Solar collectors

- types
- efficiency
- application
- statistics

Photothermal conversion

- **collecting surface (collector)**

  surface absorbing solar radiation which converts to heat

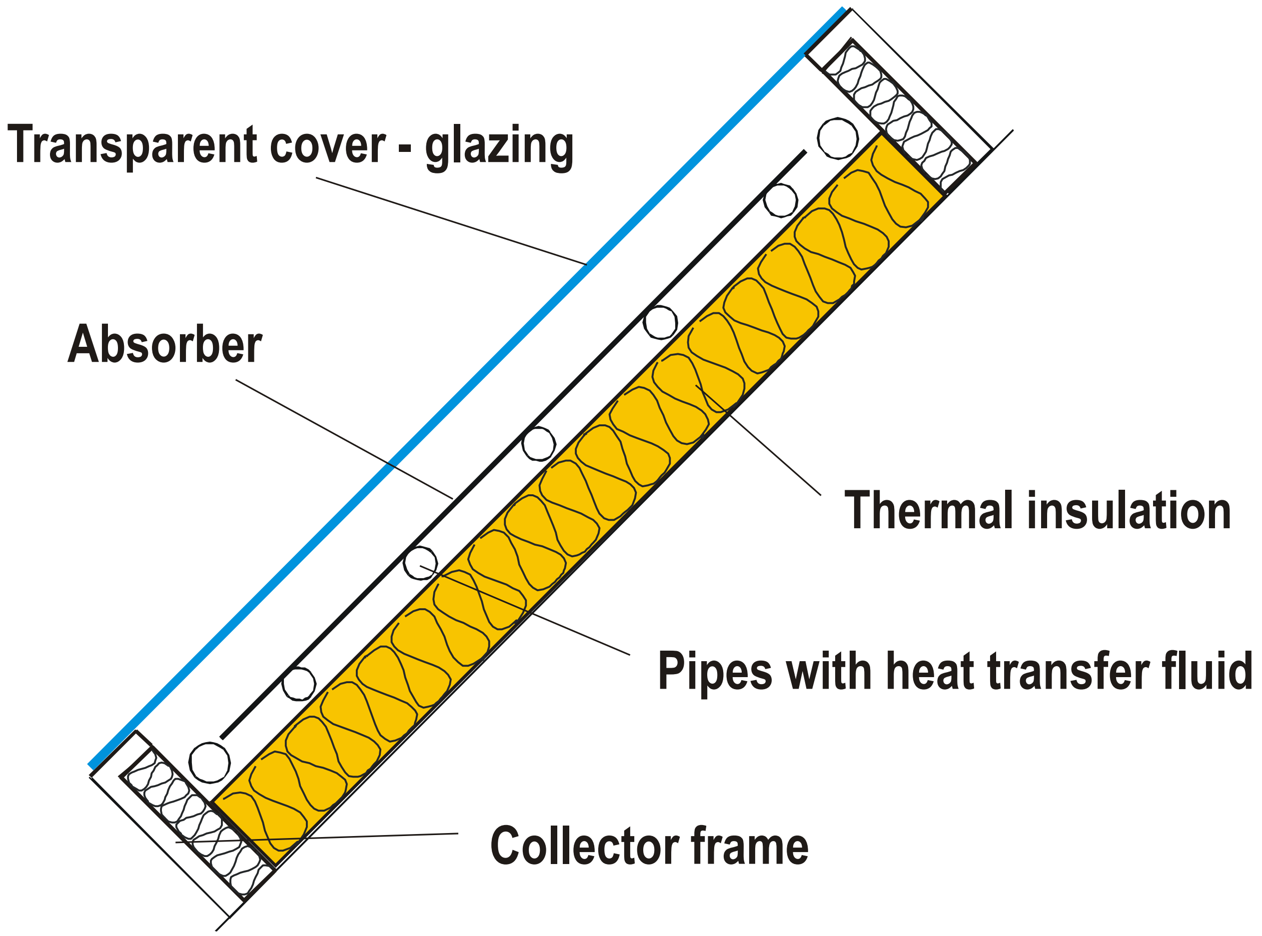
- **accummulation (heat storage)**

  storing the solar heat gains for further use
  (storage tank, wall, mass in the building space, ...)

- **consumer**

  hot water, heating, cooling, ...

Solar collector



Solar collectors

solar collectors

fluid
- liquid
- air

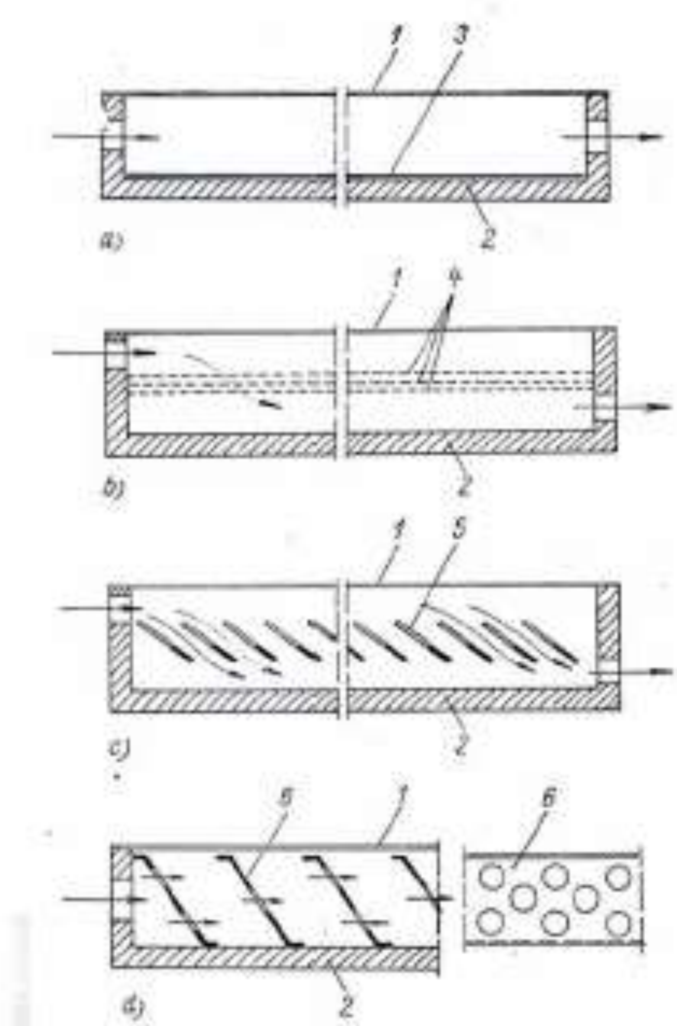
construction type
- flat plate
- tube
- concentrating

glazing
- no cover
- single
- multiple
- structure

pressure
- atmospheric (100 kPa)
- reduced (< 100 Pa)
- vacuum (< 0.1 Pa)

absorber
- plastic
- metal nonselective
- metal selective
- accummulation

Solar air collectors



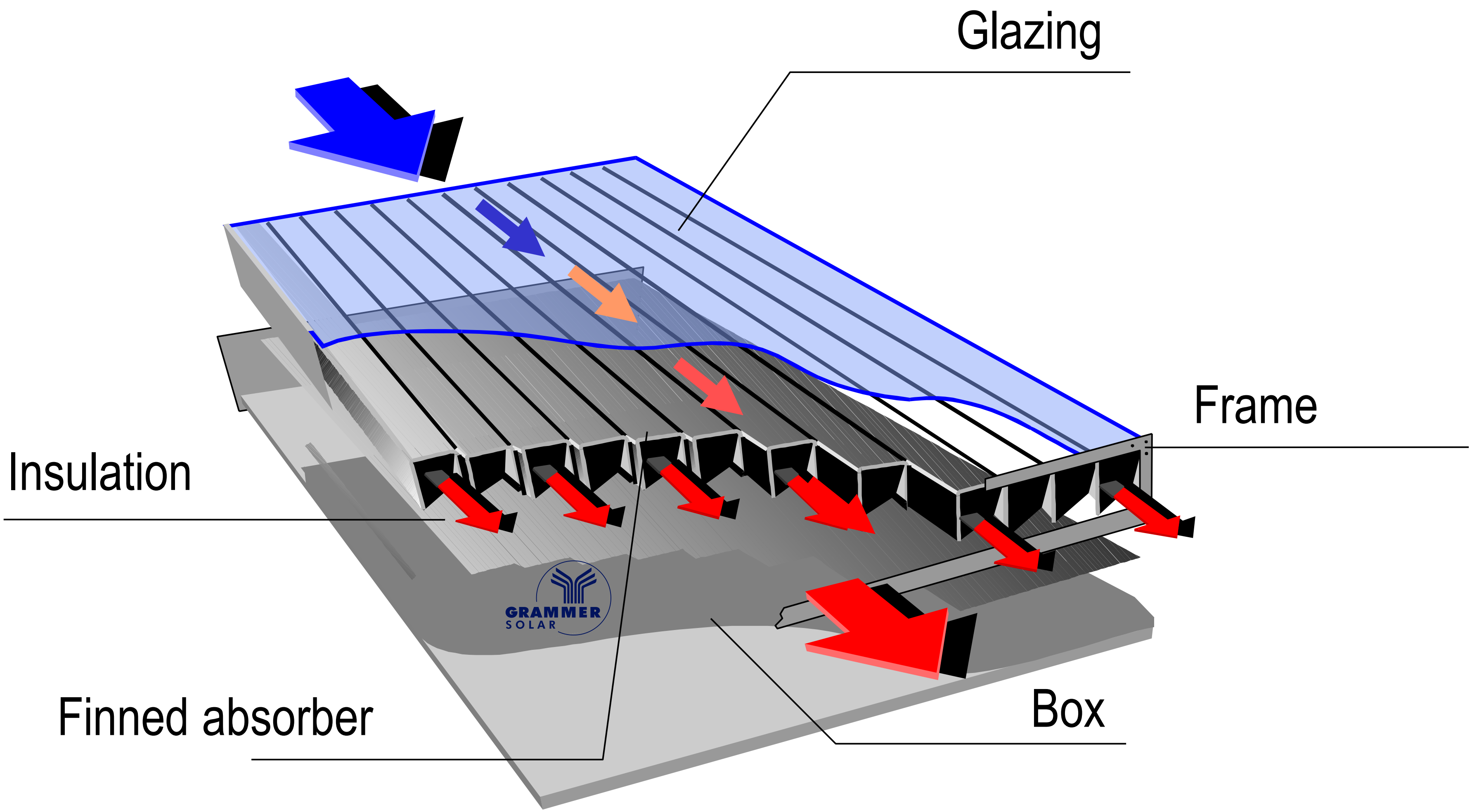
- heat transfer fluid is **air**
- heats from outer surface of absorber
- low heat capacity, high flowrates, large dimensions
- high auxilliary electricity use

- **applications:**

  agriculture – drying

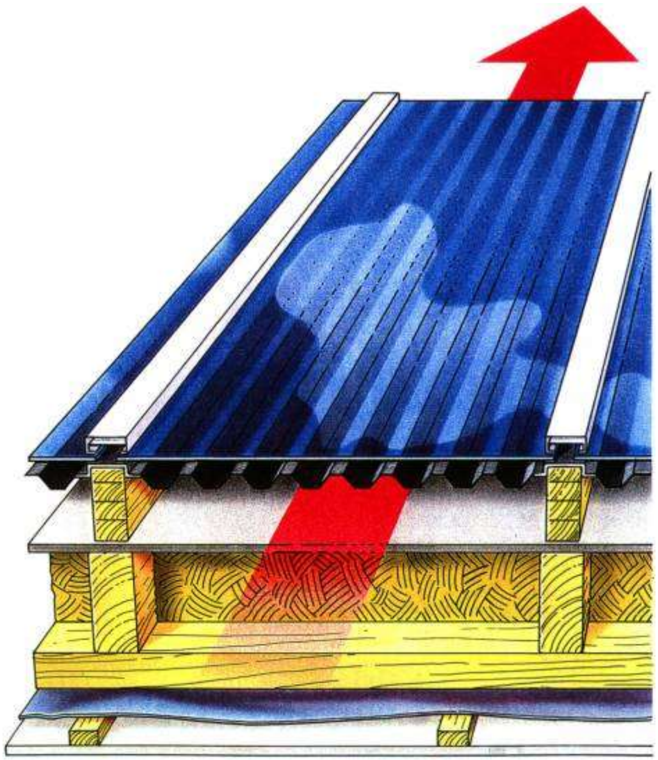
  residental – heating of ventilation air

Solar air collectors



Solar air collectors

Solar air collectors



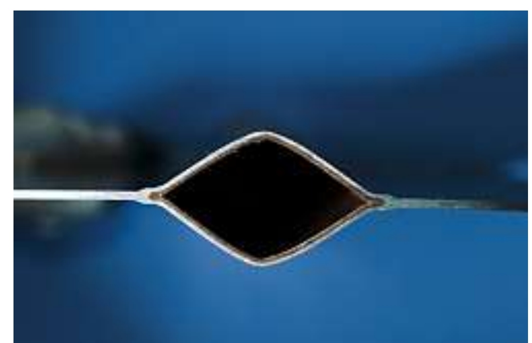
integration into roof

Solar liquid collectors

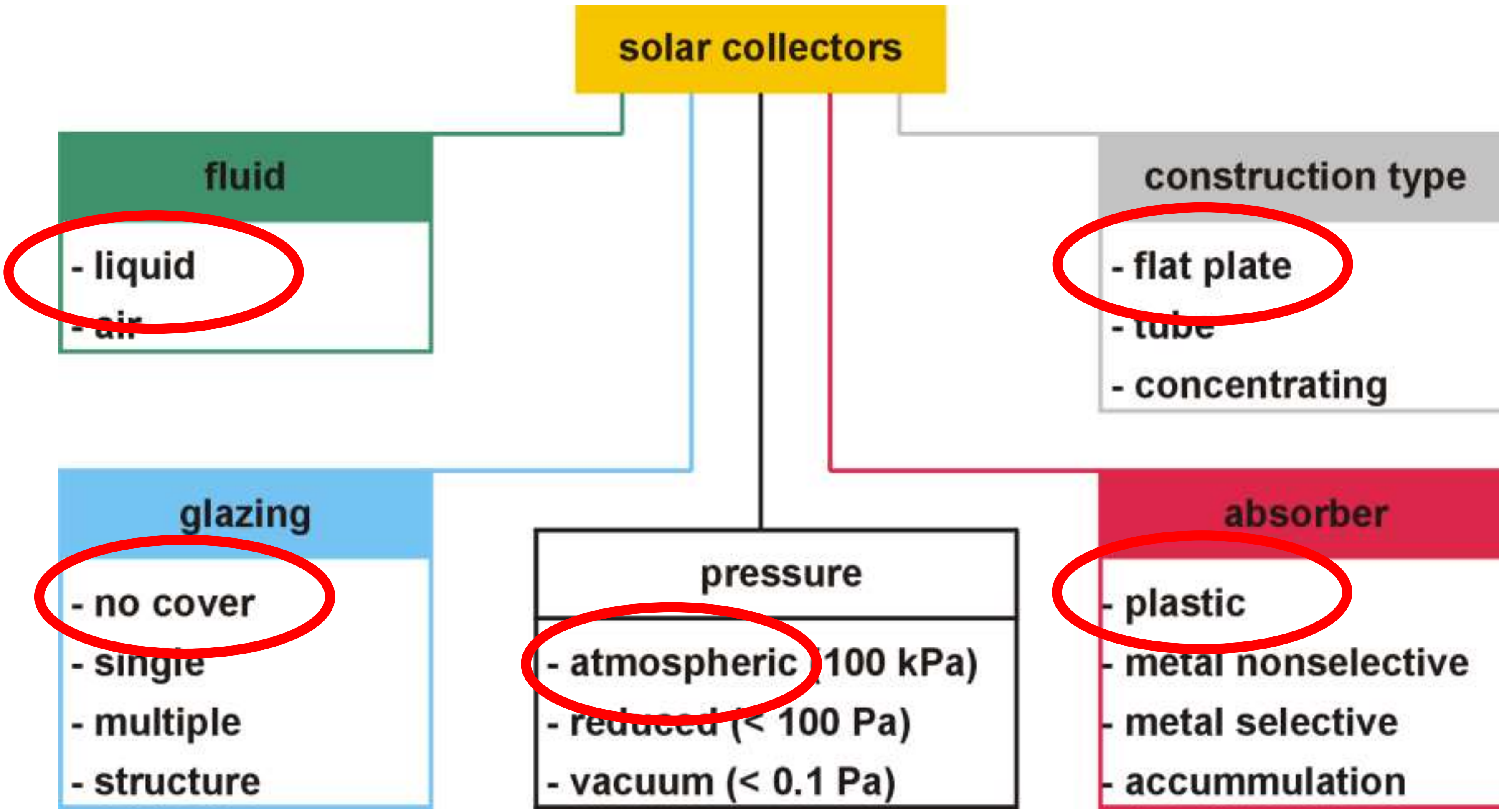
- **liquid** as heat transfer fluid

  (water, antifreeze, oil, etc.)

- energy absorbed at surface is removed by heat transfer liquid flowing inside pipes of absorber



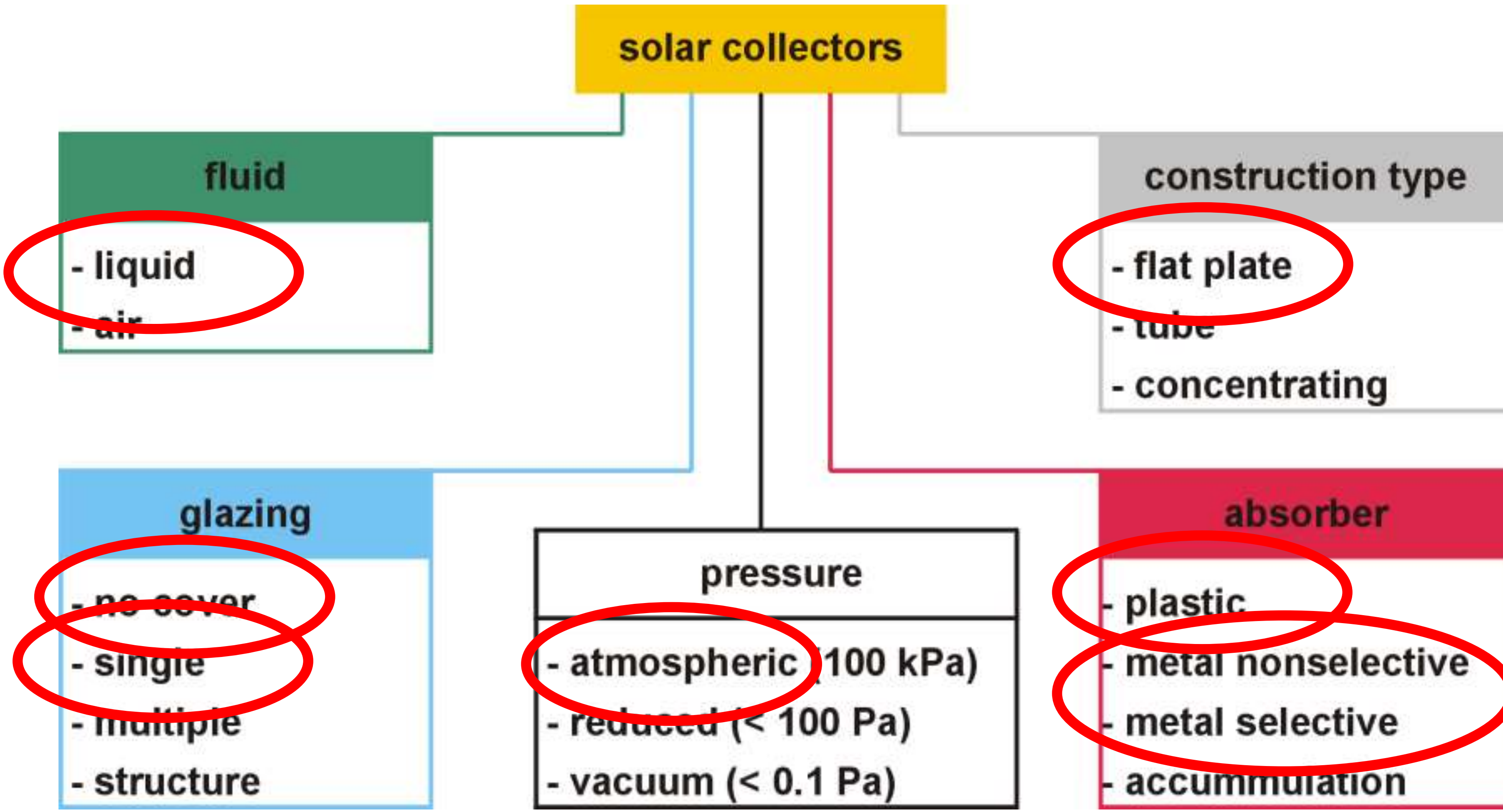
Solar collectors



Unglazed solar collectors

- temperature level < 40 °C
- seasonal applications, swimming pools
- strongly dependent on ambient conditions (temperature, wind)

