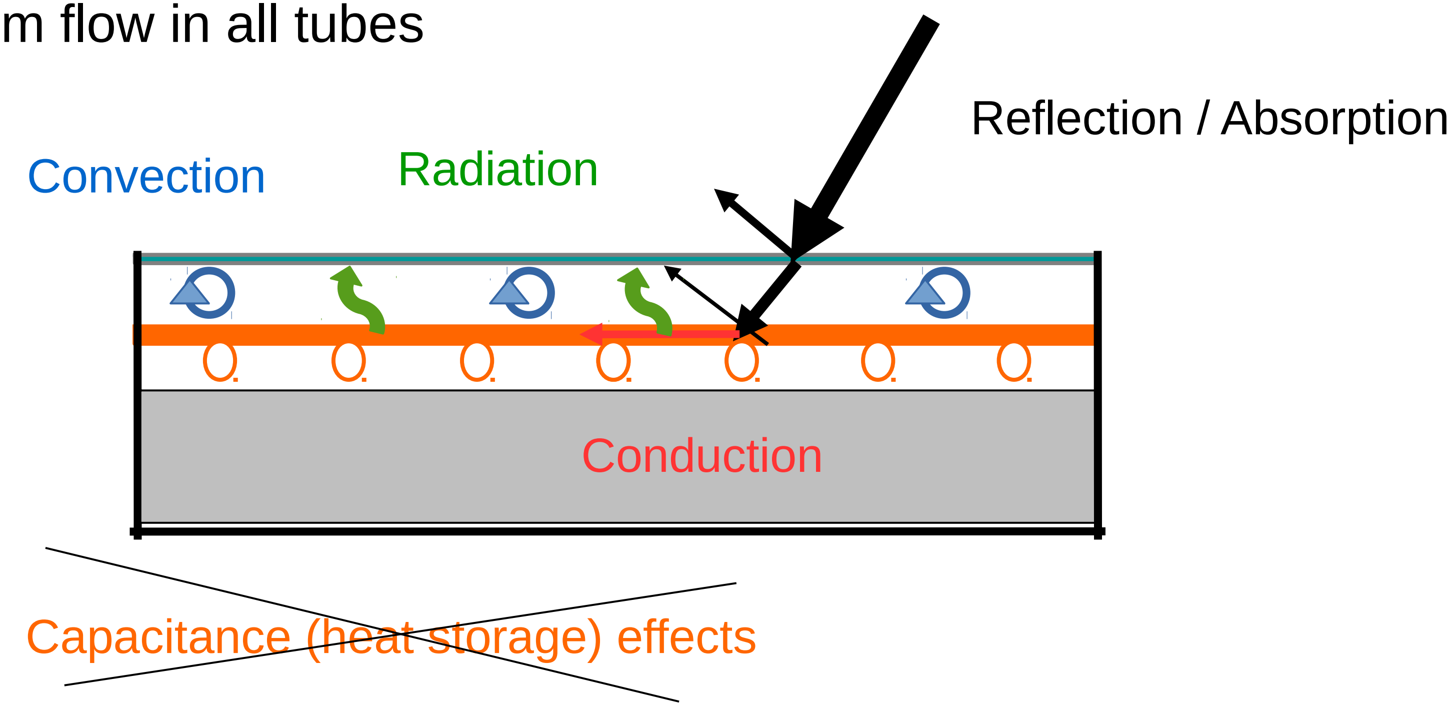
Main heat processes involved

Cross section flat plate collector: performance assessment

First simplifications:

- Steady state operation
- No absorption from covers affecting thermal losses
- Sheet (absorber) and parallel tubes
- Uniform flow in all tubes



Flat plate collectors: performance

Main heat transfer processes involved

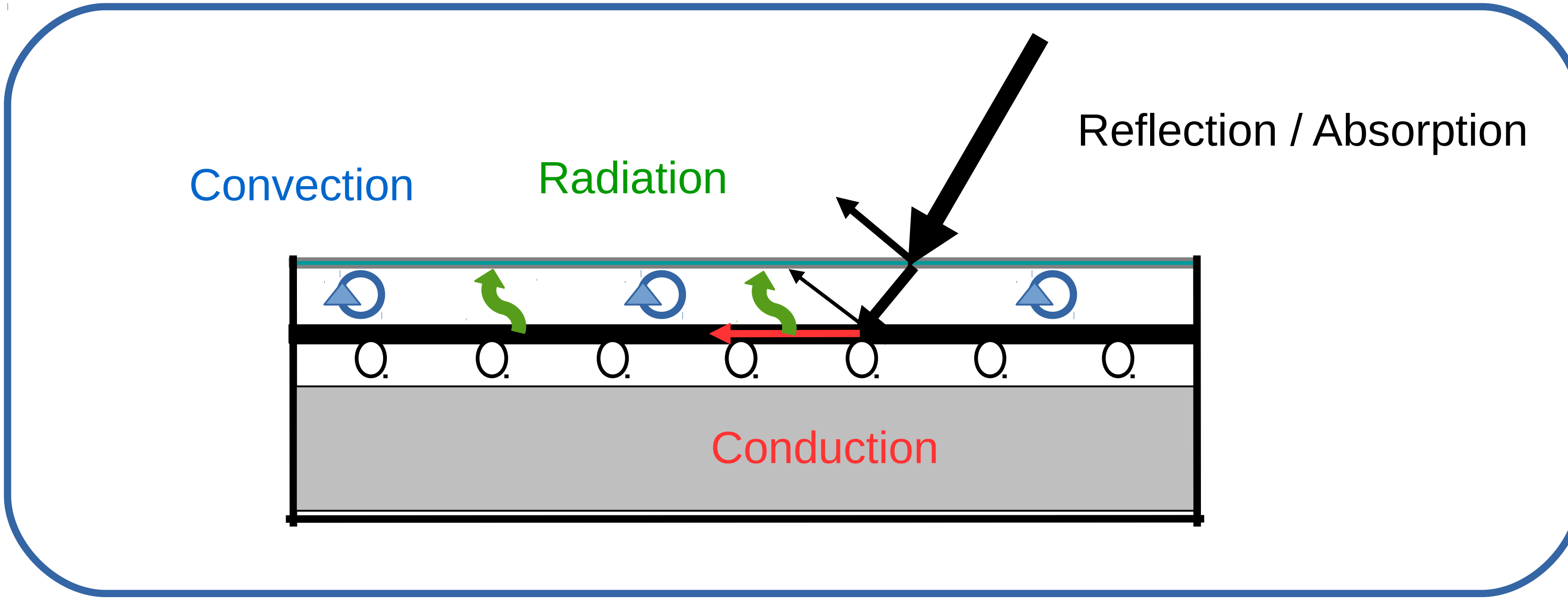
Collectors' performance

$$\eta_{Coll} = \frac{\int \dot{Q}_u \, dt}{A_{coll} \int G_T \, dt}$$

$\boxed{\dot{Q}_u \text{ : useful energy output}}$ [W]