Solar collectors



Flat plate covered solar collectors

1 frame

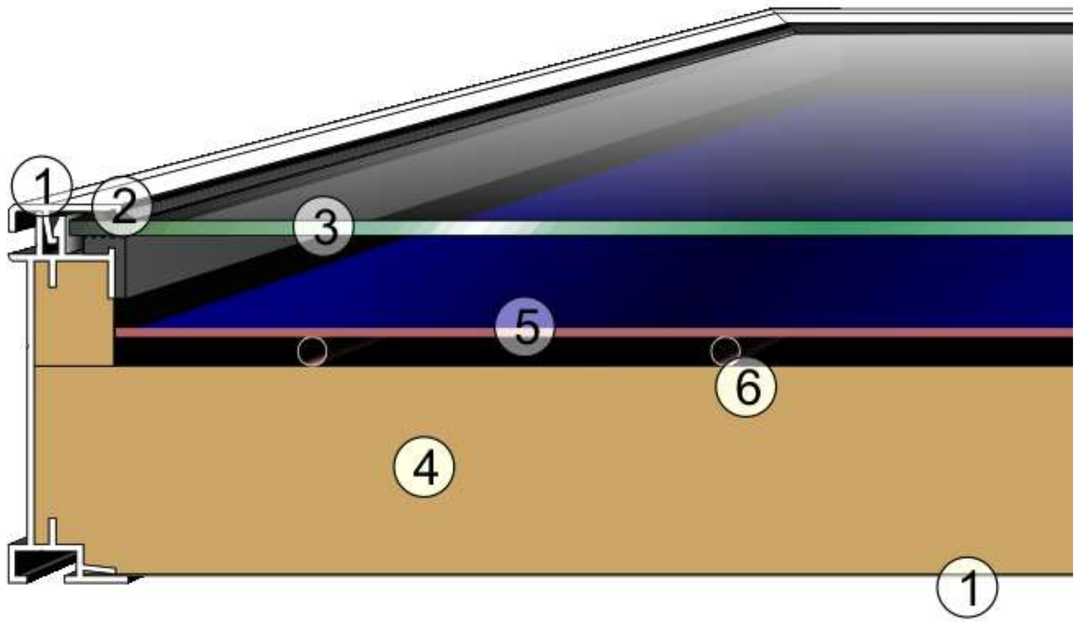
2 sealing

3 transparent cover

4 thermal insulation

5 absorber

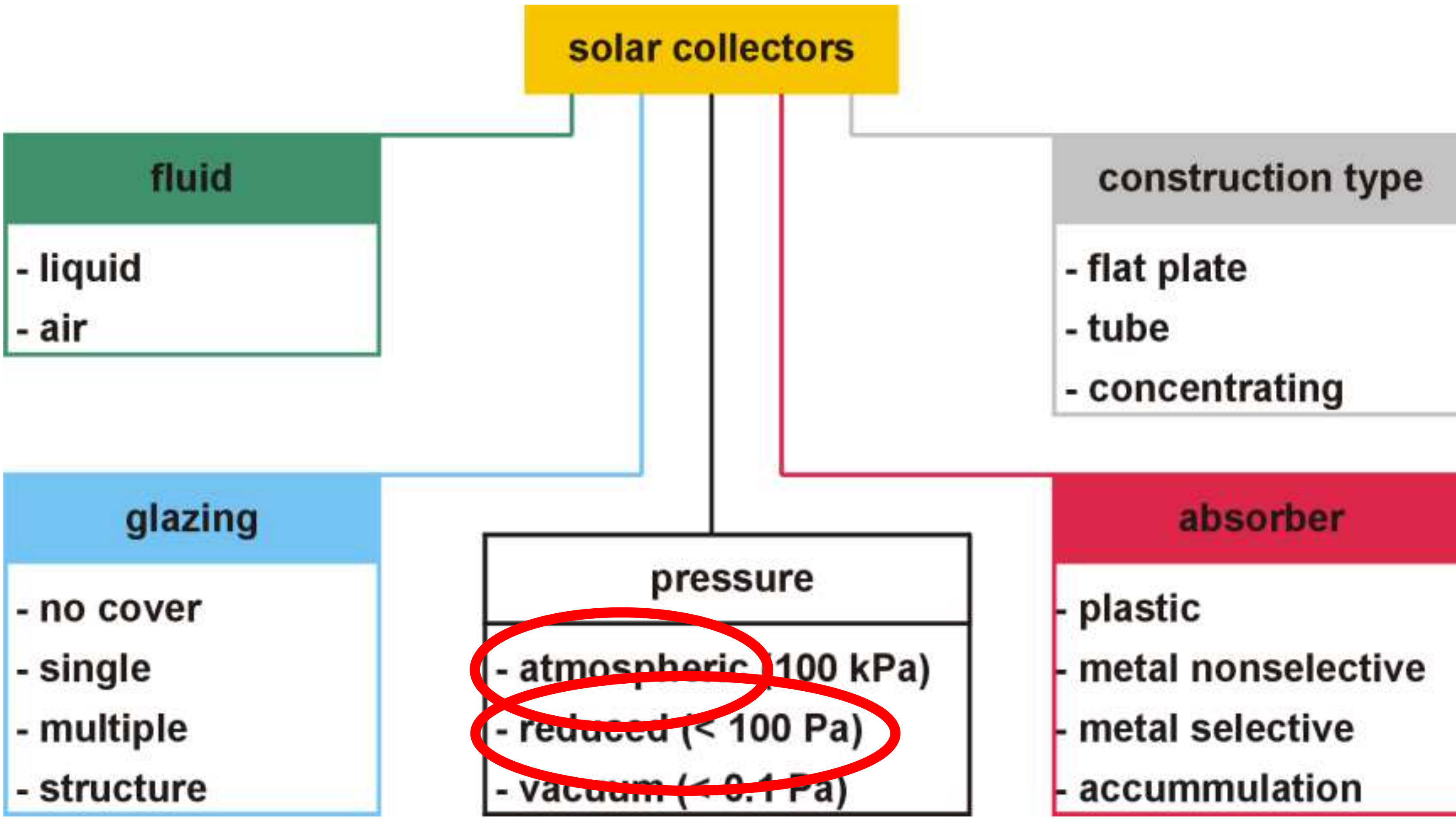
6 pipe register



Flat plate solar collectors

- suitable for building envelope integration
  - roof
  - facade

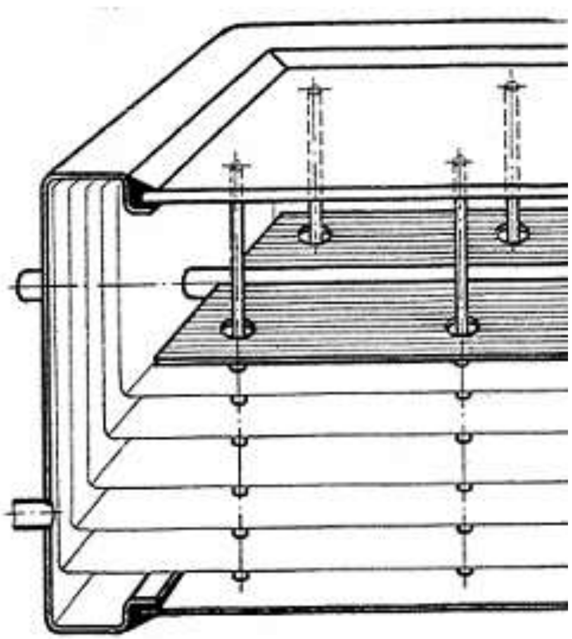
Solar collectors



Vacuum flat plate solar collectors

underpressure to reduce heat loss (absolute pressure **1 to 10 kPa**)

load upon flat cover glazing (pillars)



need for shading the radiation heat trasfer to back side (IR reflectors)

Solar collectors

solar collectors

fluid
- liquid
- air

construction type
- flat plate
- tube
- concentrating

glazing
- no cover
- single
- multiple
- structure

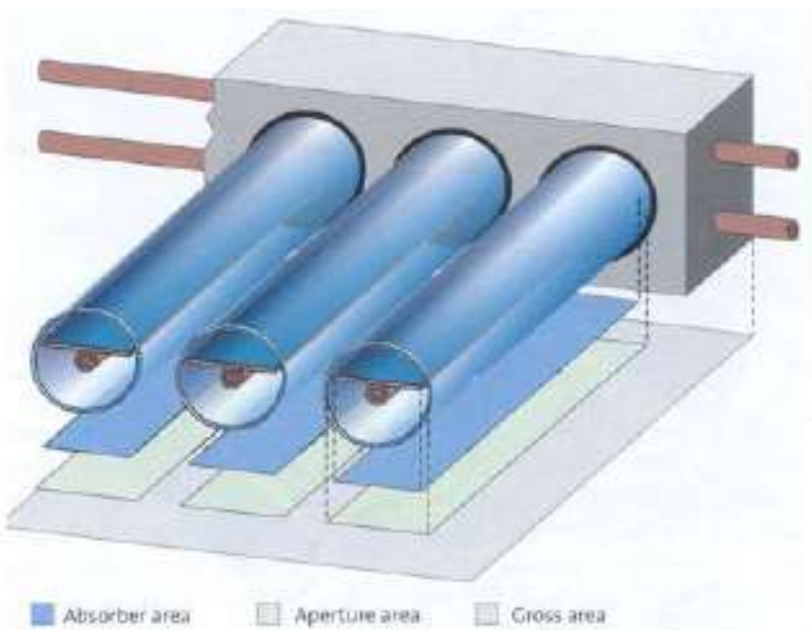
pressure
- atmospheric (100 kPa)
- reduced (< 100 Pa)
- vacuum (< 0.1 Pa)

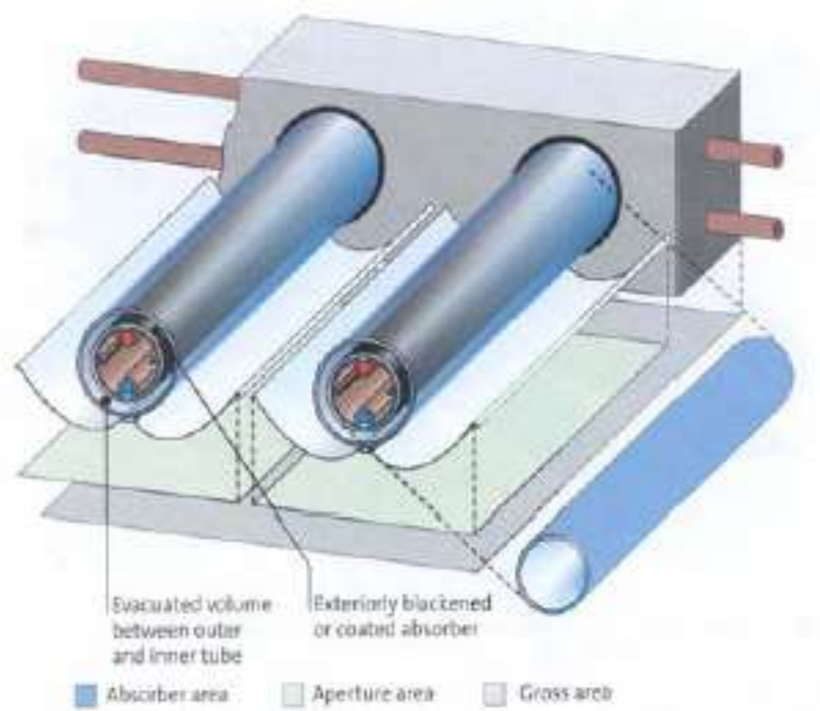
absorber
- plastic
- metal nonselective
- metal selective
- accumulation

Vacuum tube solar collectors

single vacuum tube
flat absorber

double vacuum tube (Sydney)
cylindric absorber





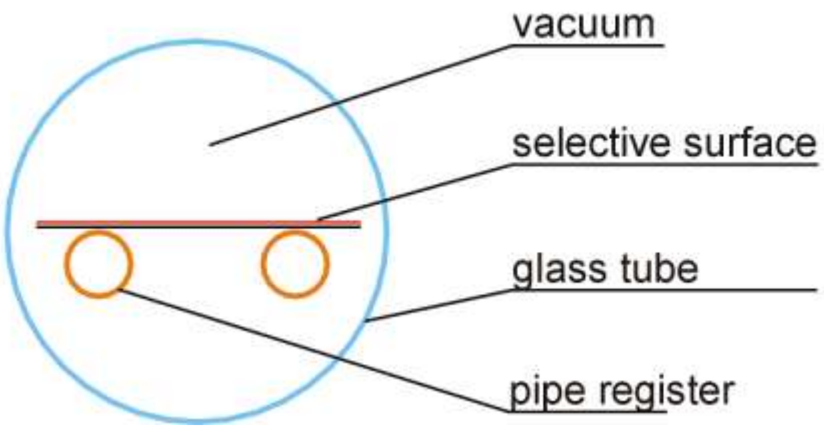
high vacuum 1 mPa

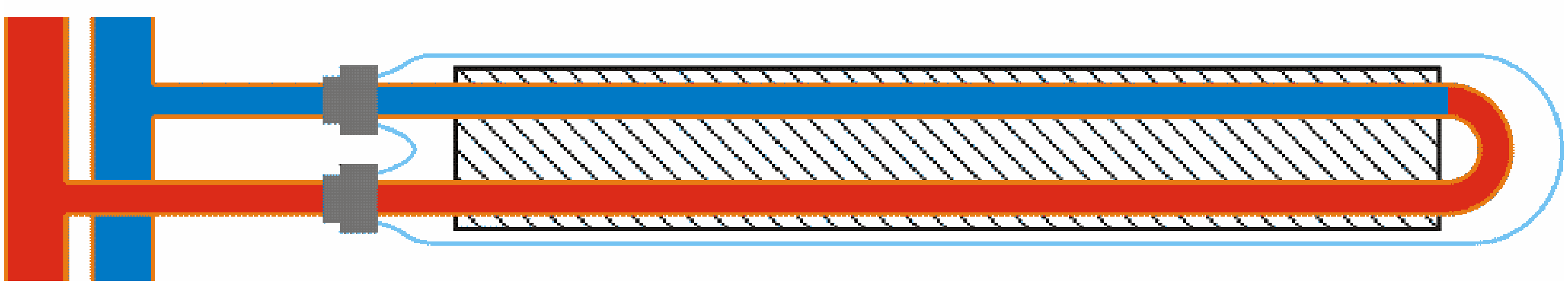
Vacuum tube solar collectors

Single vacuum tube

with flat absorber

- direct flow (DF)





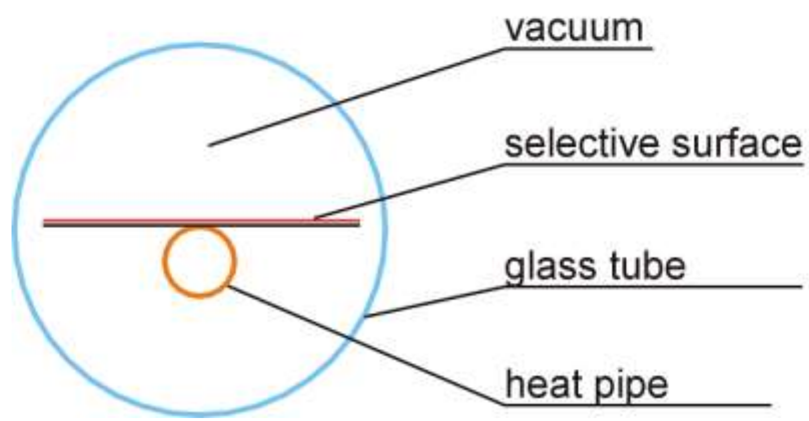
high quality heat transfer from absorber into fluid

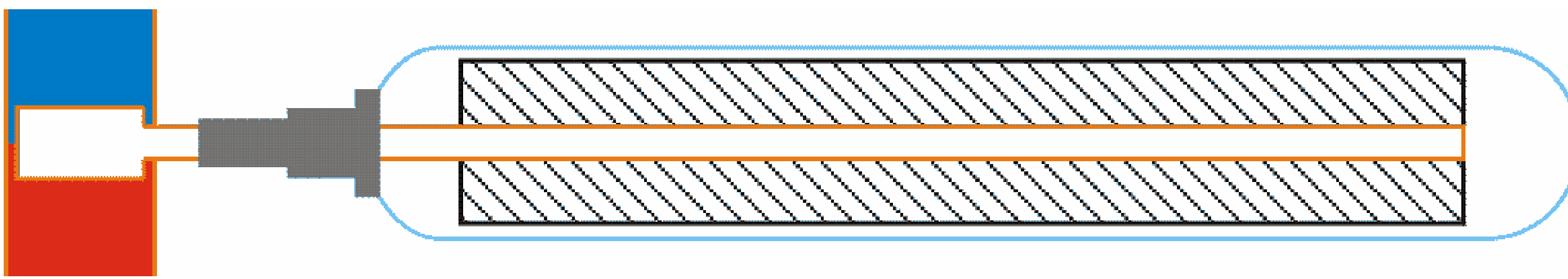
Vacuum tube solar collectors

Single vacuum tube

with flat absorber

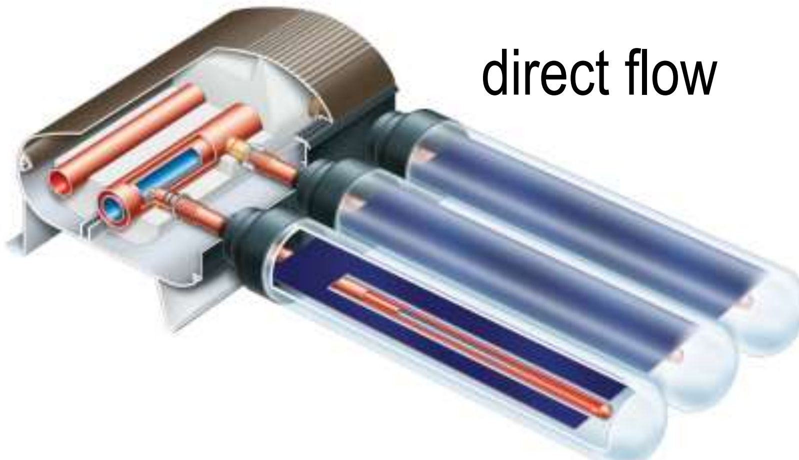
- heat pipe (HP)



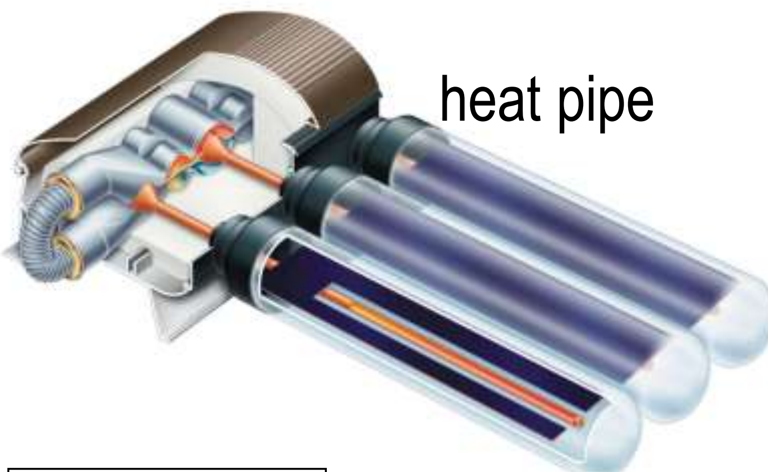


high quality heat transfer from absorber to evaporator part

Vacuum tube solar collectors



direct flow



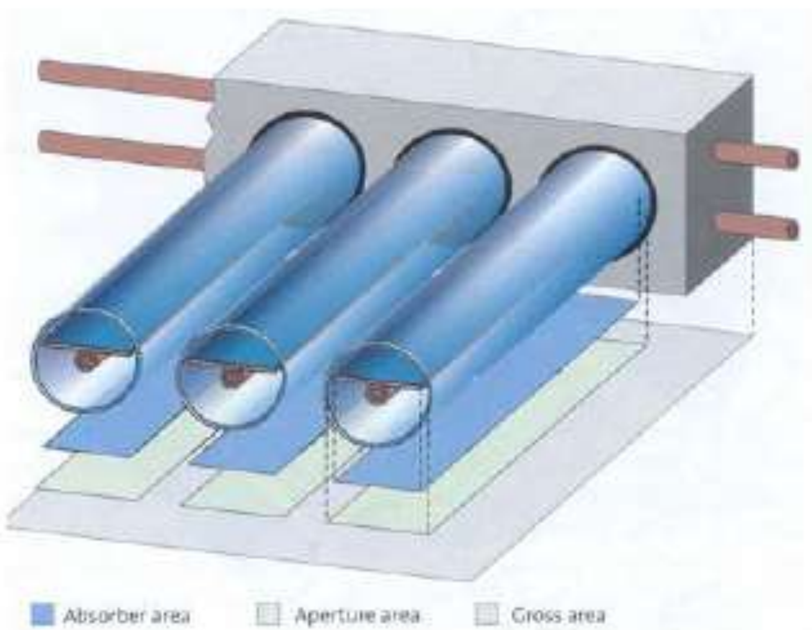
heat pipe

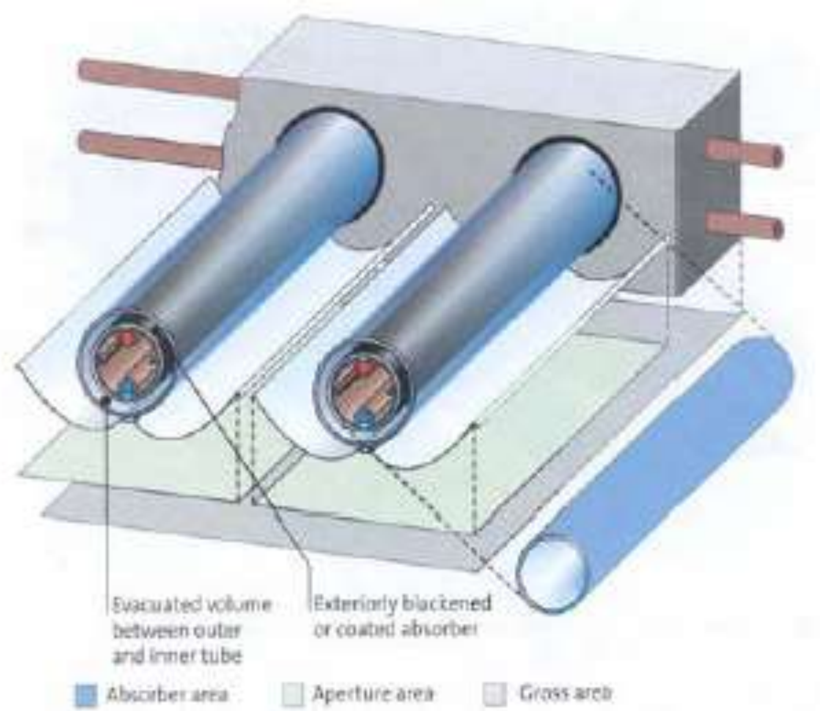
source: Viessmann

Vacuum tube solar collectors

single vacuum tube
flat absorber

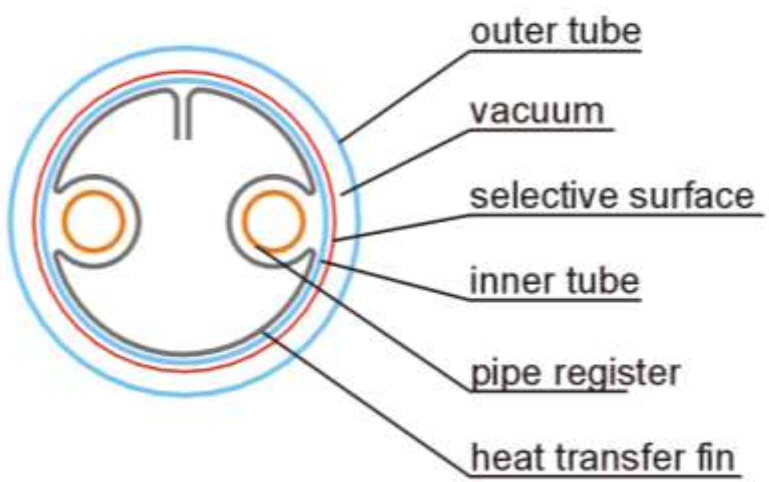
double vacuum tube (Sydney)
cylindric absorber





high vacuum 1 mPa

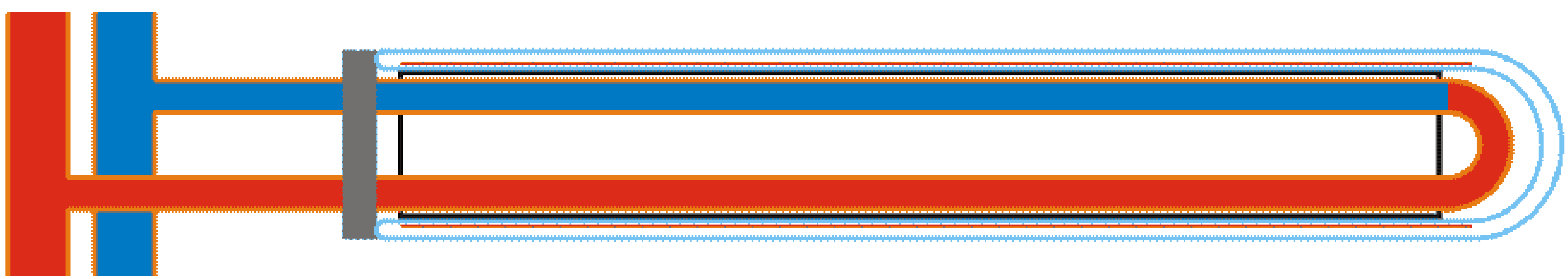
Vacuum tube solar collectors



Double vacuum Sydney tube

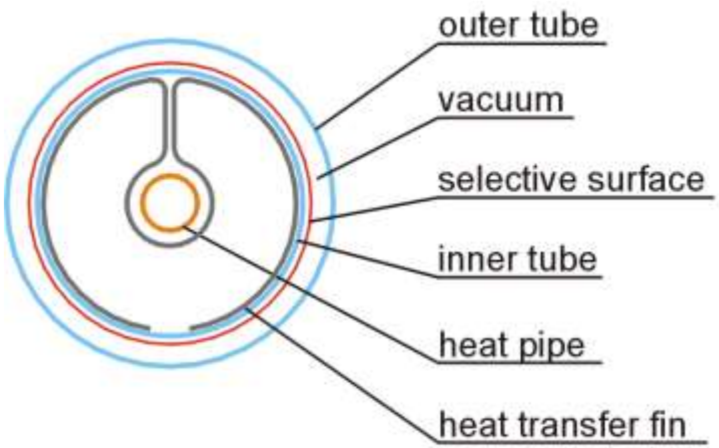
with cylindric absorber

- direct flow (DF)
  with a contact fin



heat transfer fin between absorber tube and pipe register needed!

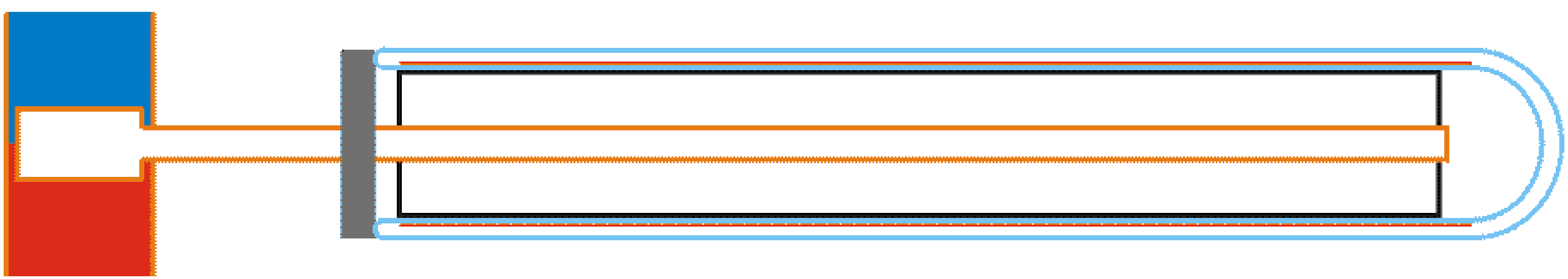
Vacuum tube solar collectors



Double vacuum Sydney tube

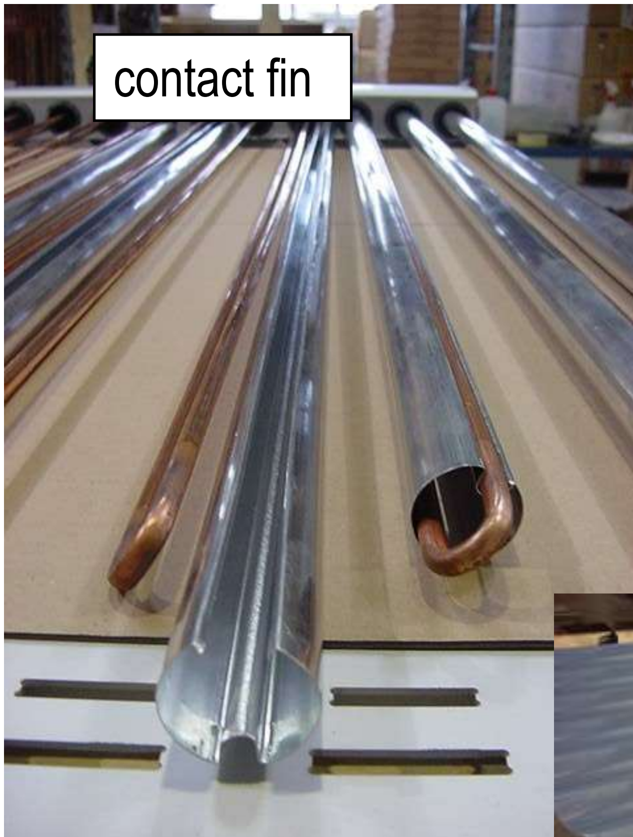
with cylindric absorber

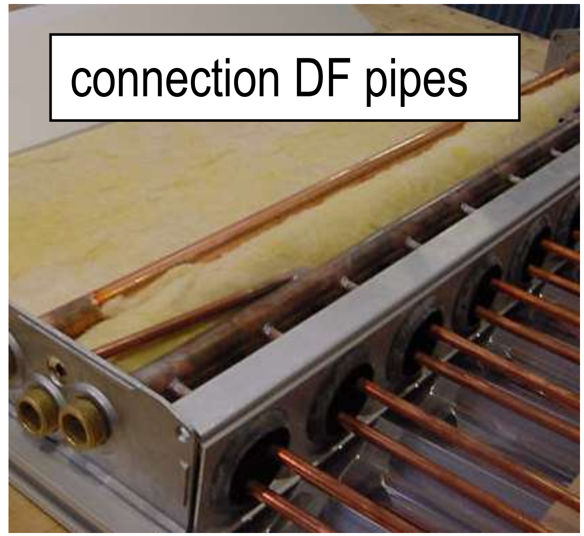
- heat pipe (HP)
  with a contact fin

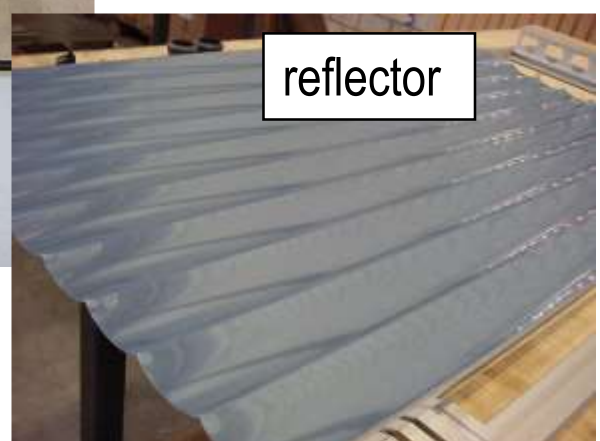


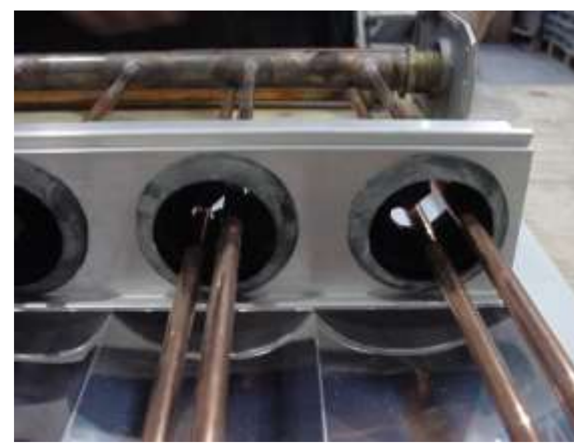
heat transfer fin between absorber tube and evaporator needed!

Vacuum tube (Sydney) solar collectors





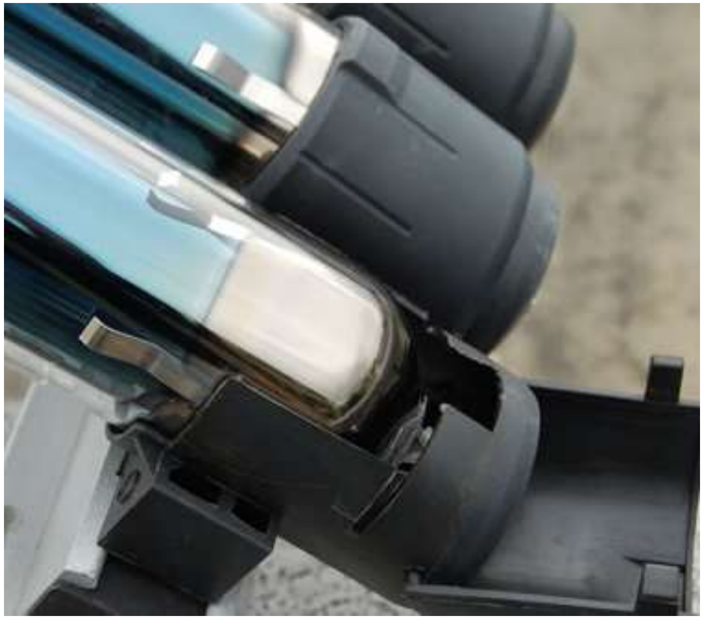


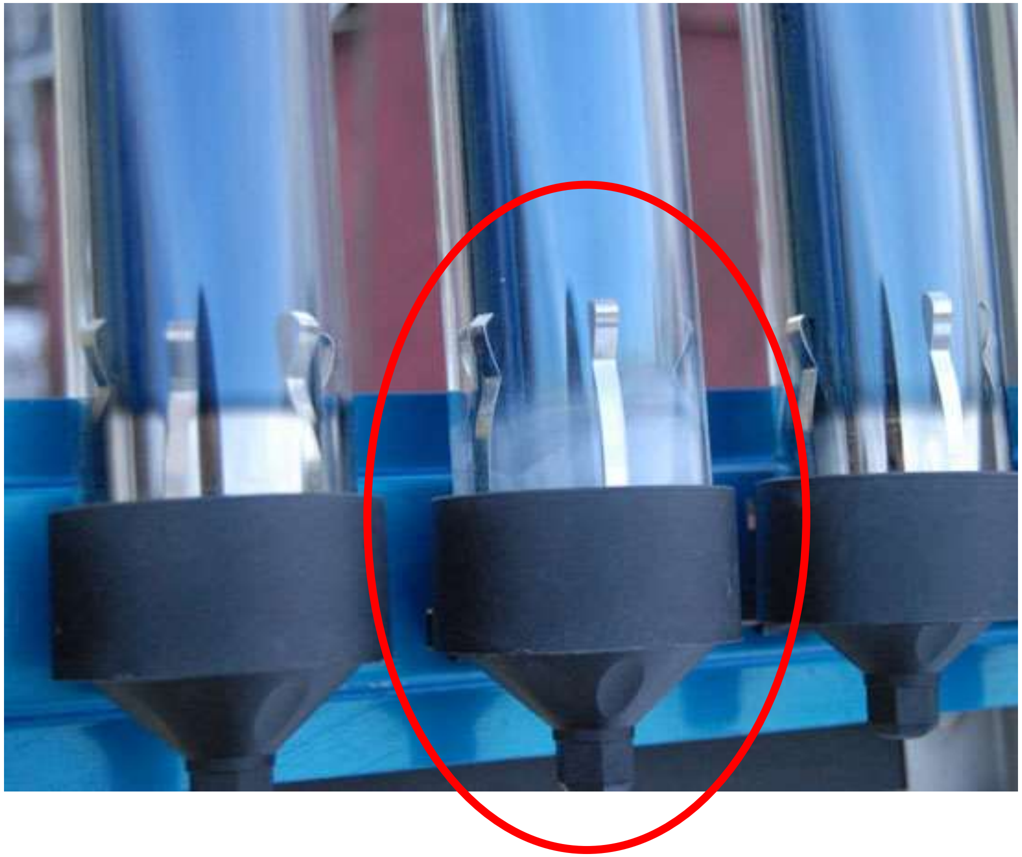


source: OPC

Vacuum tube (Sydney) solar collectors

Vacuum tube (Sydney) solar collectors





barium absorbs gases and changes colour

Vacuum tube (Sydney) solar collectors

The getter material is held inactive in a reservoir during assembly, then heated and evaporated after initial evacuation. The vaporized getter, usually a volatile metal, instantly reacts with any residual gas, then condenses on the cool walls of the tube in a thin coating, the ***getter mirror***, which continues to absorb gas.