G_T : total incident solar radiation [W/m²]

A_{coll} : total collector area [m²]



Flat plate collectors

Collectors' performance

$$\eta_{Coll} = \frac{\int \dot{Q}_u \, dt}{A_{coll} \int G_T \, dt}$$

Defining the useful energy output: $\dot{Q}_u$

$$\dot{Q}_u = A_{coll} F_R \left[S - U_L \left(T_i - T_a \right) \right] \qquad \text{[W]}$$

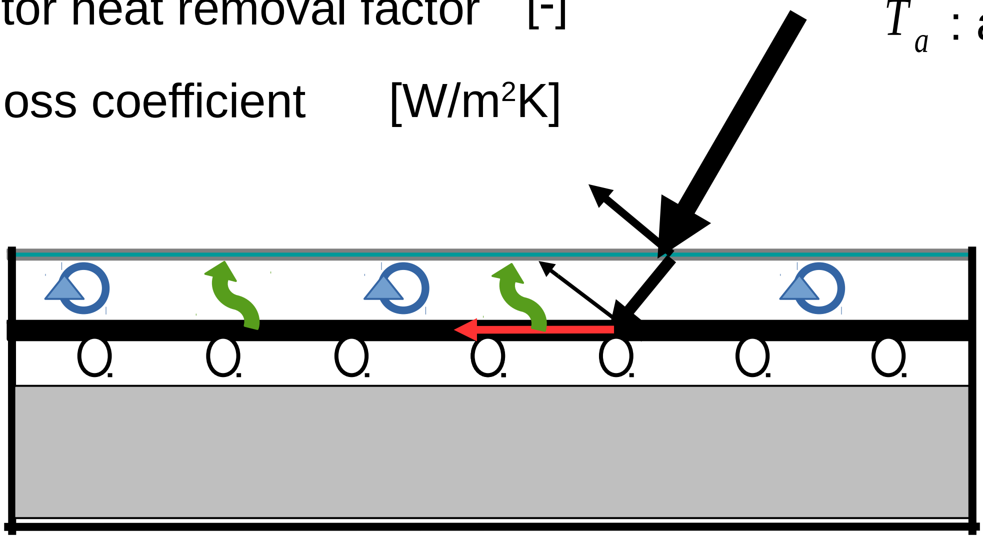
S : absorbed radiation [W/m²]

F_R : collector heat removal factor [-]

U_L : heat loss coefficient [W/m²K]

T_i : inlet fluid temperature [°C]

T_a : ambient temperature [°C]



Flat plate collectors: performance

$$\eta_{Coll} = \frac{\int \dot{Q}_u \, dt}{A_{coll} \int G_T \, dt}$$

Absorbed solar radiation:

$$S = G_b R_b (\tau\alpha)_b + G_d (\tau\alpha)_d \underbrace{\frac{(1+\cos\beta)}{2}}_{\text{view factor sky}} + \rho_g (G_b + G_d)(\tau\alpha)_g \underbrace{\frac{(1-\cos\beta)}{2}}_{\text{view factor ground}} \text{ [W/m}^2\text{]}$$

G : radiation [W/m²]

R_b : ratio of beam radiation on the tilted surface to that on a horizontal surface at any time [-]

$(\tau\alpha)$: transmittance-absorptance product [-]

β : collector tilt angle [°]

ρ_g : ground reflectivity [-]

Subscripts:

b = beam; d = diffuse; g = ground

Flat plate collectors: performance

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Flat plate collectors: performance

Absorbed solar radiation:

R_b : ratio of beam radiation on the tilted surface to that on a horizontal surface at any time [-]

$$R_b = \frac{\cos(\theta)}{\cos(\theta)_z}$$

$$\gamma = 0 \longrightarrow R_b = \frac{\cos(\Phi - \beta)\cos\delta\cos\omega + \sin(\Phi - beta)\sin\delta}{\cos\Phi\cos\delta\cos\omega + \sin\Phi\sin\delta}$$

θ : incidence angle (incident beam to collector normal) [°]

θ_z : incidence angle at zenith [°]

Φ : latitude [°]

ω : Hour angle, sun displacement [°]

β : collector tilt angle (slope) [°]

δ : declination (angular sun position at noon) [°]

γ : azimuth angle (from south, south= 0°) [°]

Flat plate collectors: performance

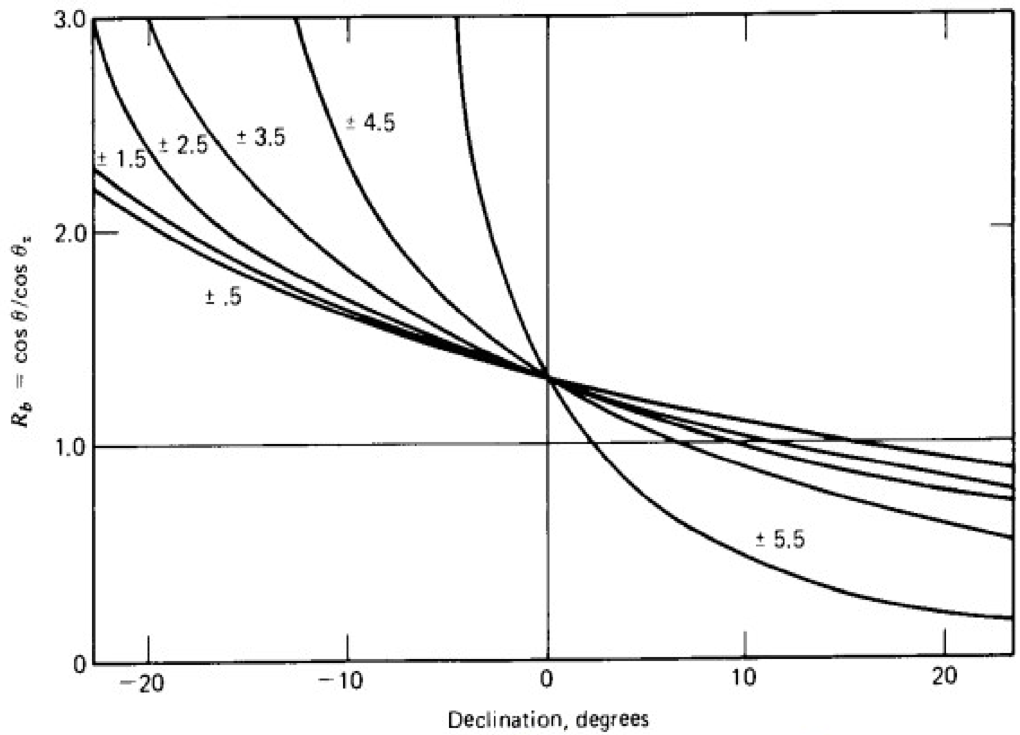
Absorbed solar radiation:

R_b : ratio of beam radiation on the tilted surface to that on a horizontal surface at any time [-]

Example:

$\beta = 50°$

$\Phi = 40°$

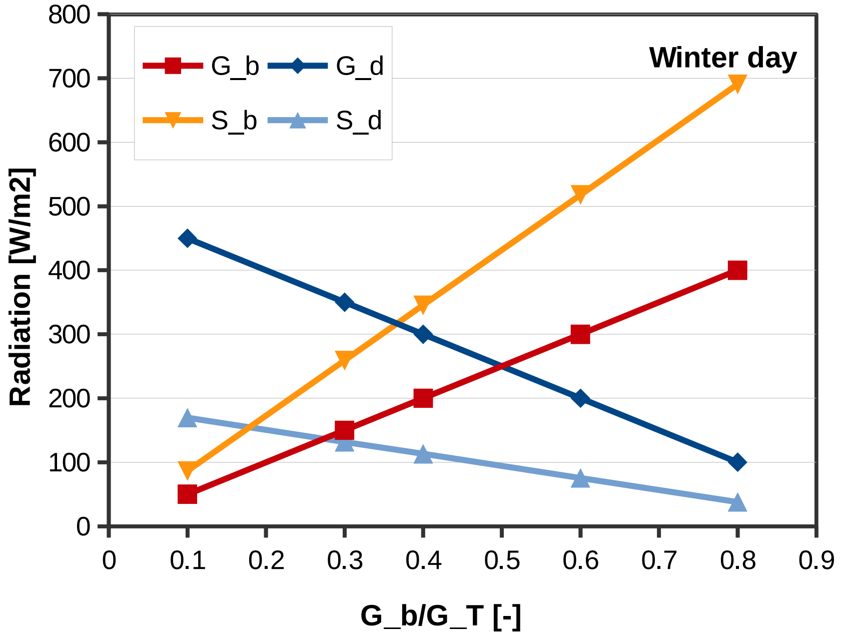


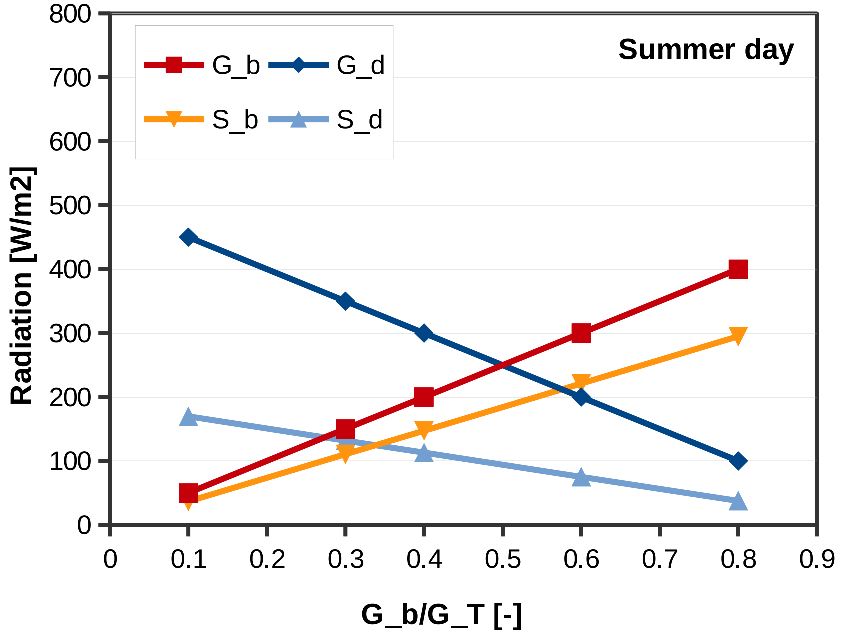
Flat plate collectors: performance

Absorbed solar radiation:

Seasonal contribution of beam and diffuse components

Example: G= 500W/m²; β =60°; α_n=0.93 (single cover collector); ρ_g=0.6 $\Phi = 40°$





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Defining the useful energy output: $\dot{Q}_u$

$$\dot{Q}_u = A_{coll} F_R \left[S - U_L \left(T_i - T_a \right) \right] \qquad \text{[W]}$$

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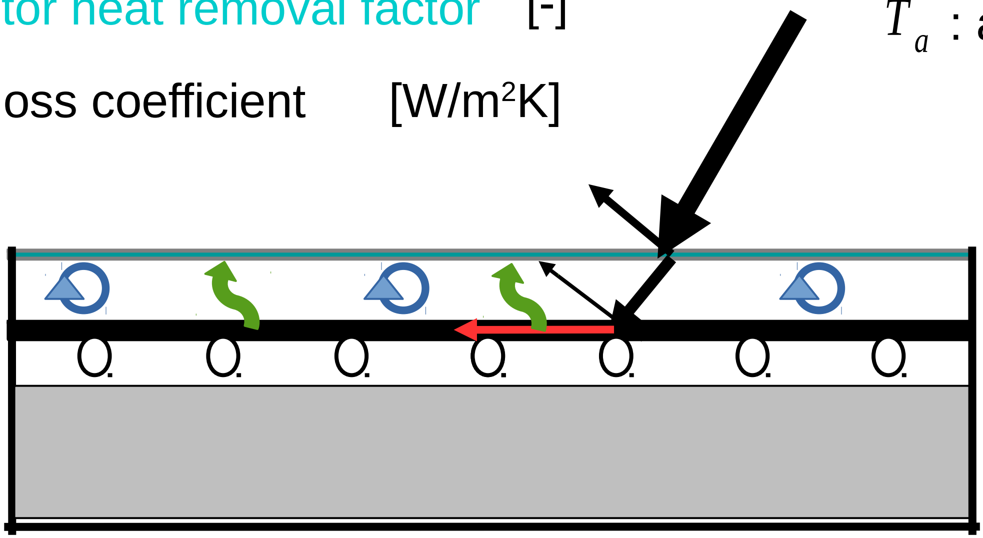