Vacuum tube (Sydney) solar collectors

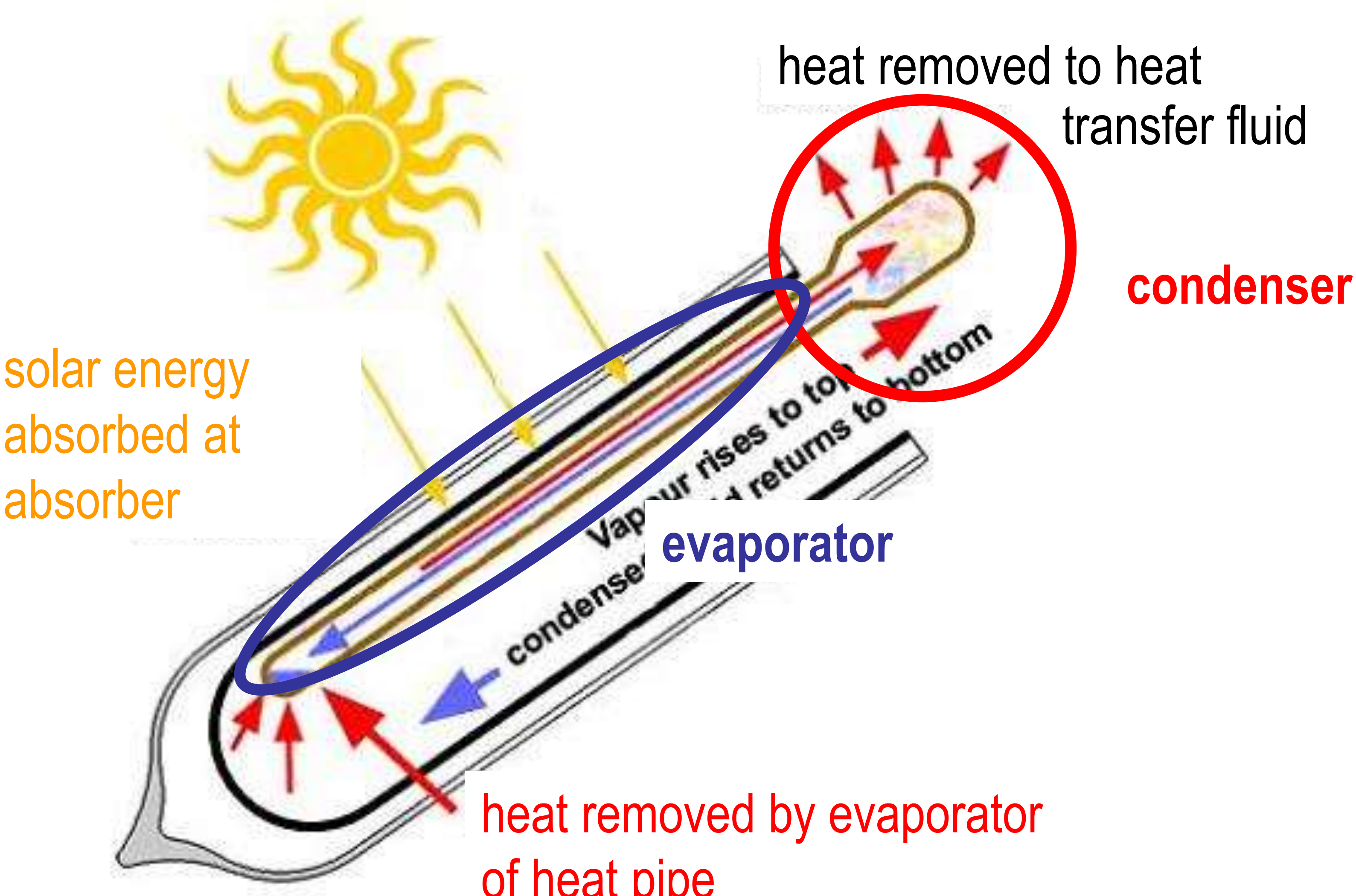
vacuum insulation = snow or frost removed very slowly

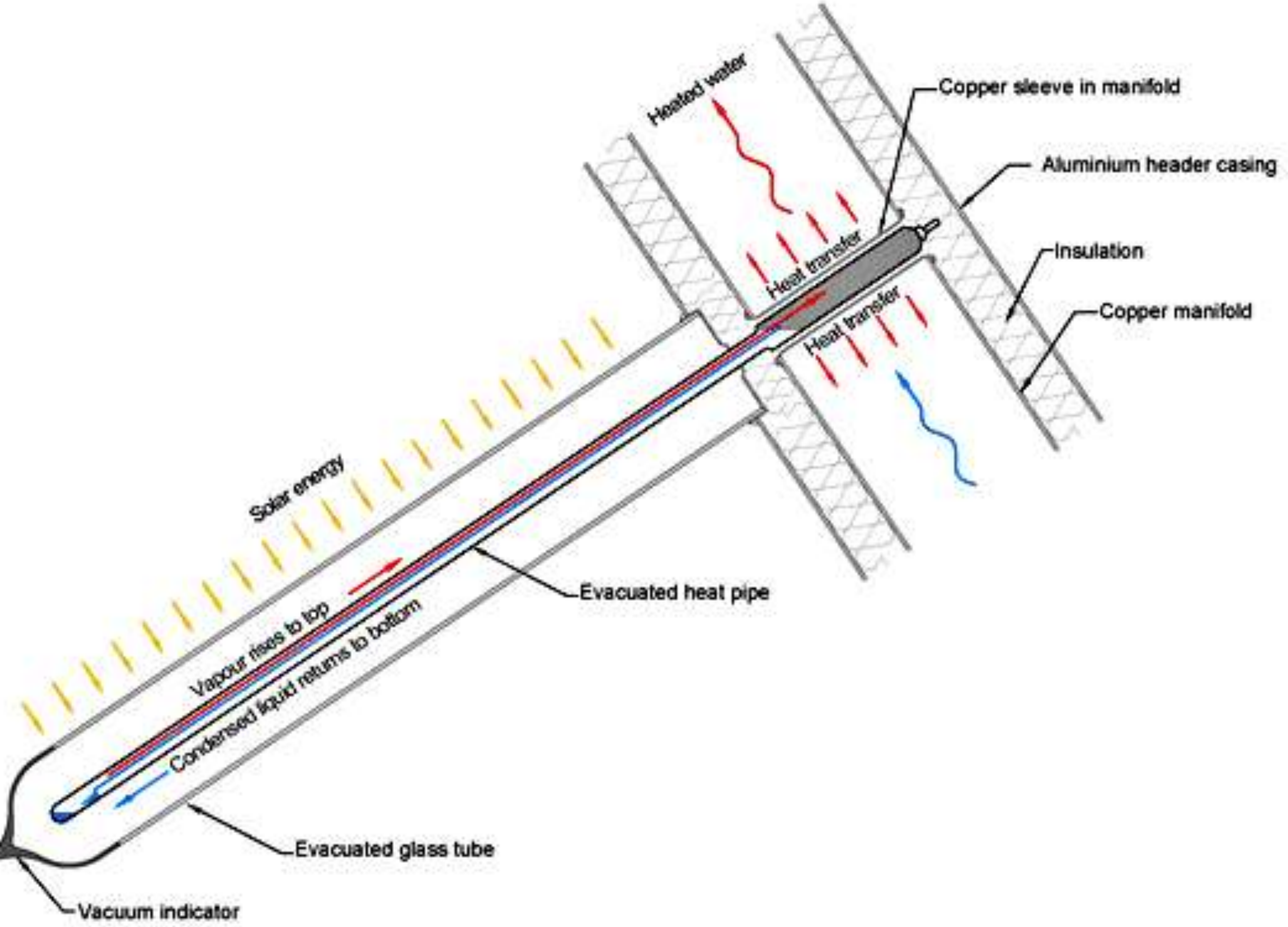
snow accummulation: problematic use of reflectors

Flat plate collectors and defrosting

heat loss allows collector operation even in periods of snow cover

Tube collector with a heat pipe





Heated water
Copper sleeve in manifold
Aluminium header casing
Insulation
Copper manifold
Heat transfer
Heat transfer
Solar energy
Vapour rises to top
Condensed liquid returns to bottom
Evacuated heat pipe
Evacuated glass tube
Vacuum indicator

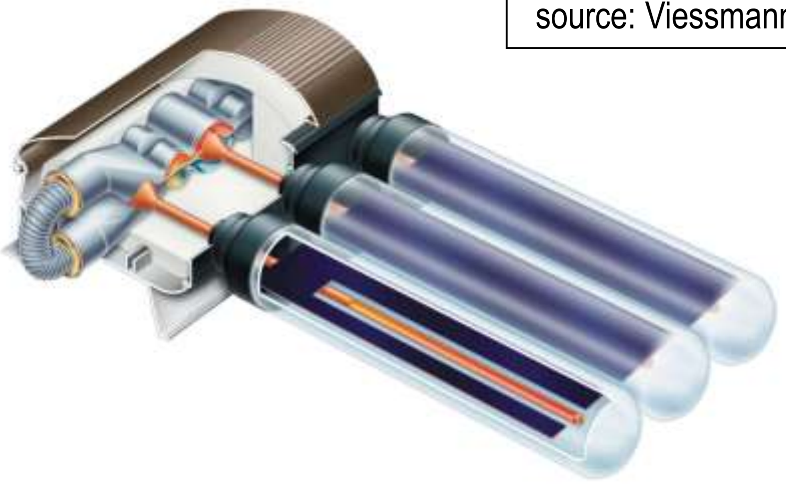
Tube collector with a heat pipe

source: Viessmann

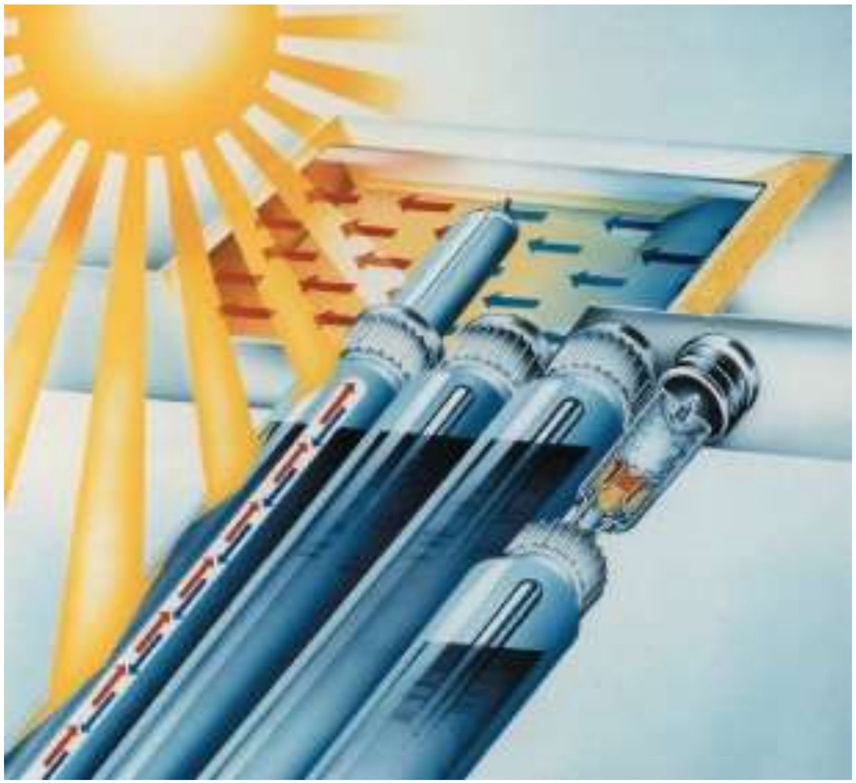
dry connection

condenser placed in a slot

slot washed by heat transfer fluid

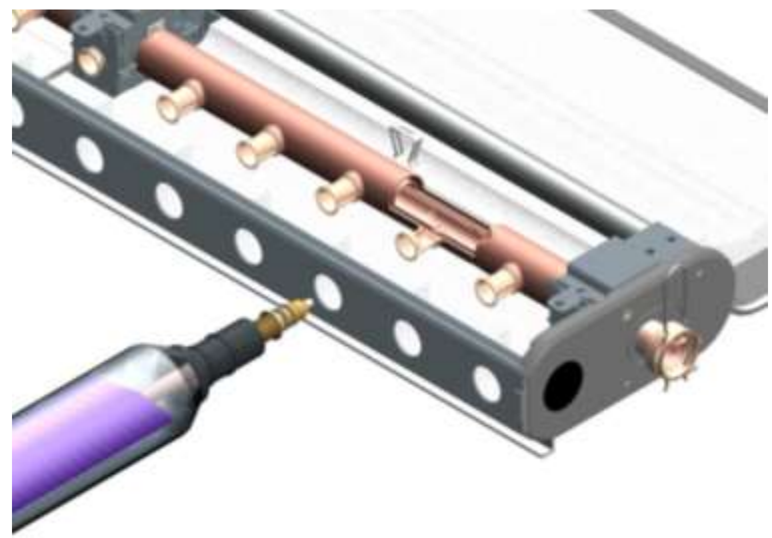


Tube collector with a heat pipe

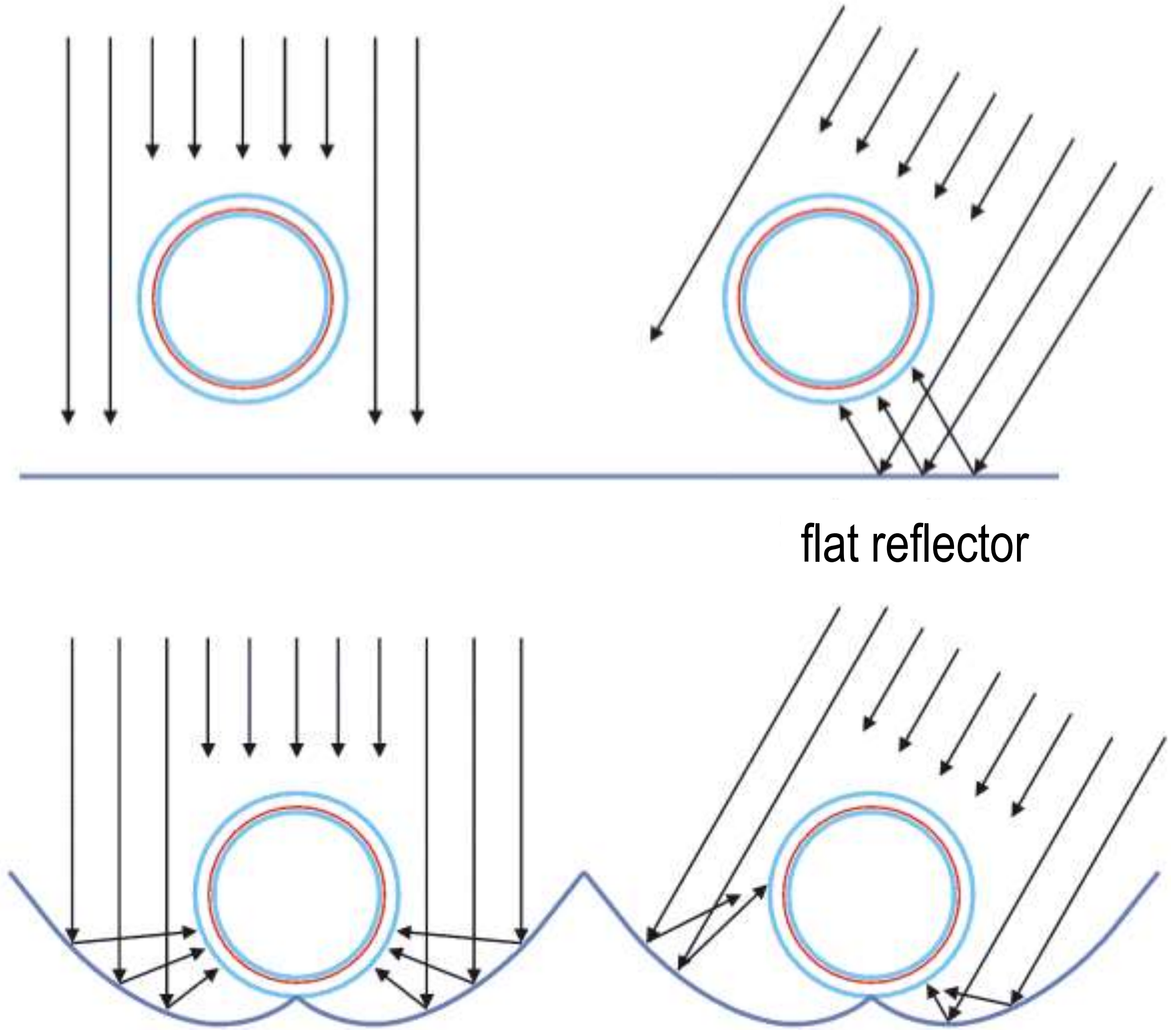


wet connection

condenser of heat pipe directly washed by heat transfer fluid



Tube collector with a reflector



flat reflector

compound parabolic reflector (CPC)

specular reflection

diffuse reflection

durability of optical quality of reflector

snow and ice accummulation, tube destruction

increase of collector active area (aperture)

Concentrating solar collectors

concentration of direct solar radiation

reflection (mirrors) x **refraction** (lenses)

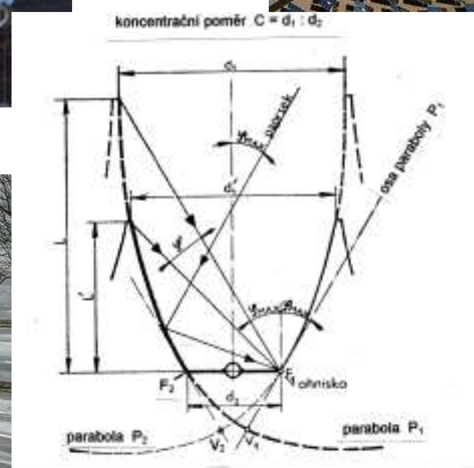
linear focus

- parabolic reflector
- Winston collector (trough form)
- collector with a Fresnel lens

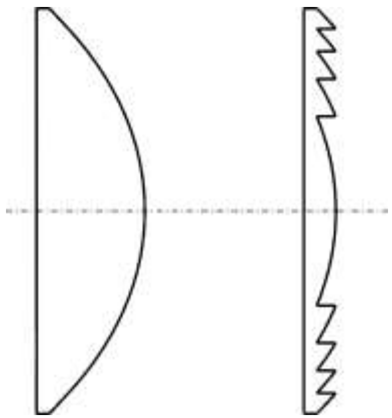
point focus

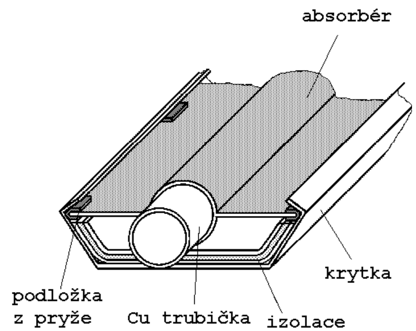
- paraboloid reflector
- heliostats

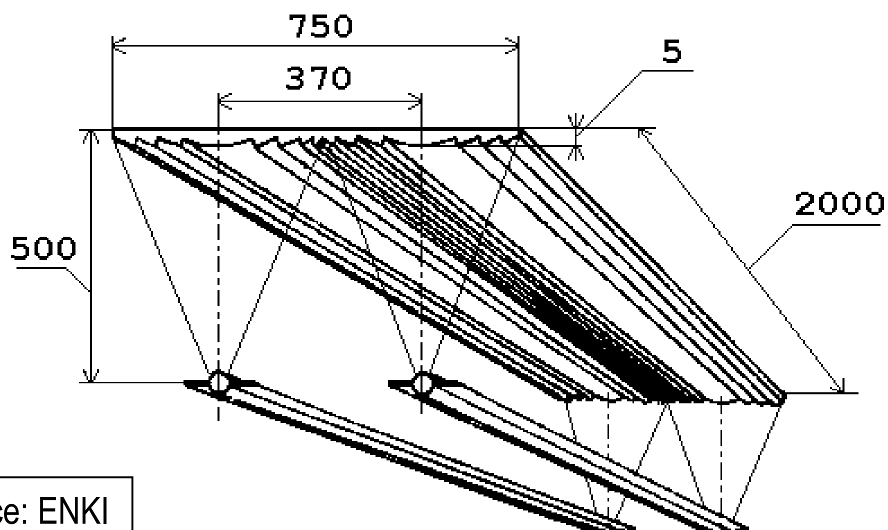
Concentrating solar collectors (reflection)



Collector with Fresnel lenses (refraction)



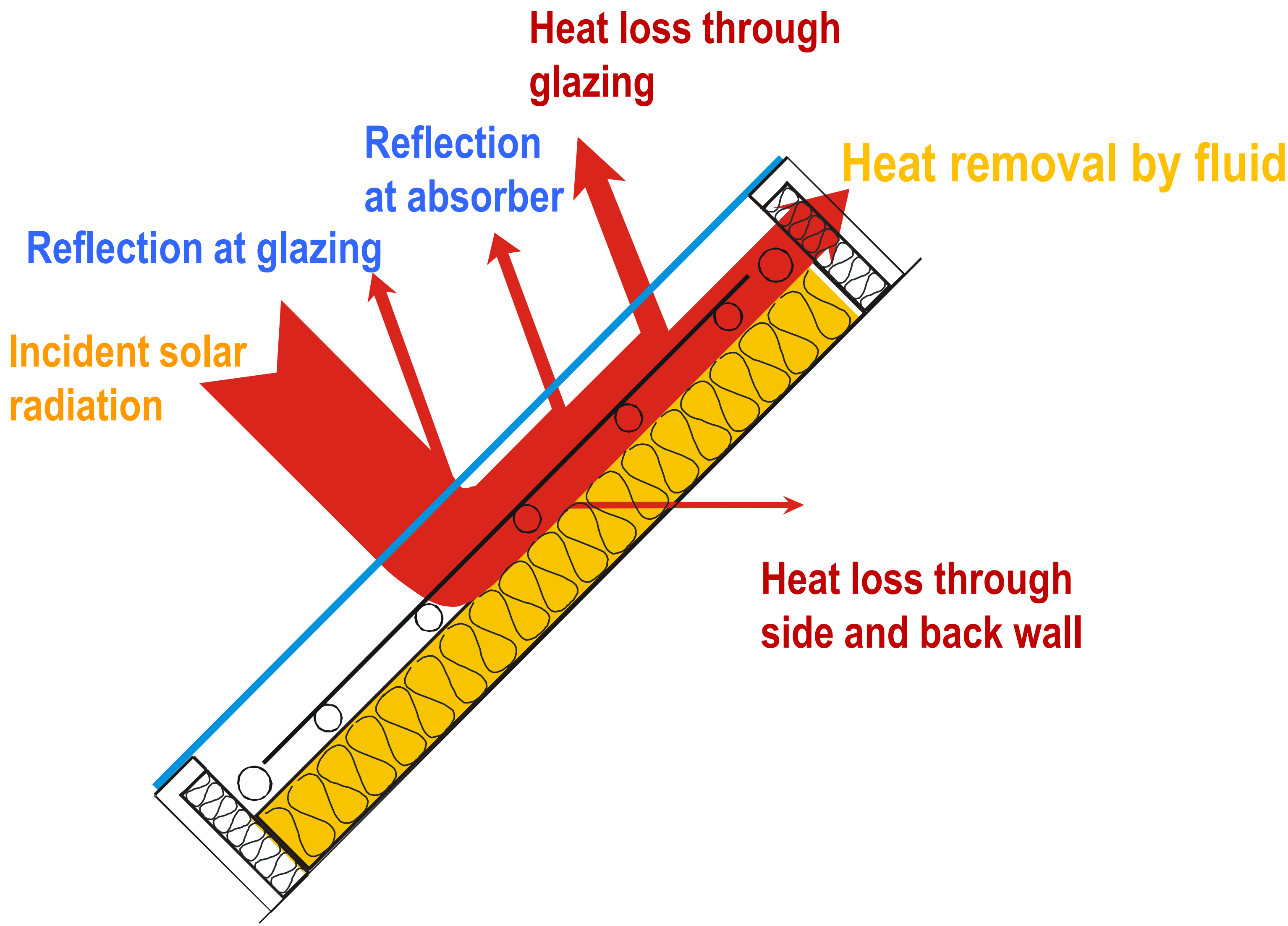




source: ENKI

- combined active and passive component

Principle and balance of solar collector

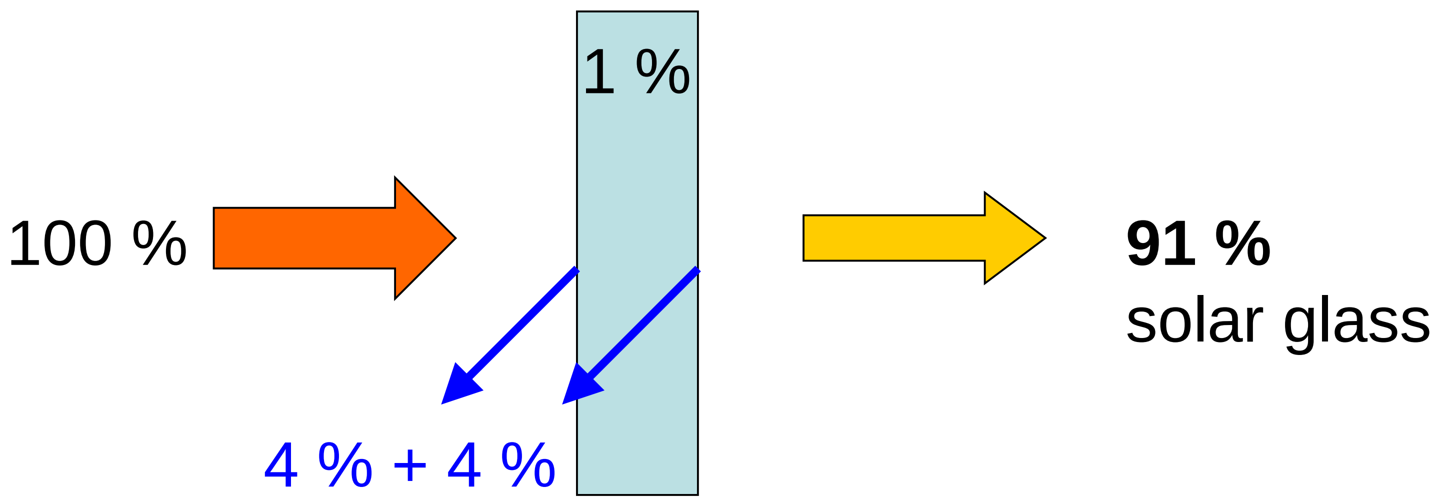


Solar collector glazing

- **single glazing**
- low-iron glass, solar glass
  - low absorbance of solar radiation
- antireflective coatings
  - reduction of reflection at interface glass-air
- prismatic glass (pyramidal texture)
  - increase of transmittance at high angles

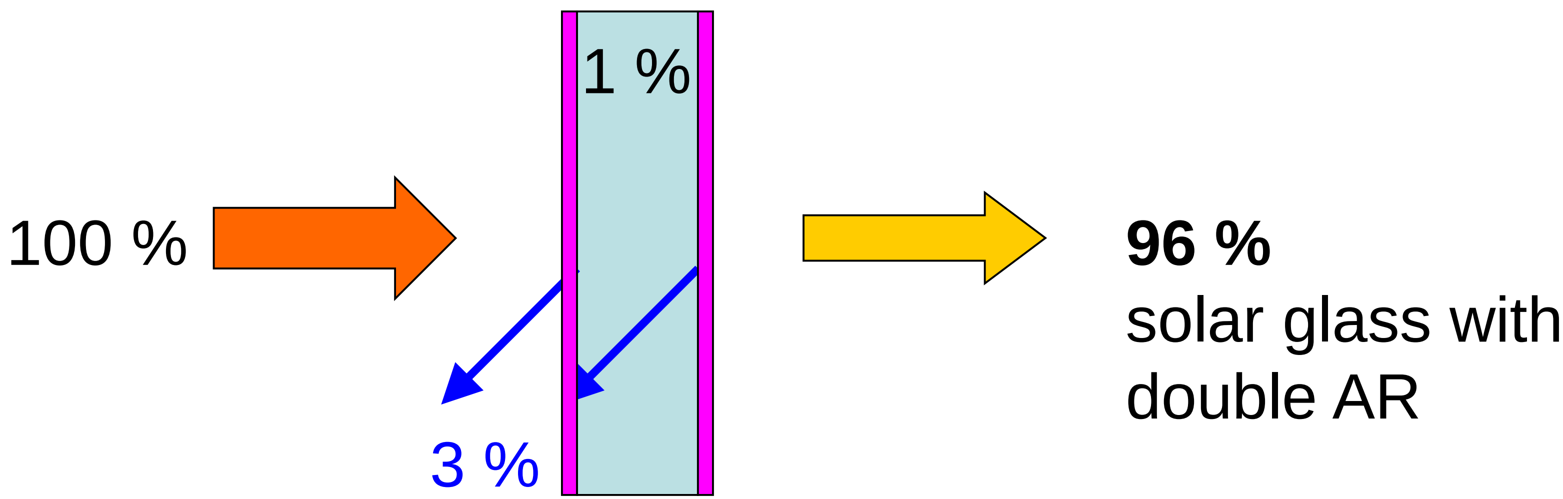
Reflection loss

reflection at each interface glass-air 4 % (normal)
independent on thickness



Antireflection (AR) coatings

reflection reduced to 1,5 % at each interface glass-iron coating with low refraction index



Solar collector absorber

radiation properties for athermanous bodies

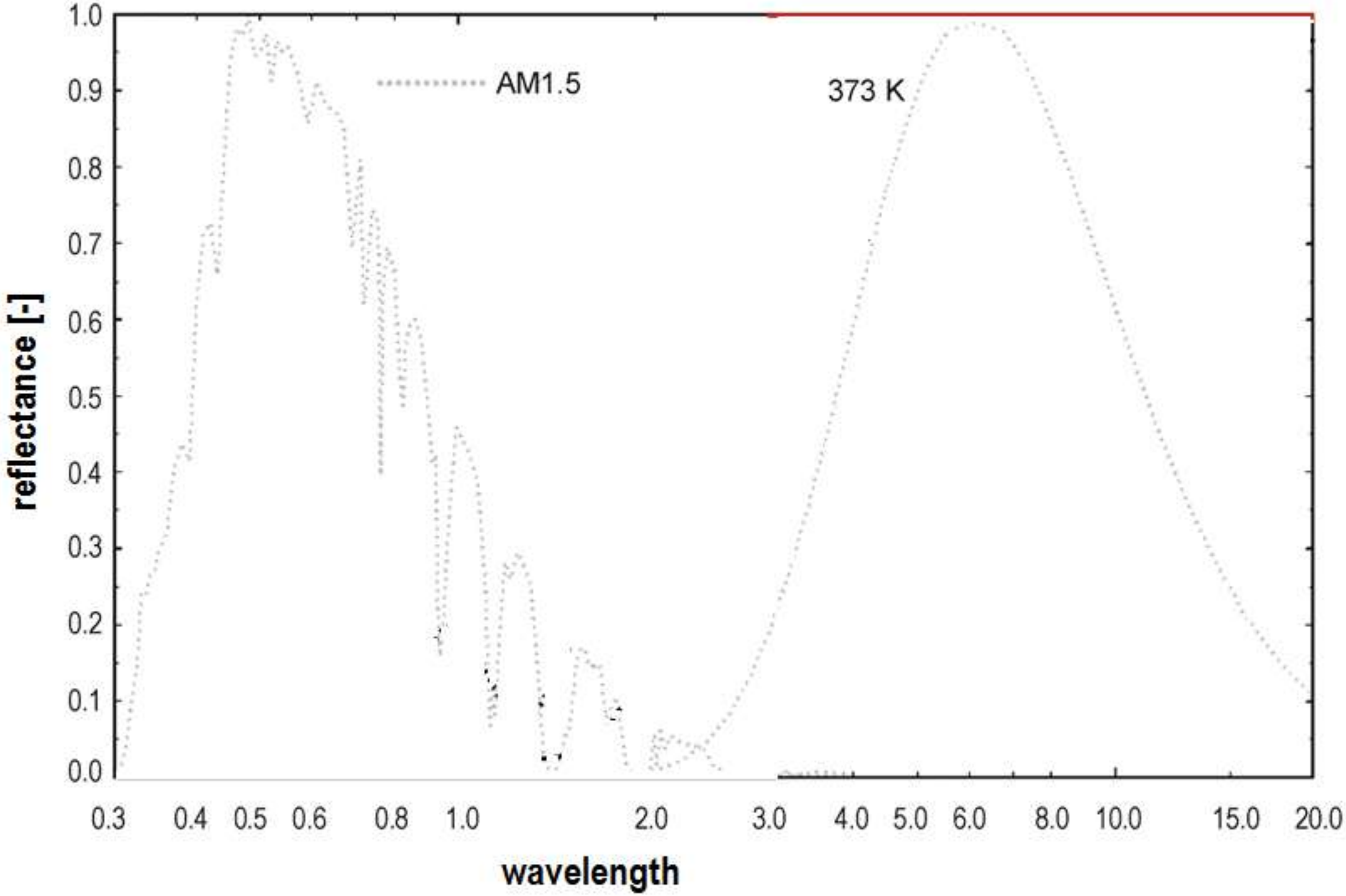
Athermanous body is such a body through which any heat radiation cannot pass.

- absorptance α + reflectance ρ = 1
- for given wavelength λ apply: absorptance α_λ = emittance ε_λ

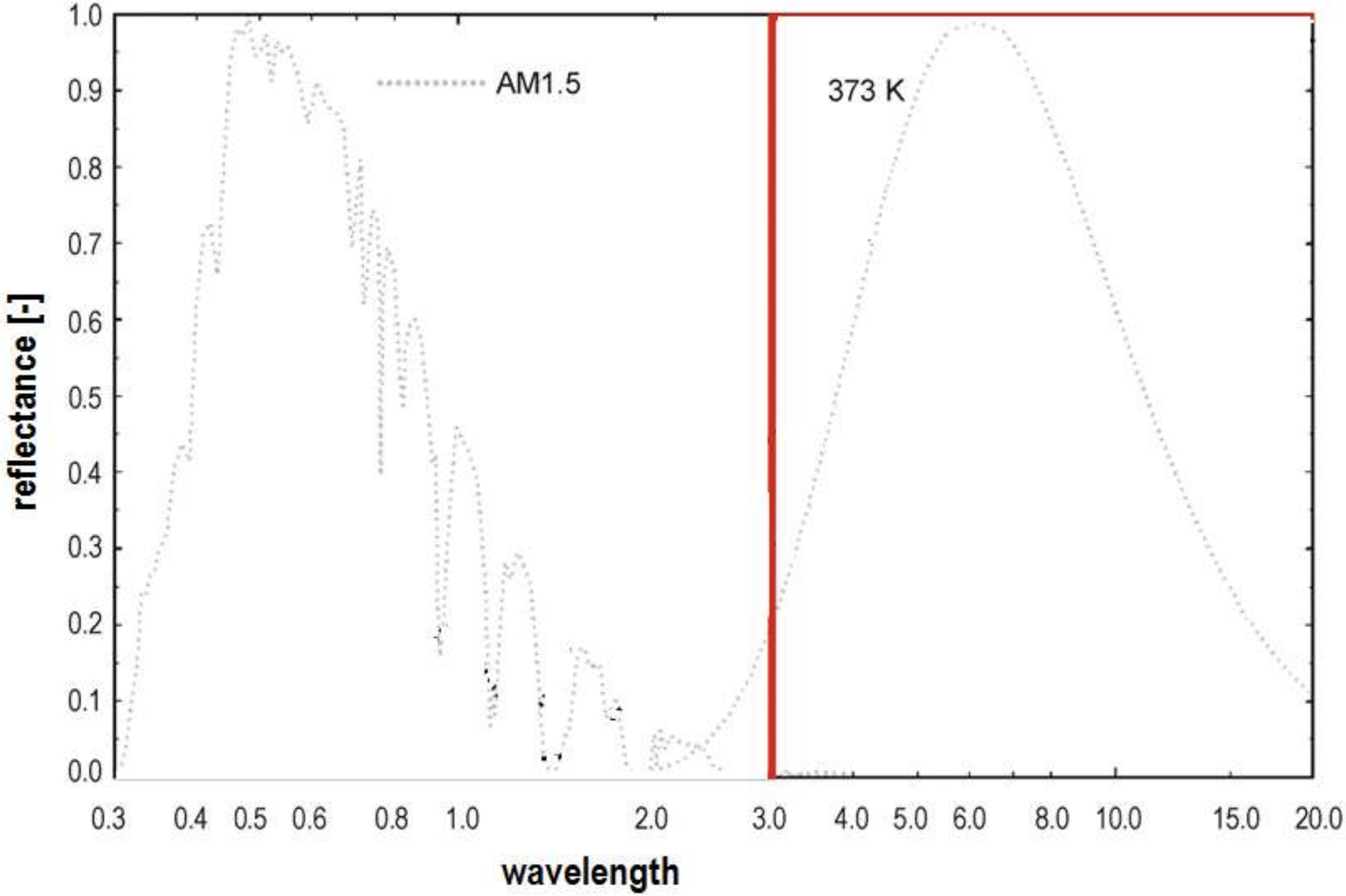
- perfect black body: $\alpha = 1$, $\rho = 0$ for all wavelengths
- perfect white body: $\alpha = 0$, $\rho = 1$ for all wavelengths
- grey body $0 < \alpha = \alpha_\lambda < 1$, $\rho = 1 - \alpha$ for all wavelengths
- **selective body** $\mathbf{0 < \alpha_\lambda < 1, \rho_\lambda = 1 - \alpha_\lambda}$