Flat plate collectors: performance

Heat removal factor: F_R

≈ effectiveness of a heat exchanger: ratio of actual heat exchange to maximum one (with minimum losses, i.e. $T_{fluid}=T_{in}$

$$F_R = \frac{\dot{m} C_p}{A_{coll} U_L}\left[1-\exp\left(\frac{-A_{coll} U_L F'}{\dot{m} C_p}\right)\right]$$

$\dot{m}$: collector mass flow rate [kg/s]

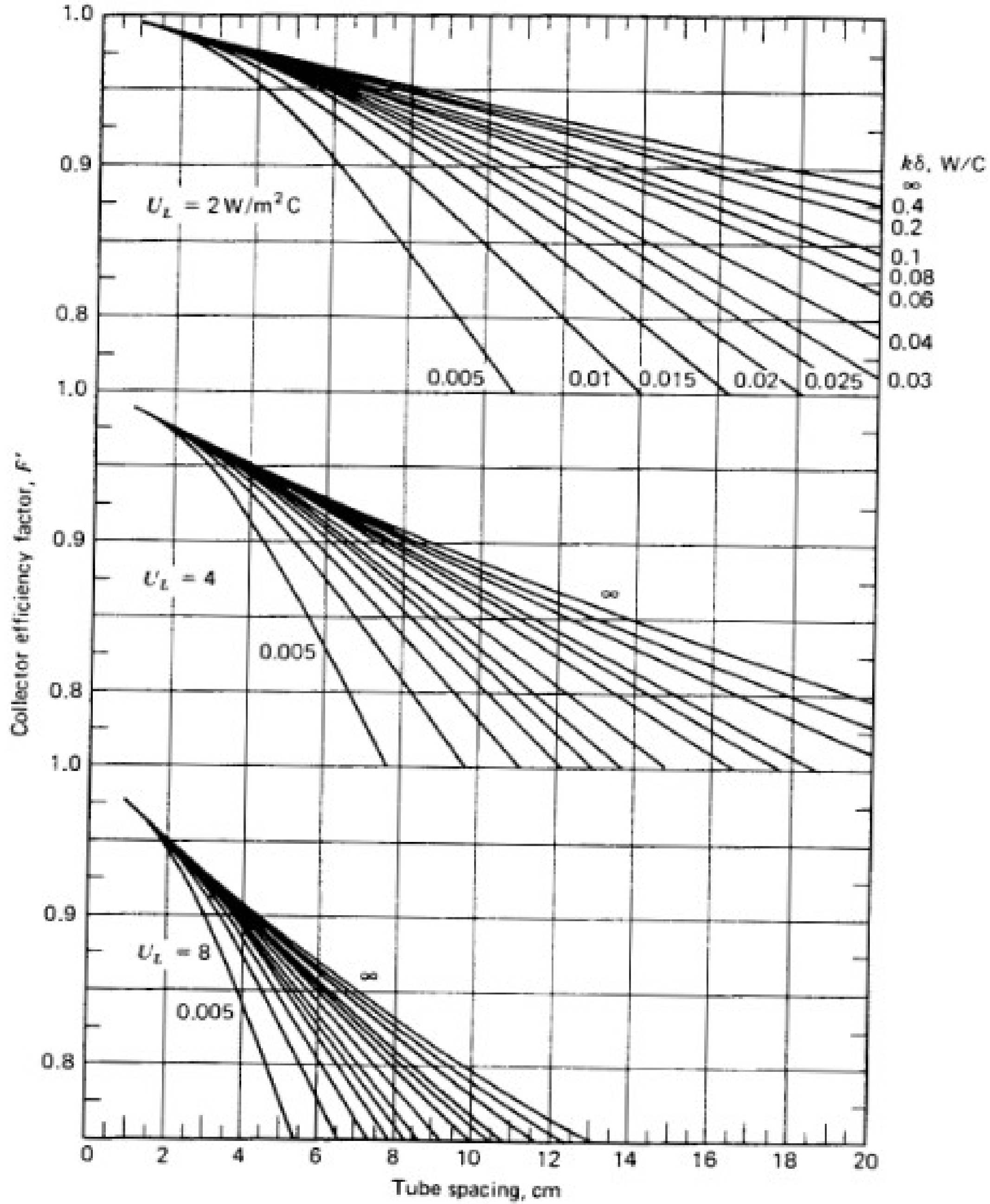
C_p: specific heat capacity fluid [kJ/KgK]

A_{coll}: collector area [m^2]

U_L: overall loss coefficient [W/Km^2**]**

F': collector efficiency factor [-]
Function of geometry (tube spacing, tube diameter, absorber thickness) and materials (loss coefficient, U_L)

Behavior of collector efficiency factor, F'



Source: Duffie and Beckman. 2013

Flat plate collectors: performance

Heat removal factor: F_R

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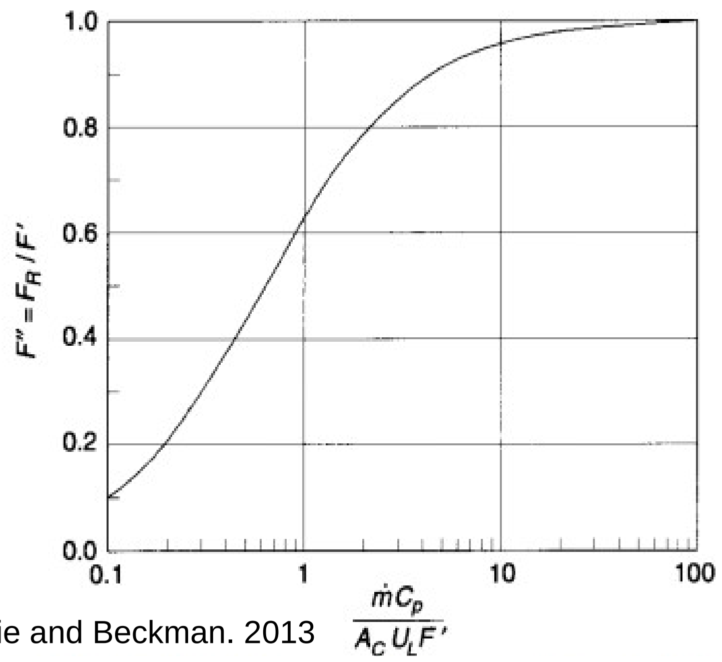
Collector flow factor [-]: effect of mass flow rate on collectors' performance