$$\boxed{\alpha_{SOL} \neq \varepsilon_{IR}}$$

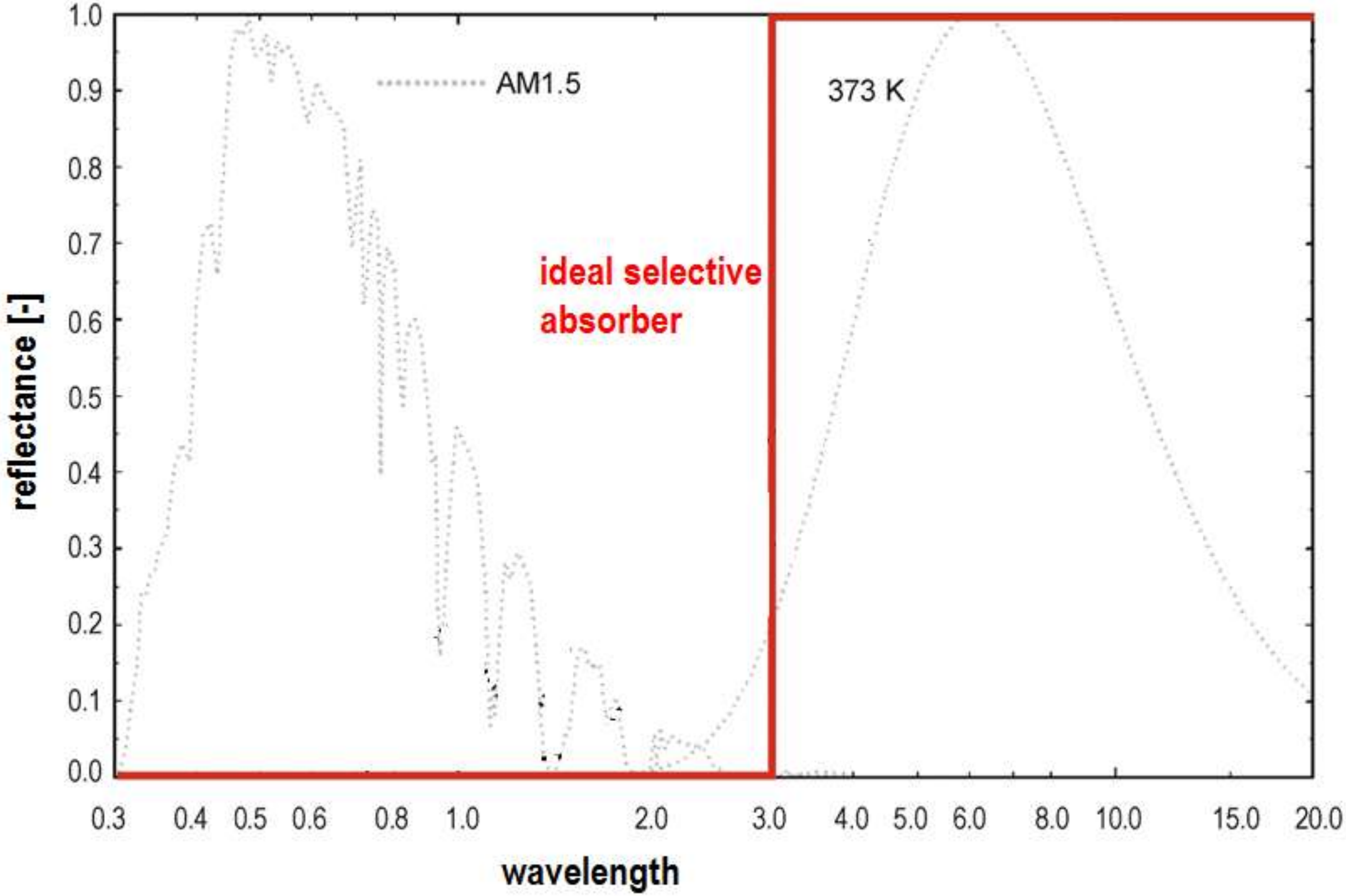
Absorber selectivity



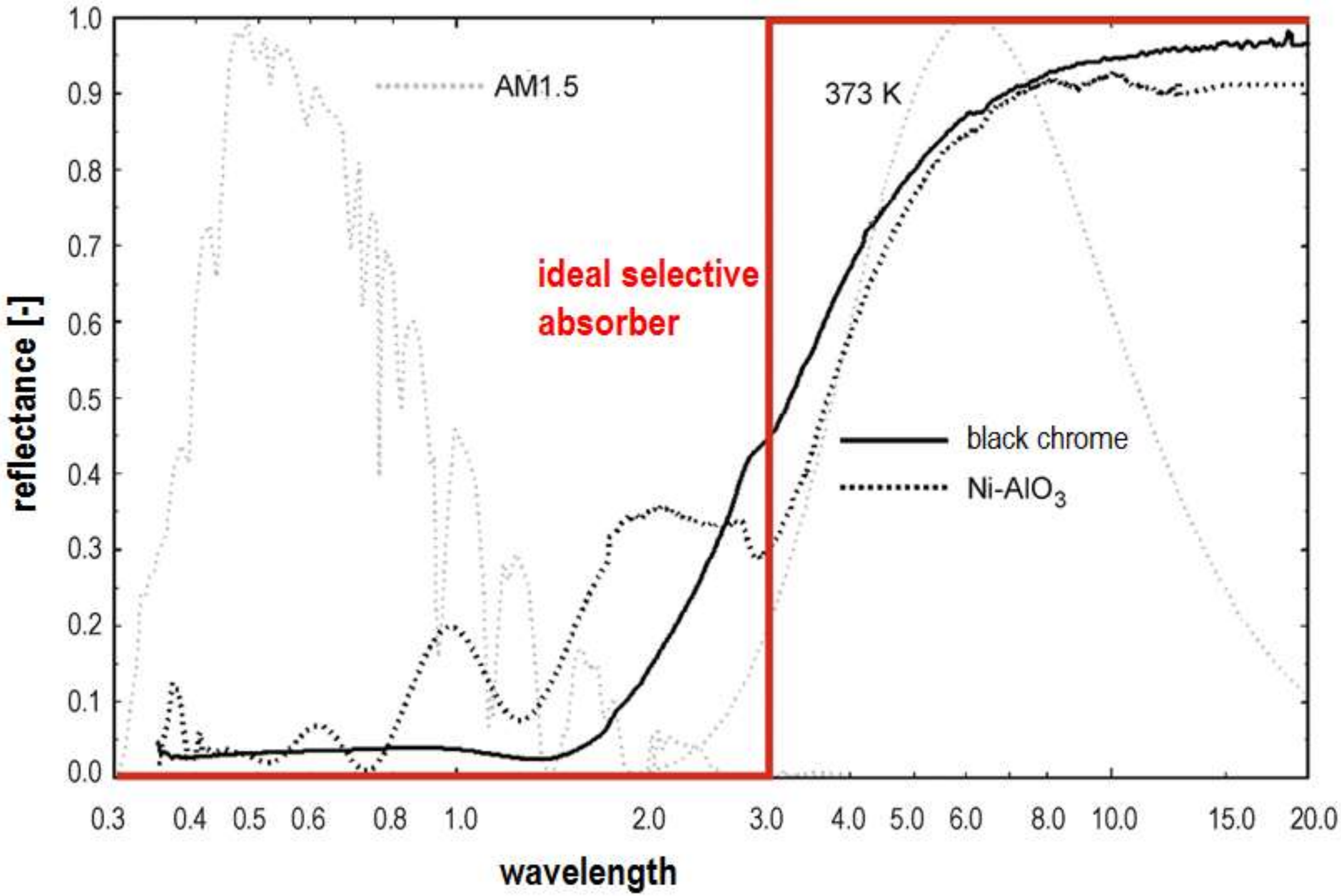
Absorber selectivity



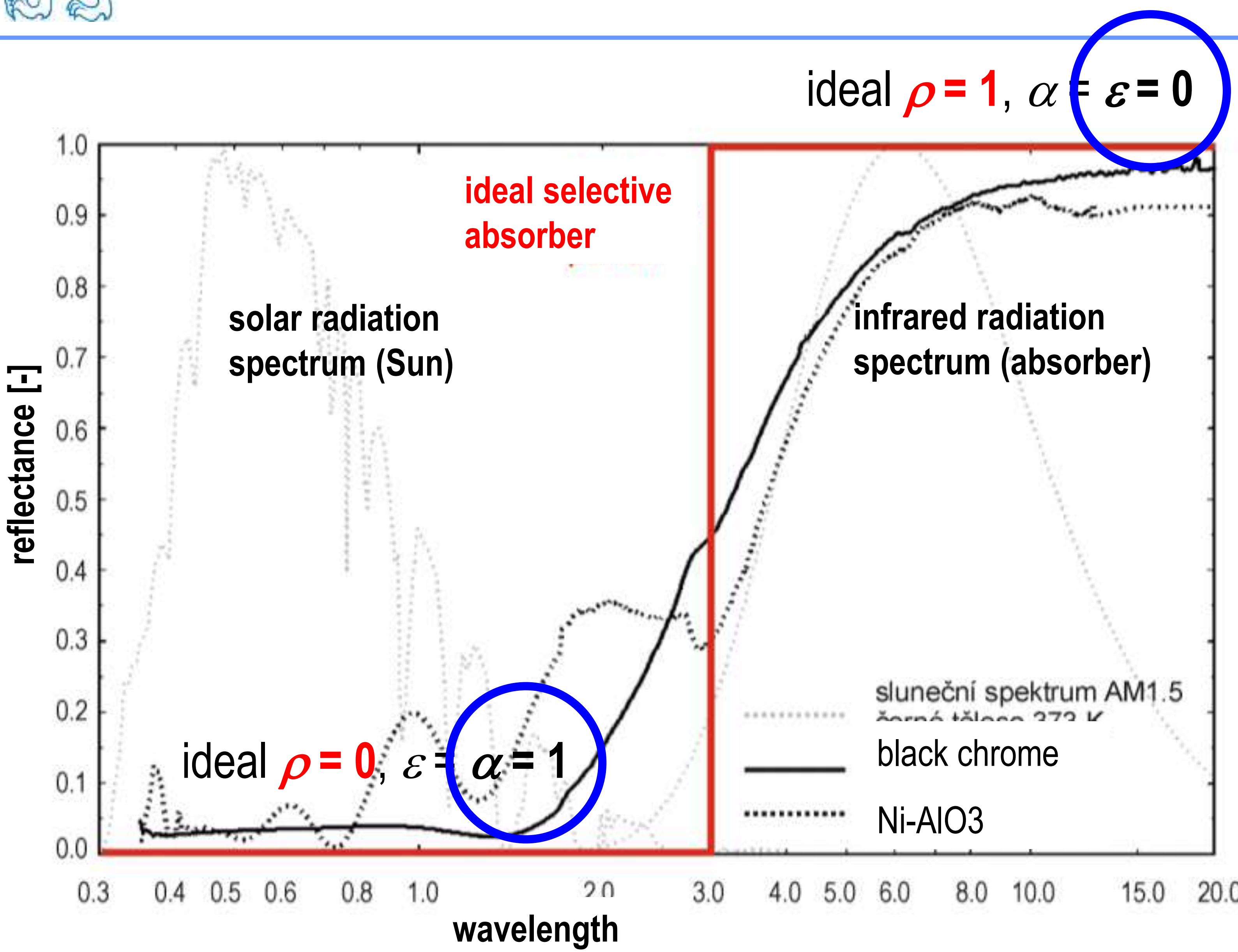
Absorber selectivity



Absorber selectivity



Absorber selectivity



Selective surfaces

galvanic

- electrochemical process
  $\alpha = 0{,}93 - 0{,}96$, $\varepsilon = 0{,}10 - 0{,}16$

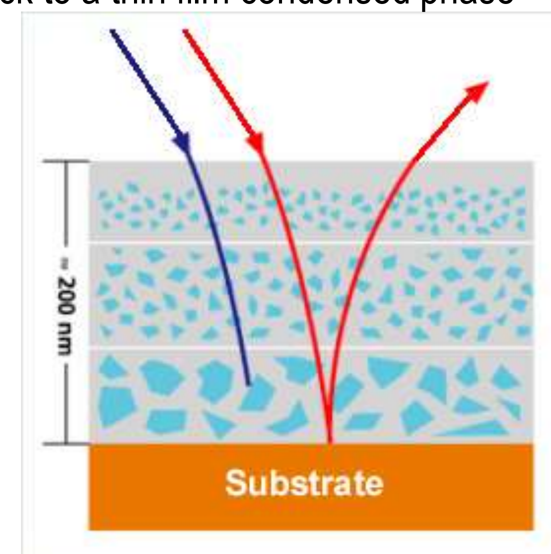
ceramic-metal (cermet)

- sputtering, physical vapour deposition process, high quality surfaces
  $\alpha = 0{,}95$, $\varepsilon = 0{,}05$

paints

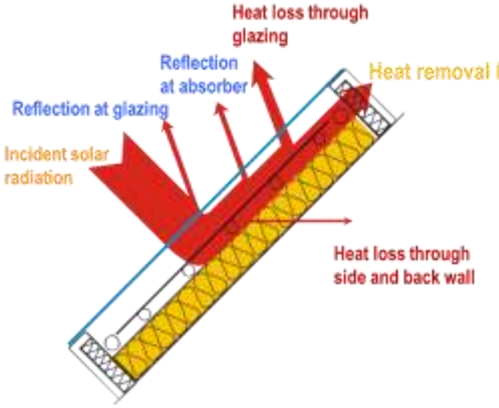
- considerably worse
  $\alpha = 0{,}92$, $\varepsilon = 0{,}85$

material goes from a condensed phase to a vapor phase and then back to a thin film condensed phase



Efficiency of solar collector

$$\eta = \boxed{\tau\alpha} - \boxed{U\frac{(t_{abs} - t_e)}{G}}$$



τ ... glazing transmittance for solar radiation [-]

α ... absorber absorptance for solar radiation [-]

optical efficiency

U ... heat loss coefficient [W/m^2.K]

t_{abs} ... mean absorber temperature [°C]

t_e ... ambient temperature [°C]

heat loss

Simple calculation

collector	C1	C2
transmittance of collector glazing:	0,90	0,90
absorptance of collector absorber:	0,90	0,90
front U-value	6 W/m^{2}K	3 W/m^{2}K
back U-value	1 W/m^{2}K	1 W/m^{2}K

calculate efficiency for given conditions:

t_e = 10 °C

G = 800 W/m^2

t_{abs} = 20 °C 80 °C

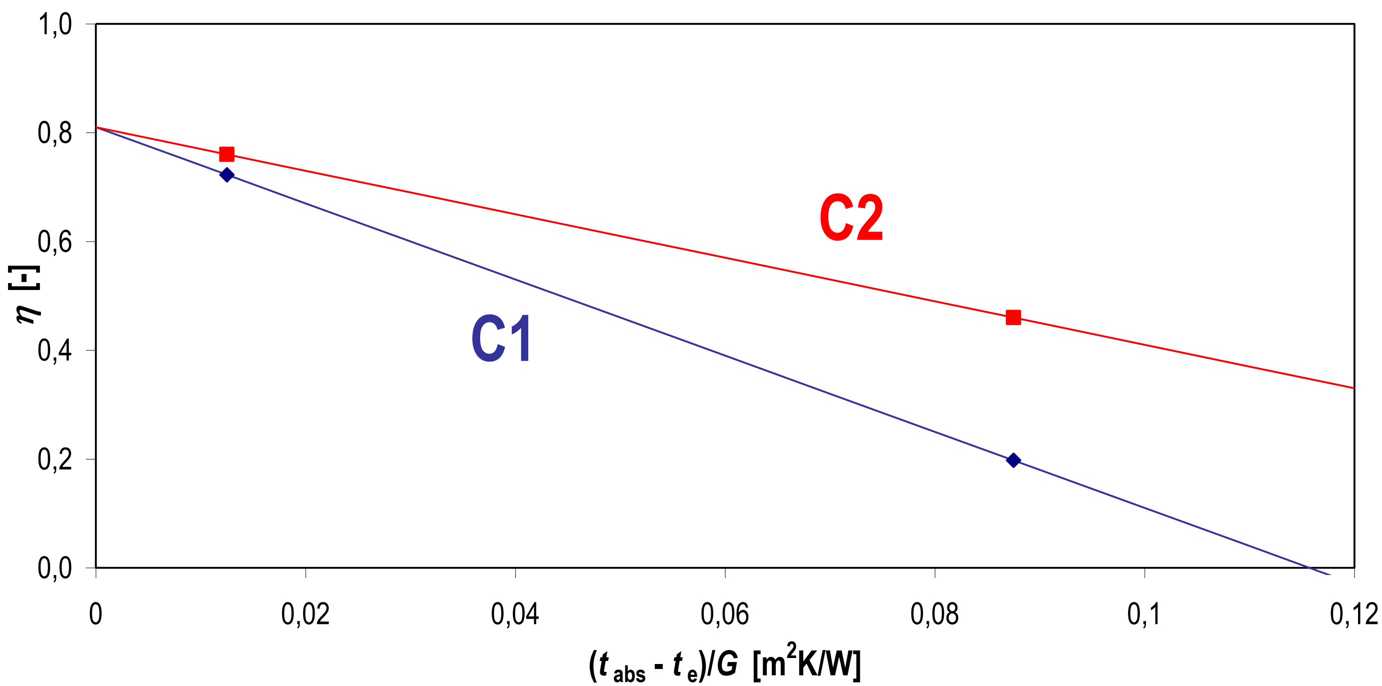
Simple calculation

Collector 1 **Collector 2**

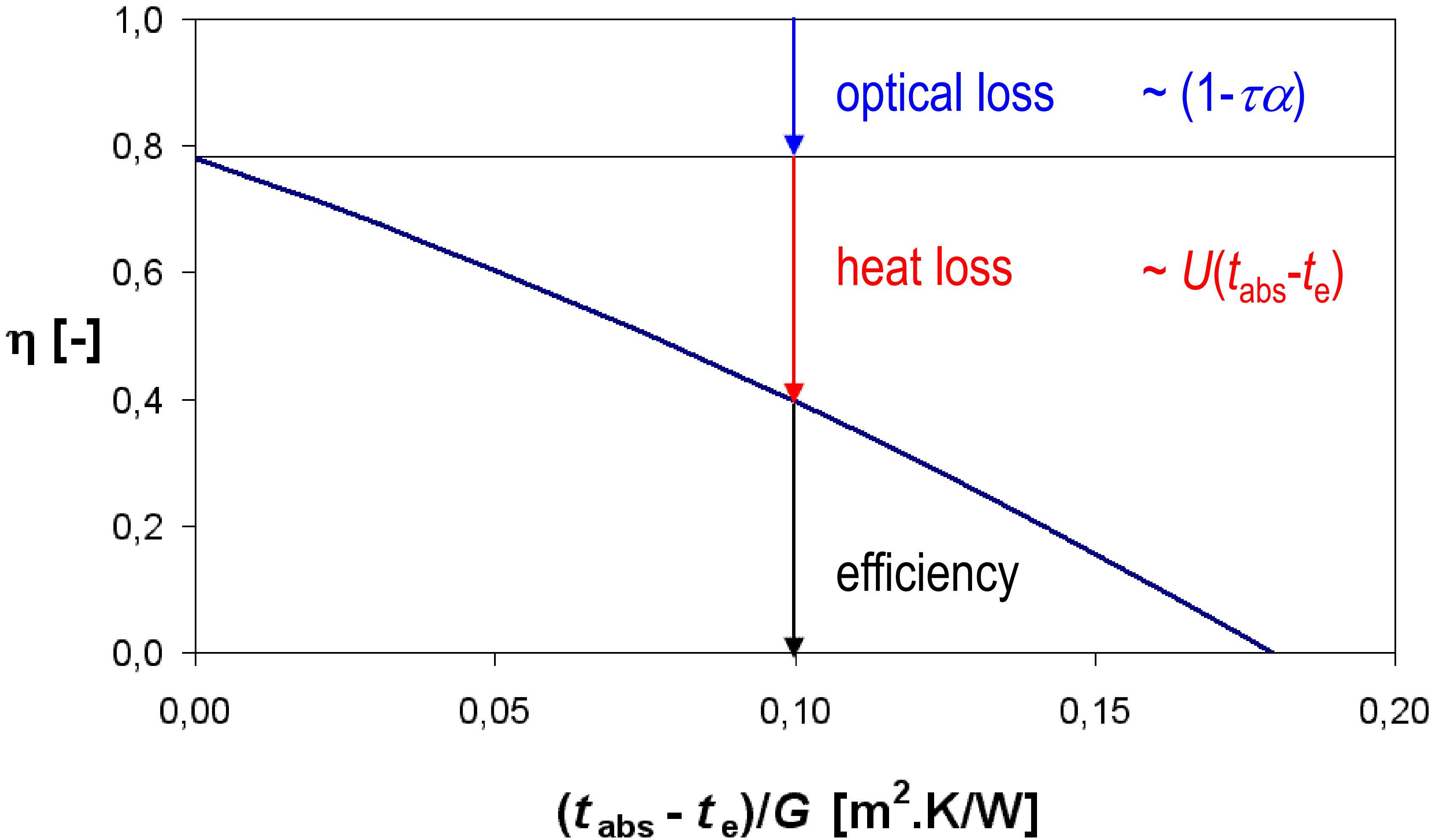
$$\eta = \tau\alpha - U\frac{(t_{abs} - t_e)}{G}$$

$$\eta = 0{,}9 \cdot 0{,}9 - (6+1)\frac{(t_{abs} - 10)}{800}$$

$$\eta = 0{,}9 \cdot 0{,}9 - (3+1)\frac{(t_{abs} - 10)}{800}$$



Efficiency of solar collector



Efficiency of solar collector

$$\eta = F' \cdot \left[\tau\alpha - U \frac{(t_m - t_e)}{G} \right]$$

***F'* ... efficiency factor** **> 0.90**

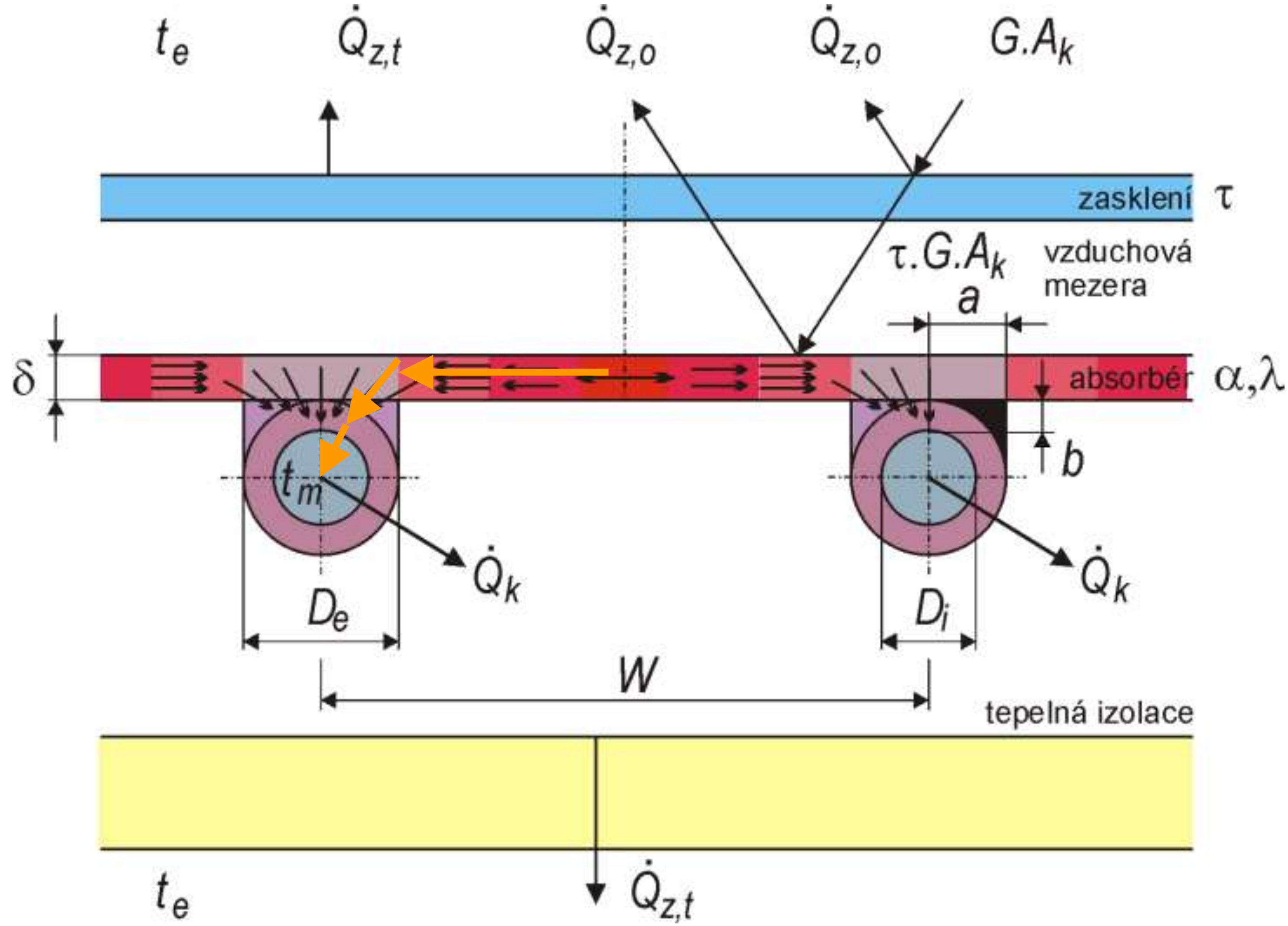
depends on geometry and thermal properties of absorber