$$F'' = \frac{F_R}{F'}$$



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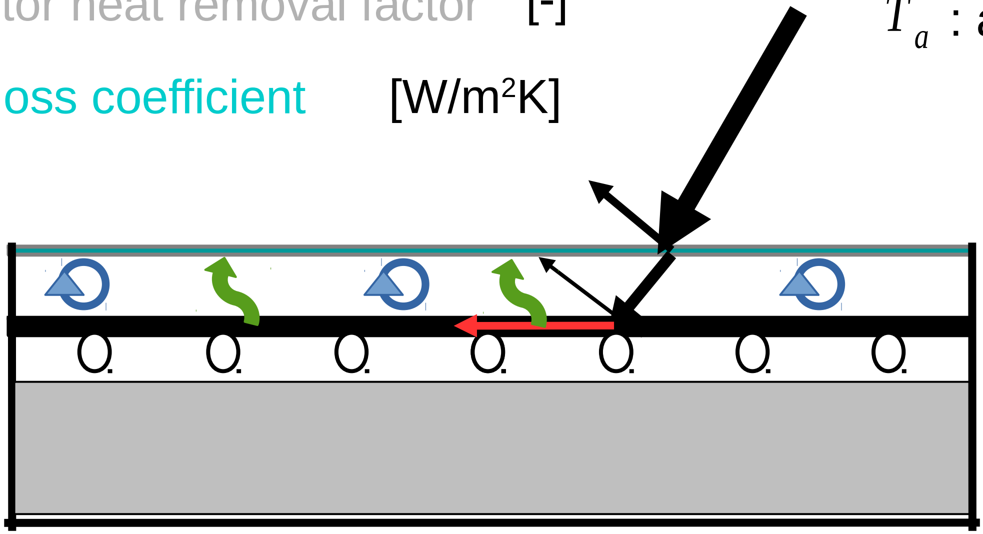
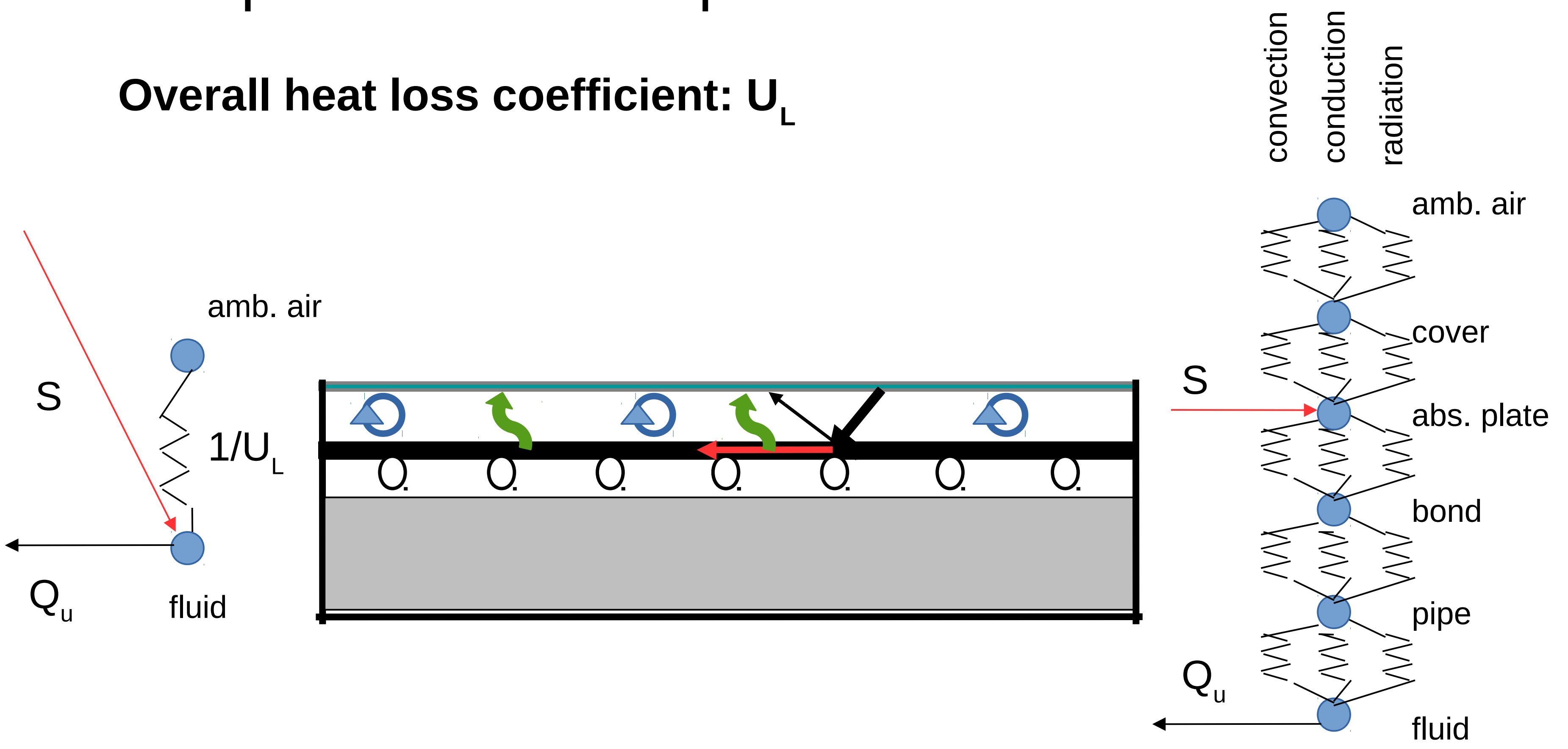