……….quality heat transfer from the absorber to the heat transfer fluid

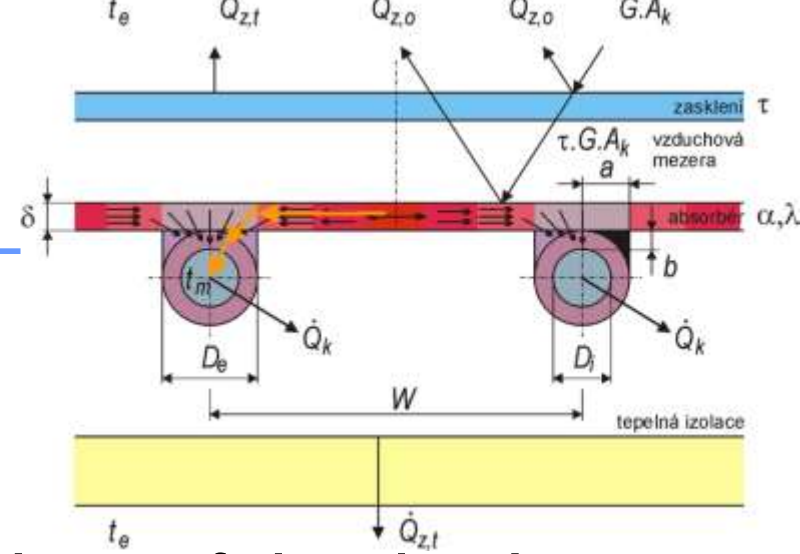
t_m ... mean fluid temperature

$t_m = (t_{k1} + t_{k2})/2$

Heat transfer from absorber surface



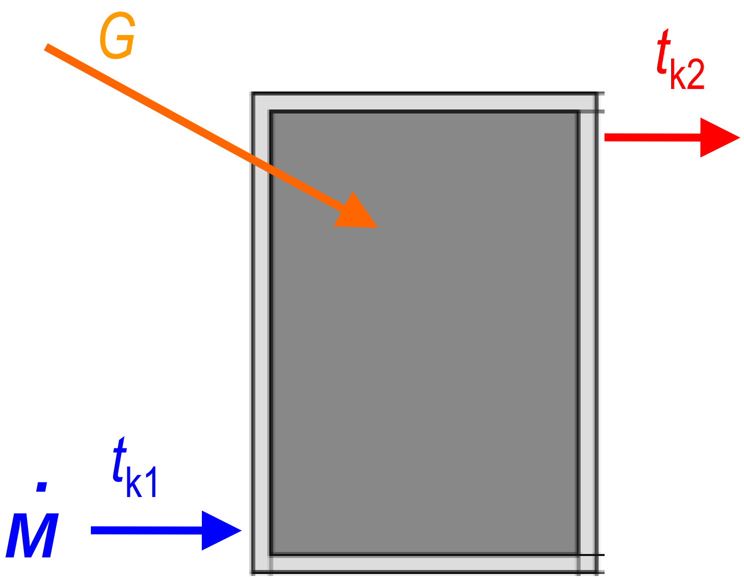
Efficiency factor *F'*



depends on

- geometry of absorber:
  - **pipe distance, pipe dimension, thickness of pipe-absorber bond, absorber thickness**
- physical properties of absorber:
  - **thermal conductivity of absorber, thermal conductance of the bond pipe-absorber**
- flow regime in pipes: **heat transfer from pipe wall to fluid**
- total heat loss coefficient of collector *U*

Determination of heat output by testing



heat output [W]

solar collector power

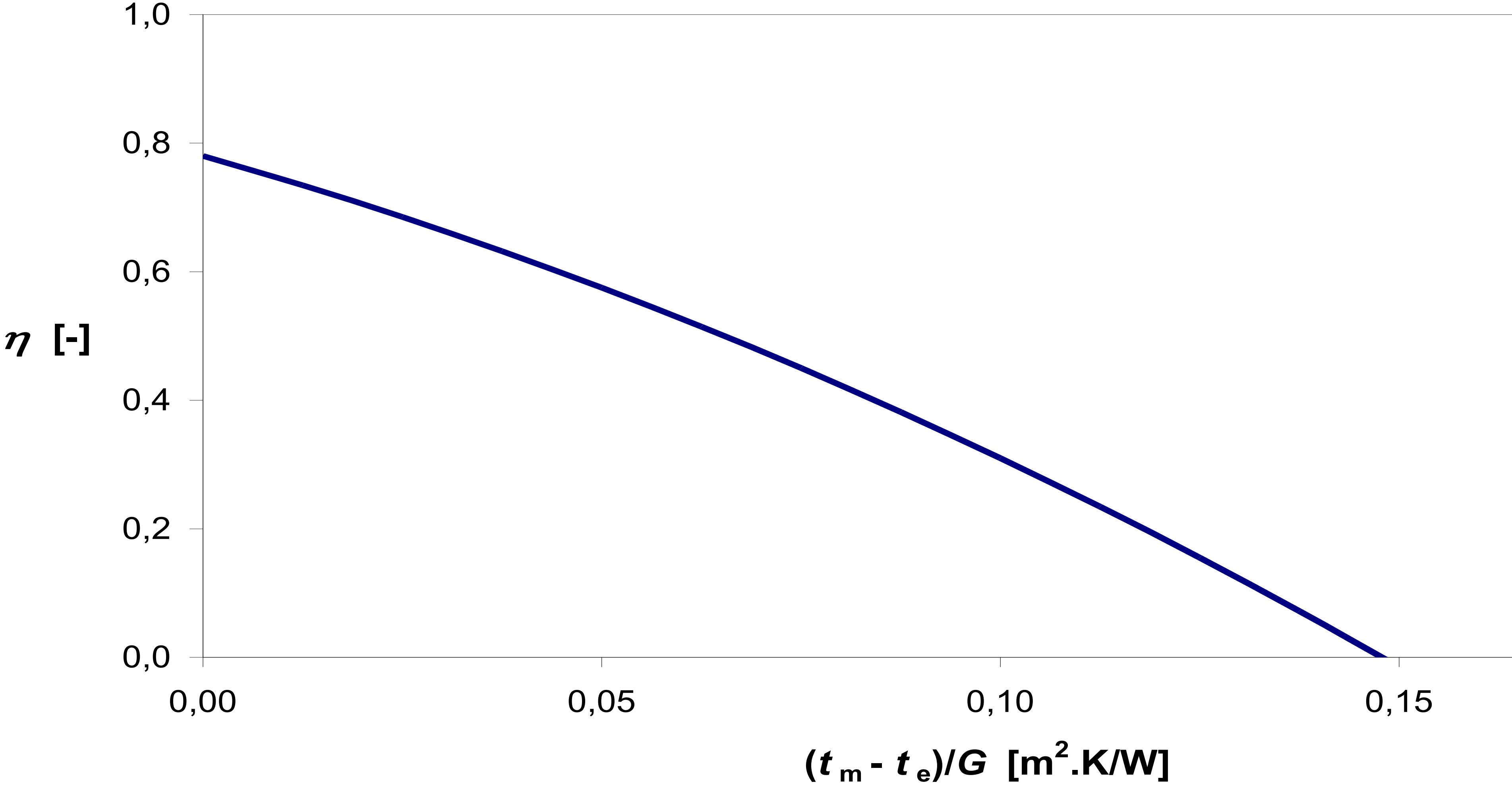
$$\dot{Q}_k = \dot{M} \cdot c \cdot (t_{k2} - t_{k1})$$

efficiency [-]

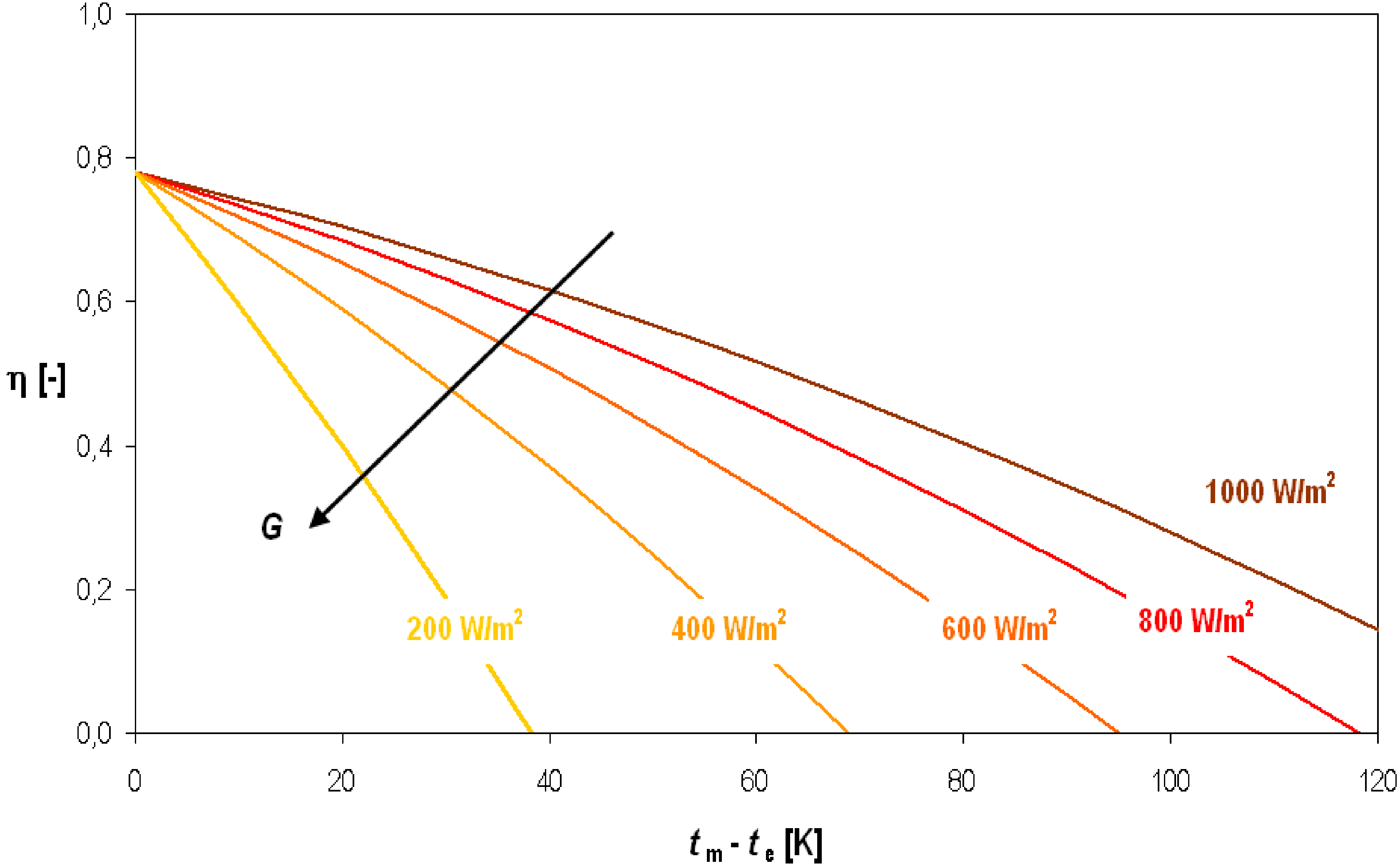
$$\eta = \frac{\dot{Q}_k}{G \cdot A_k}$$

tested at clear sky, G > 700 W/m^2, normal incidence, w > 3 m/s

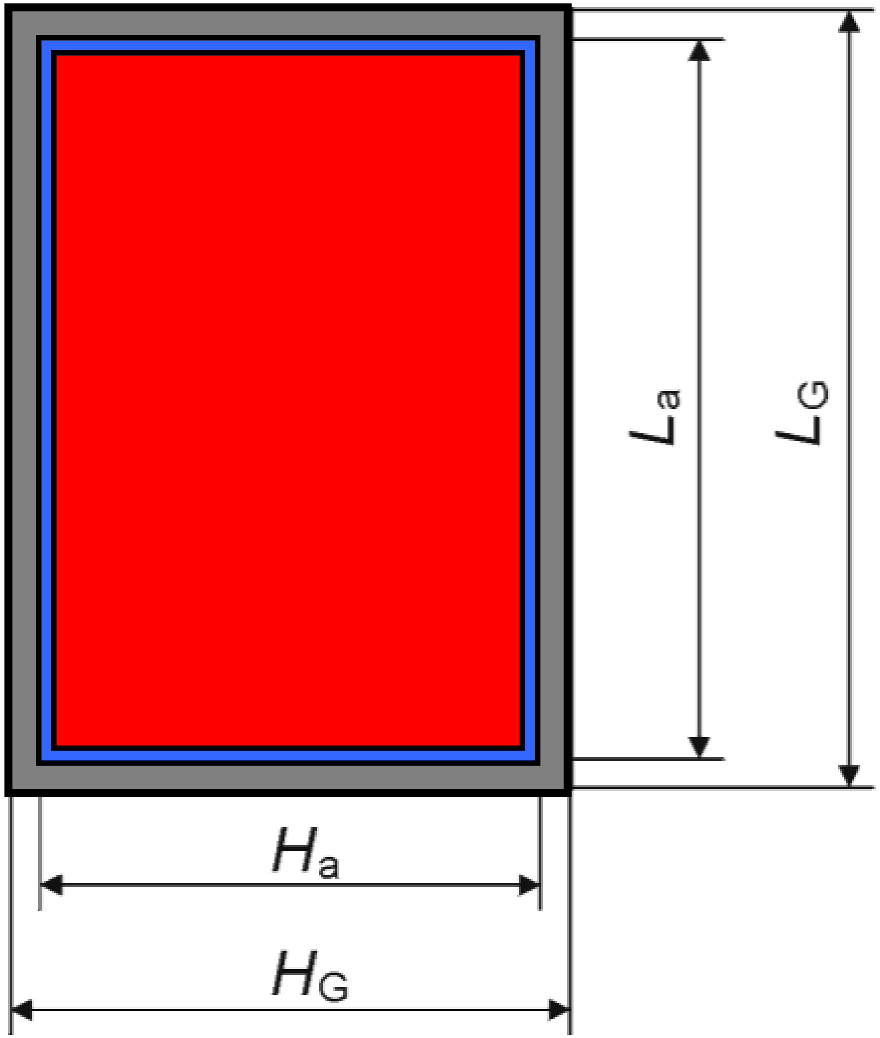
Efficiency characteristic



Efficiency characteristic = f (t_m – t_e)



Reference collector area A_k



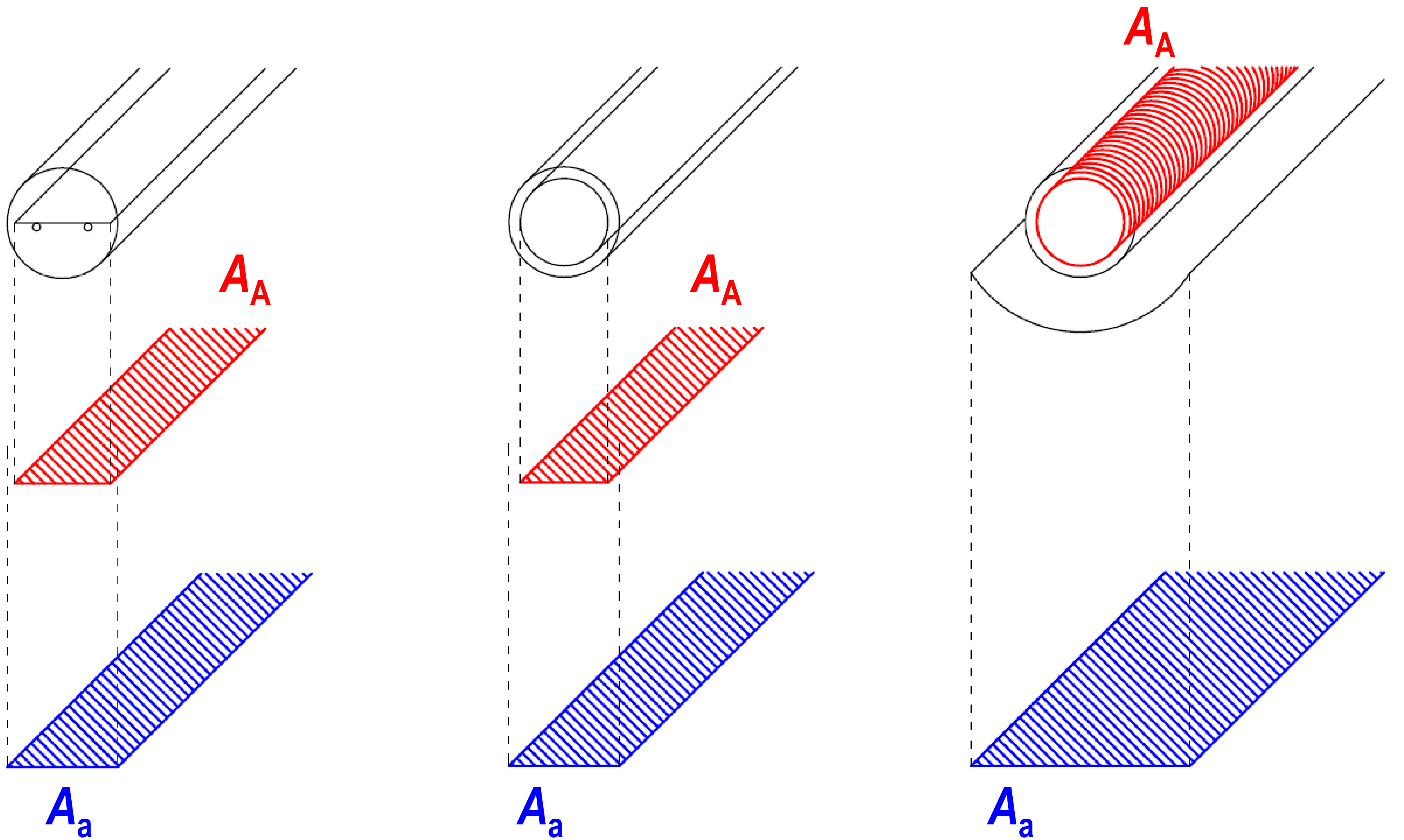
$$\eta = \frac{\dot{Q}_k}{G \cdot A_k}$$

gross area: A_G

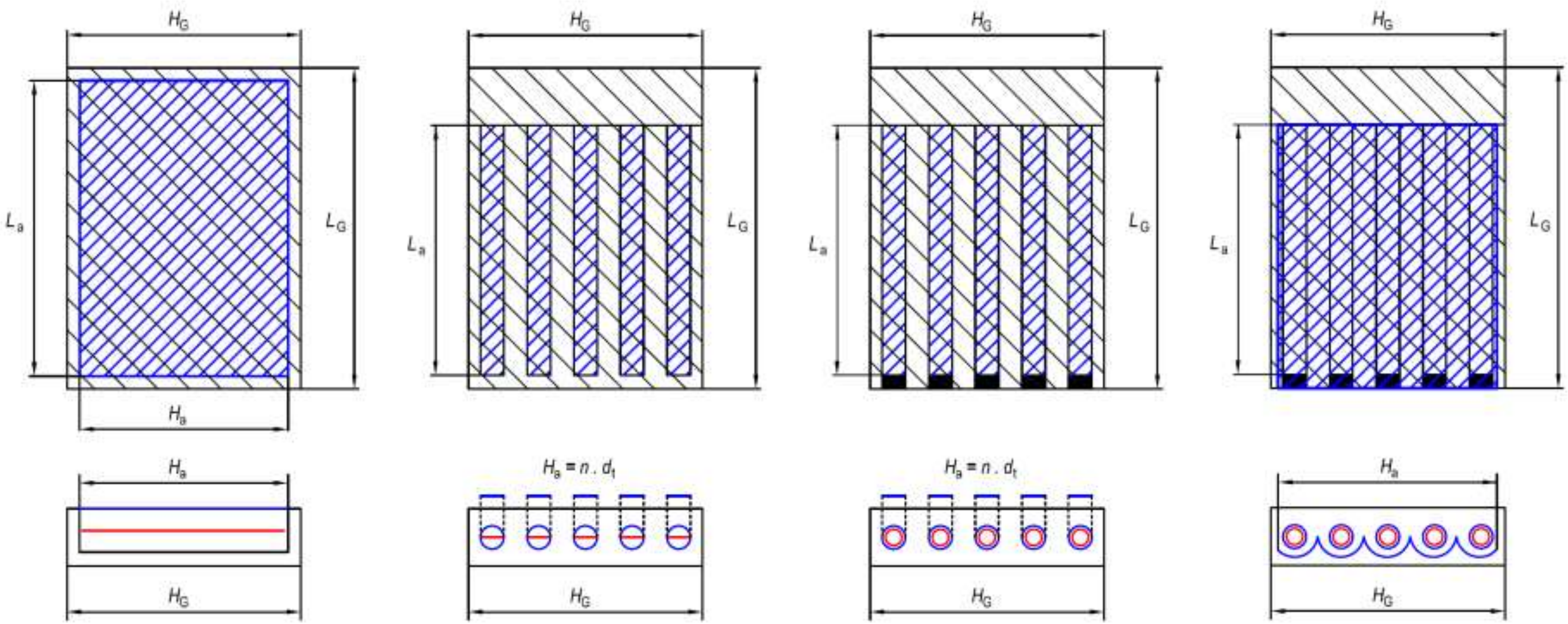
aperture area: A_a

absorber area: A_A

Reference collector area A_k



Reference collector area A_k



$A_a = 0{,}9\ A_G$ $A_a = 0{,}75\ A_G$ $A_a = 0{,}6\ A_G$ $A_a = 0{,}8\ A_G$

- aperture: comparison of collector quality, construction
- gross area: decision on potential for given application (limited space on roof)