Flat plate collectors: performance

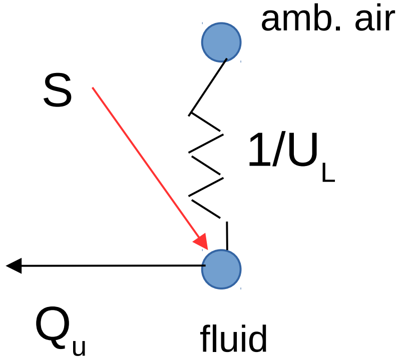
Overall heat loss coefficient: U_L

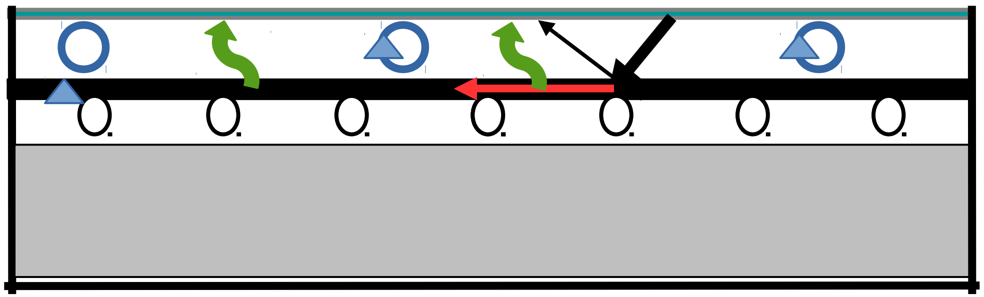


Flat plate collectors: performance

Overall heat loss coefficient: U_L

Often determined experimentally





Conduction:

$$q_{cond} = \frac{\lambda}{d}\left(T_1 - T_2\right)$$

λ: thermal conductivity [W/mK]

d: thickness [m]

Convection:

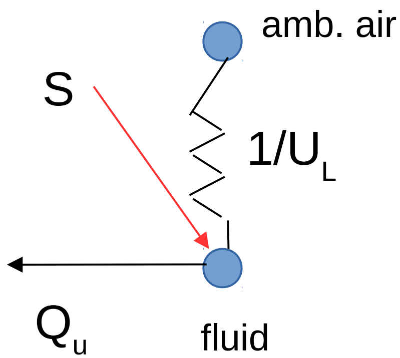
$$q_{conv} = h_i\left(T_1 - T_2\right)$$

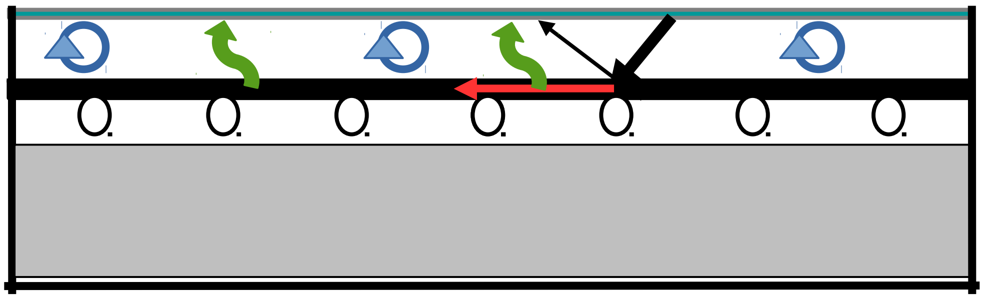
h_i: convective heat transfer coefficient [W/K]

Flat plate collectors: performance

Overall heat loss coefficient: U_L

Often determined experimentally





Radiation:

$$q_{rad} = \sigma \varepsilon \left(T_1^4 - T_2^4 \right)$$

σ: Stephan-Boltzmann constant [W/m^2K^4]

<u>ε: emissivity [-]</u> → **<u>Selective surface!</u>**

T: absolute temperature [K]

Flat plate collectors: performance

Overall heat loss coefficient: U_L

Often determined experimentally

Radiation:

$$q_{rad} = \sigma\varepsilon\left(T_1^4 - T_2^4\right)$$

ε: emissivity [-]

	ε	α
"TINOX" [1]	0.04	0.95
Copper polished[2]	0.23-0.52	0.18
Aluminum polished[2]	0.09	0.30

1 http://www.almecogroup.com/uploads/1074-ALMECO_TinoxEnergy_ENG_S402_05_2013_mail.pdf

2 www.engineeringtoolbox.com

Flat plate collectors: performance

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Defining the useful energy output:

$\dot{Q}_u$

$$\dot{Q}_u = A_{coll} F_R \left[\boxed{S} - U_L \left(\boxed{T_i} - T_a \right) \right] \quad \text{[W]}$$

S : absorbed radiation [W/m²]

F_R : collector heat removal factor [-]

U_L : heat loss coefficient [W/m²K]

T_i : inlet fluid temperature [°C]

T_a : ambient temperature [°C]

→ Determining S is not an easy task (requires detailed hourly data of radiation and angles variations)

→ Standard (european) collector test procedures often refer to the mean fluid temperature, not the inlet one!

Flat plate collectors: performance

$$\eta_{Coll} = \frac{\int \dot{Q}_u \, dt}{A_{coll} \int G_T \, dt}$$

Defining the useful energy output:

$\dot{Q}_u$

$$\dot{Q}_u = A_{coll} F_R \left[S - U_L \boxed{\left(T_i - \right.} \left. T_a \right) \right] \quad \text{[W]}$$

S : absorbed radiation [W/m²]

F_R : collector heat removal factor [-]

U_L : heat loss coefficient [W/m²K]

T_i : inlet fluid temperature [°C]

T_a : ambient temperature [°C]

$$\dot{Q}_u = A_{coll} \boxed{F_{av}} \left[S - U_L \boxed{\left(T_m - \right.} \left. T_a \right) \right] \quad \text{[W]}$$

$$T_m = \frac{T_i + T_{out}}{2}$$

T_i : average fluid temperature [°C]

T_a : ambient temperature [°C]

Flat plate collectors: performance

$$\eta_{Coll} = \frac{\int \dot{Q}_u \, dt}{A_{coll} \int G_T \, dt}$$

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U_L : heat loss coefficient [W/m²K]

T_i : inlet fluid temperature [°C]

T_a : ambient temperature [°C]

$$\dot{Q}_u = A_{coll} F_{av} \left[\boxed{G_T (\tau\alpha)_n K_{\tau\alpha}} - U_L (T_m - T_a) \right] \text{[W]}$$

G_T: global incident radiation on coll. plane [W/m²]

$(\tau\alpha)_n$: average transmittance-absorptance product for beam (normal) radiation [-]

$K_{\tau\alpha}$: incident angle modifier – function of θ (effective incident angle!) [-]

Flat plate collectors: performance

$$\eta_{Coll} = \frac{\int \dot{Q}_u \, dt}{A_{coll} \int G_T \, dt}$$

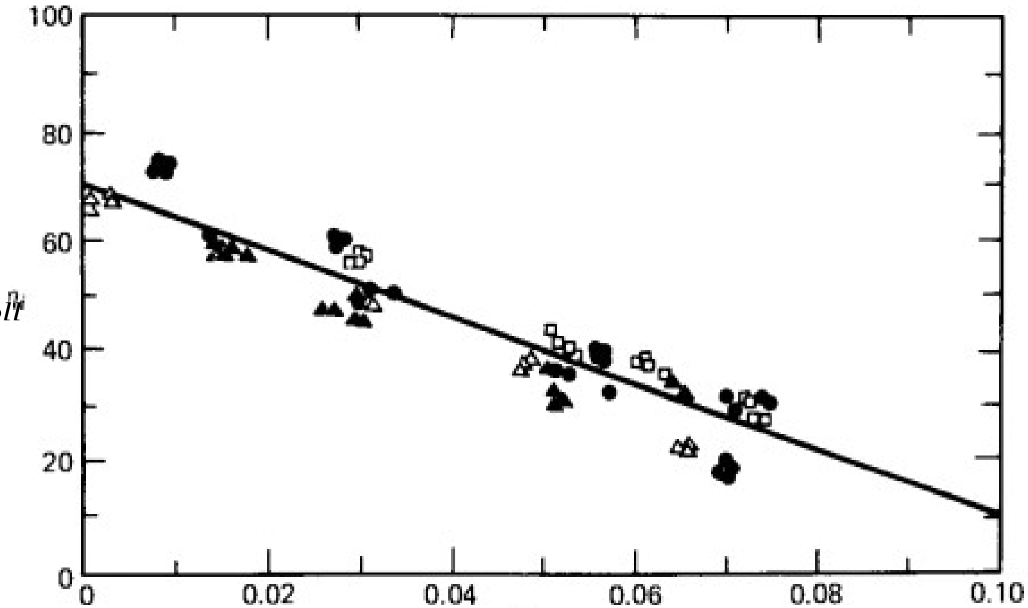
$$\dot{Q}_u = A_{coll} F_{av} \left[G_T (\tau\alpha)_n K_{\tau\alpha} - U_L (T_m - T_a) \right]$$

$$\eta_{coll} = F_{av} (\tau\alpha)_n - \frac{F_{av} U_L (T_m - T_a)}{G_T}$$

Data scatters from linear dependency:

- U_L is a function of temperature
- F_{av} is also weak function of temperature

η_{coll}



$$\frac{(T_m - T_a)}{G_T}$$

Source: Duffie and Beckman. 2013

Flat plate collectors: performance

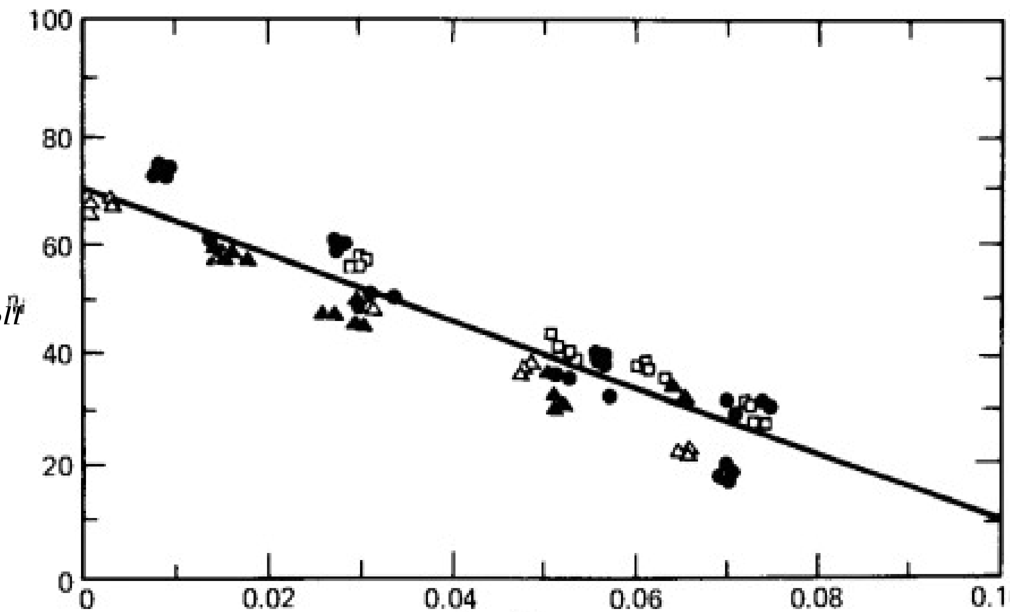
$$F_{av} U_L = c_1 + c_2 (T_m - T_a)$$

$$\eta_{coll} = F_{av} (\tau\alpha)_n - c_1 \frac{(T_m - T_a)}{G_T} - c_2 \frac{(T_m - T_a)^2}{G_T}$$

Data scatters from linear dependency:

- U_L is a function of temperature
- F_{av} is also weak function of temperature

η_{coll}



$\frac{(T_m - T_a)}{G_T}$

Source: Duffie and Beckman. 2013

Flat plate collectors: performance

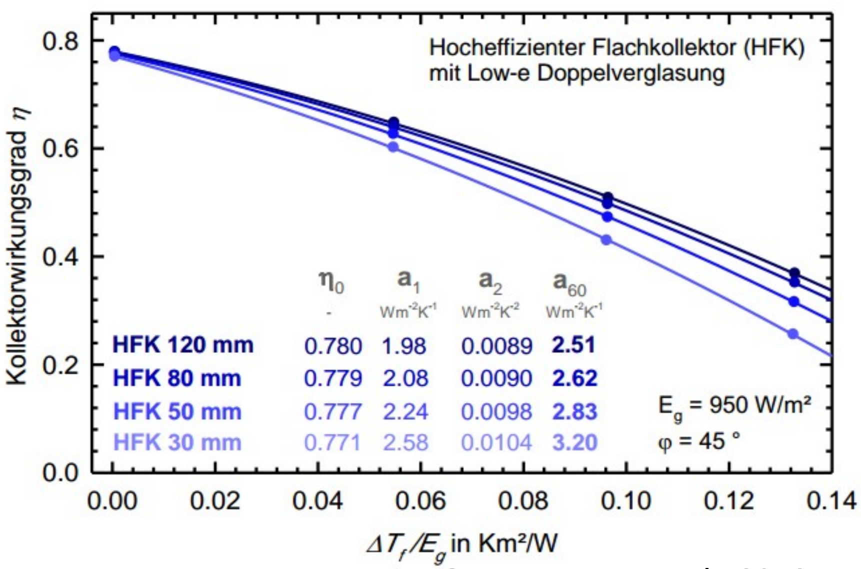
$$F_{av} U_L = c_1 + c_2 (T_m - T_a)$$

$$\eta_{coll} = \boxed{F_{av} (\tau\alpha)_n} - c_1 \frac{(T_m - T_a)}{G_T} - c_2 \frac{(T_m - T_a)^2}{G_T}$$

$$\eta_{coll} = \boxed{\eta_0} - c_1 \frac{(T_m - T_a)}{G_T} - c_2 \frac{(T_m - T_a)^2}{G_T}$$

η_0: zero loss efficiency [-]

Not optical efficiency!!!!



Source: Föste et al., 2013

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Flat plate collectors: performance

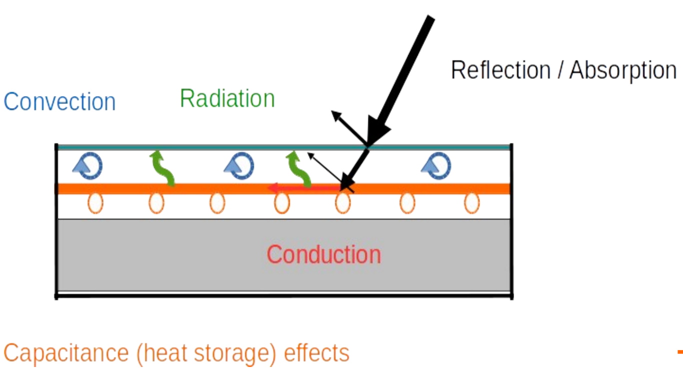
Collectors' DYNAMIC performance

European Standard EN 12975-2

Thermal Solar Systems and Components – Solar Collectors CEN2001

$$\dot{Q}_u = \underbrace{F'(\tau\alpha)_{en} K_{\theta b}(\theta) G_b}_{\text{beam}} + \underbrace{F'(\tau\alpha)_{en} K_{\theta d} G_d}_{\text{diffuse}} - \boxed{c_6 u G} - c_1 (T_m - T_a) - c_2 \left((T_m - T_a)^2 \right) - \boxed{c_3 u (T_m - T_a)} + \boxed{c_4 u (E_L - \sigma T_a^4)} - \boxed{c_5 \frac{dT_m}{dt}}$$

Wind speed dependence of zero losses



Wind speed dependence of heat losses

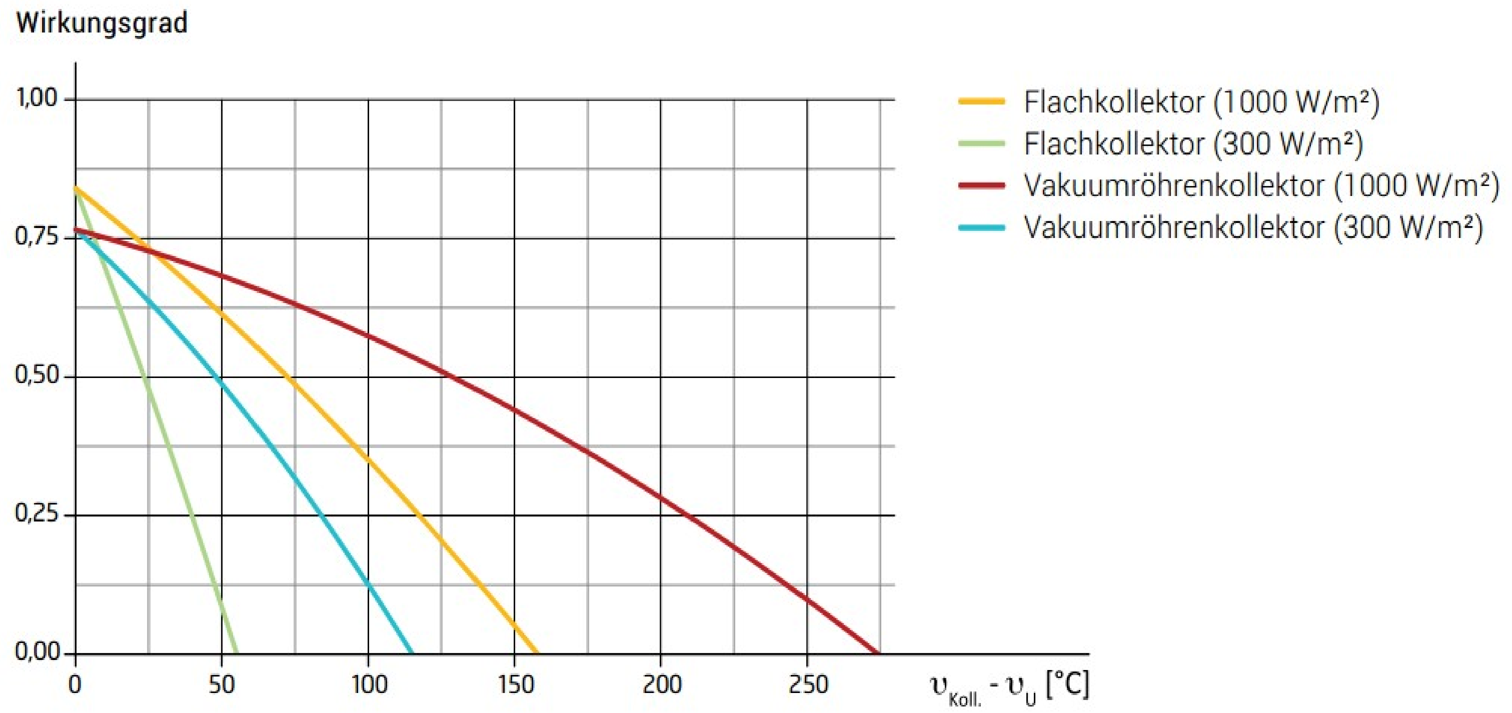
Long-wave irradiance

Thermal capacitance / Thermal inertia processes

Source:Fischer, Müller-Steinhagen., 2001

Flat plate collectors: performance

$$\eta_{coll}=\eta_0-c_1\frac{(T_m-T_a)}{G_T}-c_2\frac{(T_m-T_a)^2}{G_T}$$



Source: Corradini et al., 2014

Flat plate collectors: performance

$$\eta_{coll} = \eta_0 - c_1 \frac{(T_m - T_a)}{G_T} - c_2 \frac{(T_m - T_a)^2}{G_T}$$

Collector database: http://www.solarkeymark.dk/CollectorCertificates

Collector Type	η_0 [-]	c_1 [W/m²K]	c_2 [W/m²K]	c_{eff} [J/m²K]
Vacuum tube	0.789	1.370	0.005	10.80
Vacuum tube + reflector	0.614	0.285	0.011	17.50
High tech flat plate	0.797	2.833	0.013	4.85
-Low tech flat plate	0.711	4.878	0.044	33.51

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