Efficiency characteristic

$$\eta = \eta_0 - a_1 \cdot \frac{t_m - t_e}{G} - a_2 \cdot \frac{(t_m - t_e)^2}{G}$$

η_0 „optical" efficiency [-], better: zero-loss efficiency

a_1 linear heat loss coefficient [W/(m^2.K)]

„related to difference between absorber and ambient temperature"

a_2 quadratic heat loss coefficient [W/(m^2.K^2)] „simplified approach for the radiation losses"

values $\boldsymbol{\eta_0}$, $\boldsymbol{a_1}$, $\boldsymbol{a_2}$ related to **reference area A_k (aperture is preferred)**

coefficients are given by producer, supplier or testing institute based on **test report in accordance to EN 12975-2**

Theory x testing

$$\eta = F'\tau\alpha - F'U \cdot \frac{t_m - t_e}{G}$$

$$\eta = \eta_0 - a_1 \cdot \frac{t_m - t_e}{G} - a_2 \cdot \frac{(t_m - t_e)^2}{G}$$

$\eta_0 = F'\tau\alpha$ *zero-loss efficiency*

$a_1 + a_2(t_m - t_e) = F'U$ *heat loss coefficient*

Typical coefficients *)

Collector type	η_0	a_1	a_2
	-	$W/(m^2K)$	$W/(m^2K^2)$
Unglazed	0.85	20	-
Glazed with nonselective absorber	0.75	6.5	0.030
Glazed with selective absorber	0.78	4.2	0.015
Vacuum single tube (flat absorber)	0.75	1.5	0.008
Vacuum tube Sydney	0.65	1.5	0.005

*) referenced to aperture area

Heat output (power) of solar collector

solar collector power (normal incidence, clear sky)

$$\dot{Q}_k = \eta \cdot A_k \cdot G = A_k[\eta_0 G - a_1 \cdot (t_m - t_e) - a_2 \cdot (t_m - t_e)^2]$$

η_0 „optical“ efficiency [-], a_1 linear heat loss c. [W/(m^2.K)] a_2 quadratic heat loss c. [W/(m^2.K^2)]

installed (nominal) **power**

– for defined conditions (according to ESTIF):

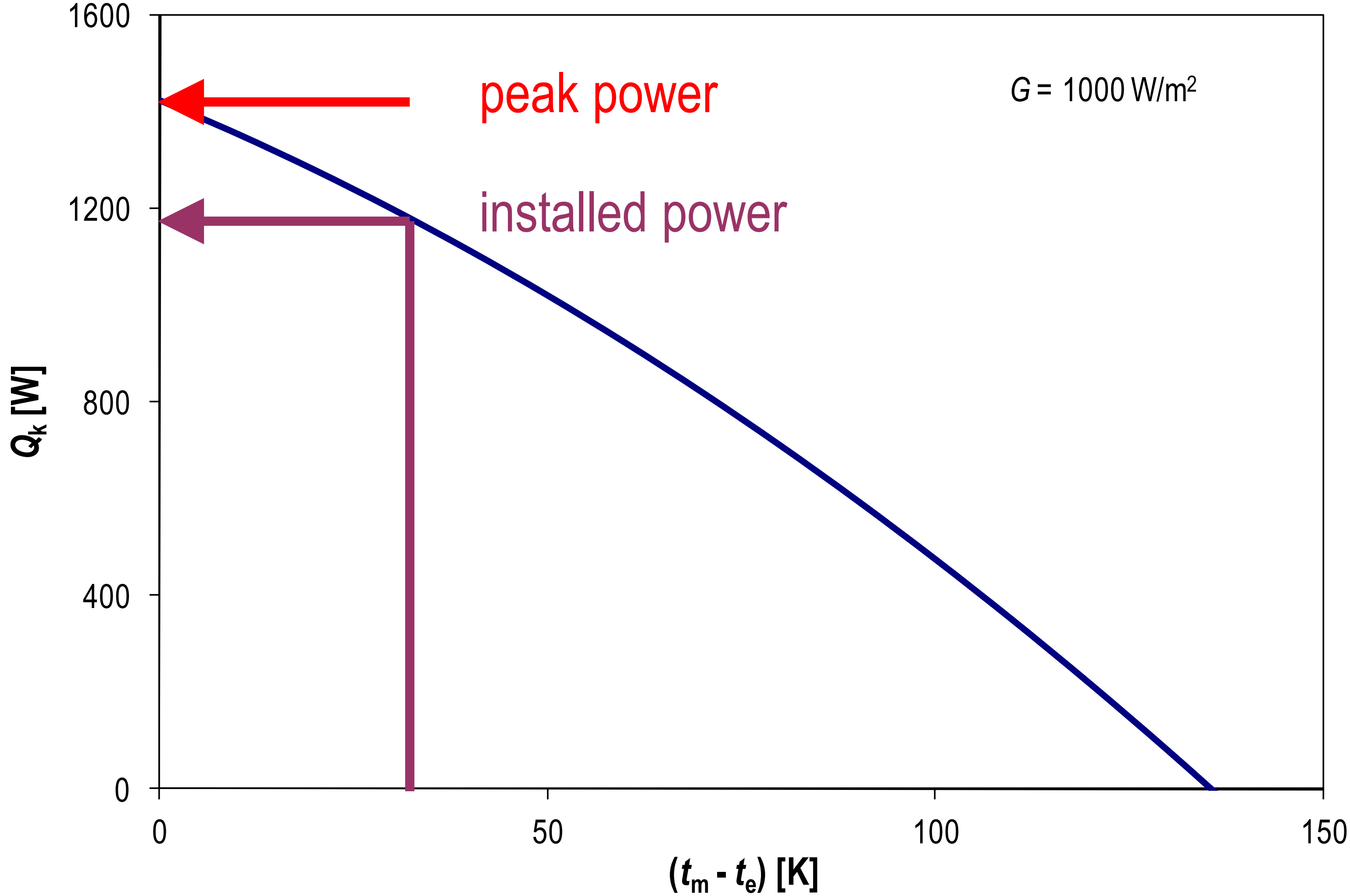
G = 1000 W/m^2 t_e = 20 °C t_m = 50 °C

peak power (without heat loss)

$$\dot{Q}_{k,peak} = A_k \eta_0 G$$

G = 1000 W/m^2

Heat output (power) of solar collector



Efficiency and power calculation

	flat-plate	vacuum tube	
$\eta_{0,a}$	0,75	0,65	-
$a_{1,a}$	3,5	1,5	W/m^2K
$a_{2,a}$	0,015	0,005	W/m^2K^2
A_G	4		m^2
A_a	3,6	2,4	m^2
calculation of daily efficiency for April, Prague city, slope 45°, azimuth 45°			
$G_{T,m}$	473		W/m^2
$t_{e,s}$	12,1		°C
$t_{k,m}$	40		°C

Efficiency and power calculation

$$\eta_k = \eta_0 - a_1 \cdot \frac{t_{k,m} - t_{e,s}}{G_{T,m}} - a_2 \cdot \frac{(t_{k,m} - t_{e,s})^2}{G_{T,m}}$$

$$\dot{Q}_{k,m} = \eta_k \cdot A_k \cdot G_{T,m}$$

$$Q_{k,day} = \eta_k \cdot A_k \cdot H_{T,day}$$

- mean daily solar irradiance

$$G_{T,m} = \frac{H_{T,day,th}}{\tau_t}$$

- daily solar irradiation

$$H_{T,day} = \tau_r \cdot H_{T,day,th} + (1 - \tau_r) \cdot H_{T,day,dif}$$

$$H_{T,day} = \text{3.64 kWh/m2.day}$$

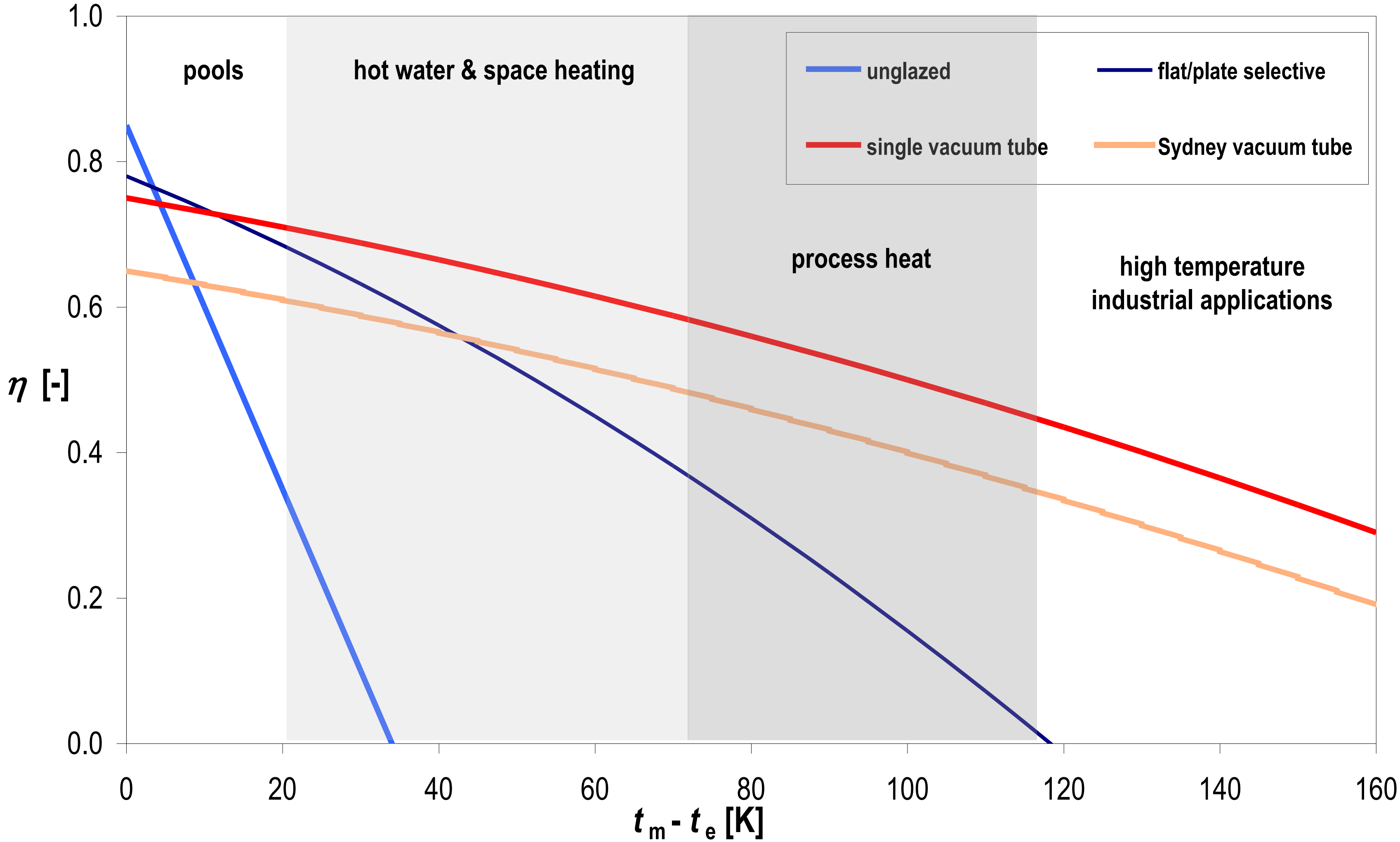
	flat-plate	vacuum tube	
η_k	0,52	0,55	-
$Q_{k,m}$	884	628	W
$Q_{k,day}$	6,8	4,8	kWh/day

Nominal conditions (ESTIF)

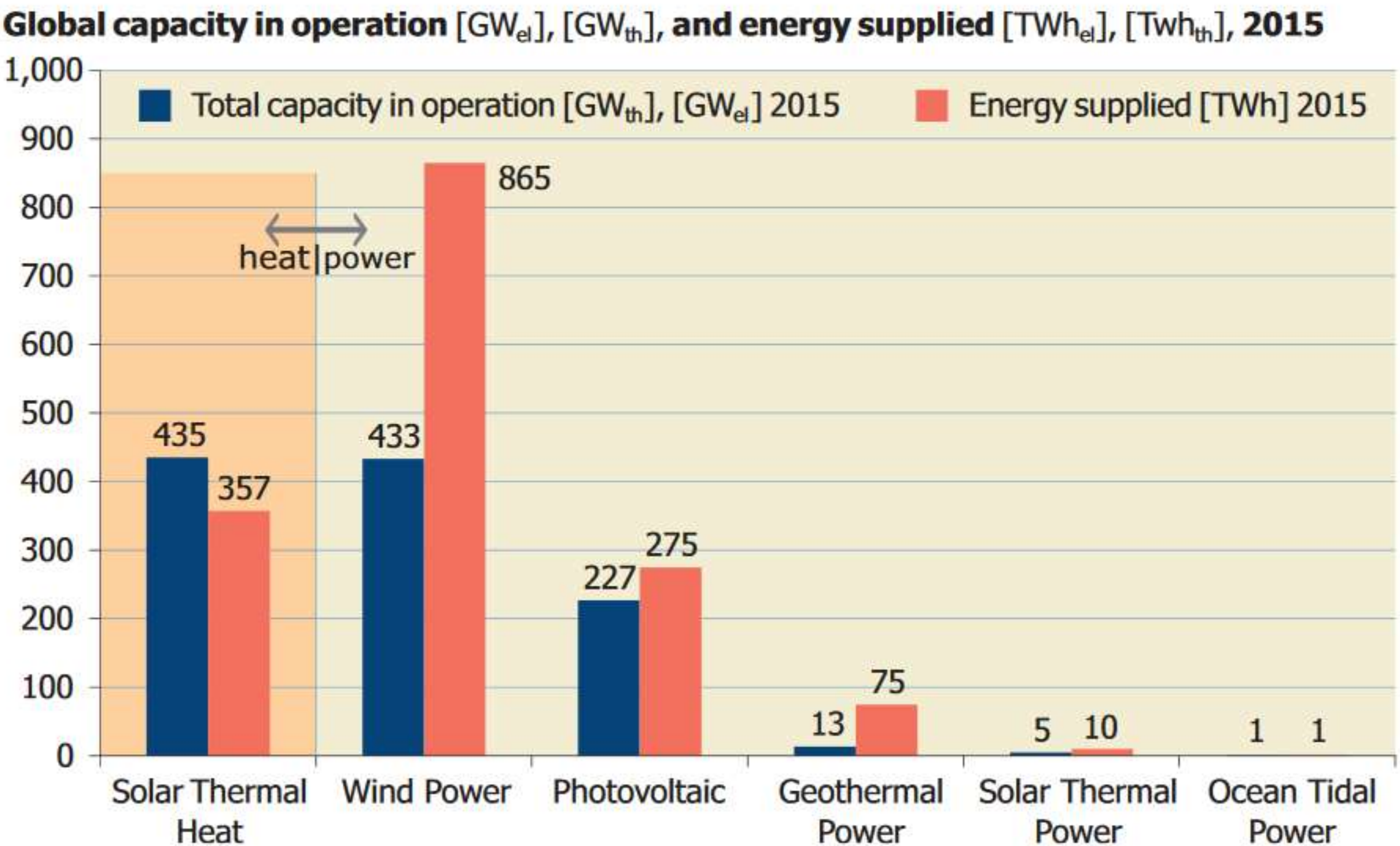
$$\dot{Q}_{k,peak} = A_k \eta_0 G$$

	flat-plate	vacuum tube	
G	1000		W/m^2
$t_{e,s}$	20		°C
t_m	50		°C
η_k	0,63	0,60	
$Q_{k,nom}$	2273	1441	W
$Q_{k,peak}$	2700	1560	W

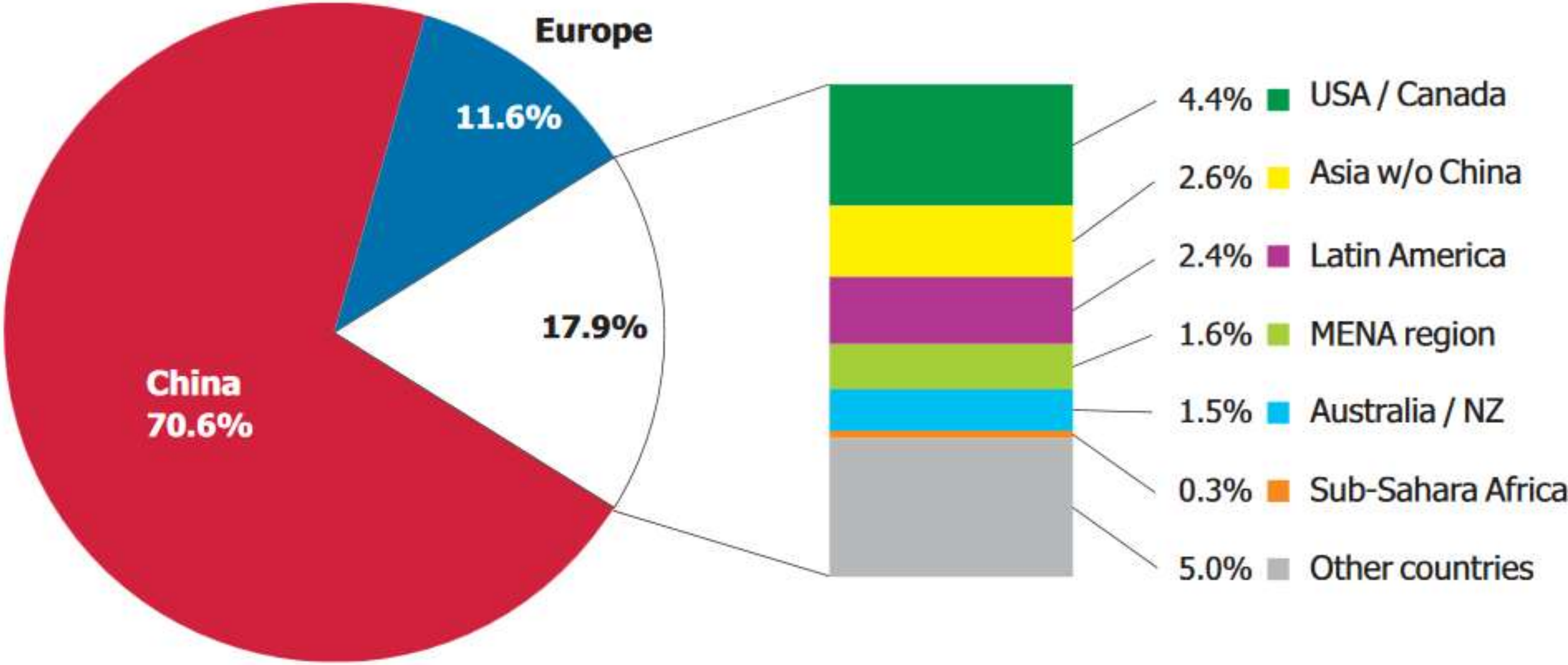
Solar collector / applications



Solar collectors in the World



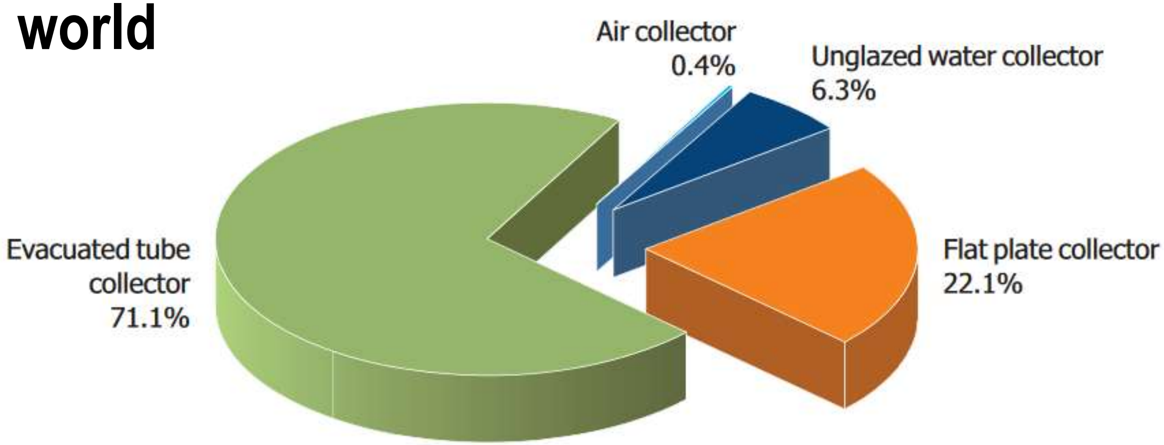
Solar collectors installed (valid for 2015)



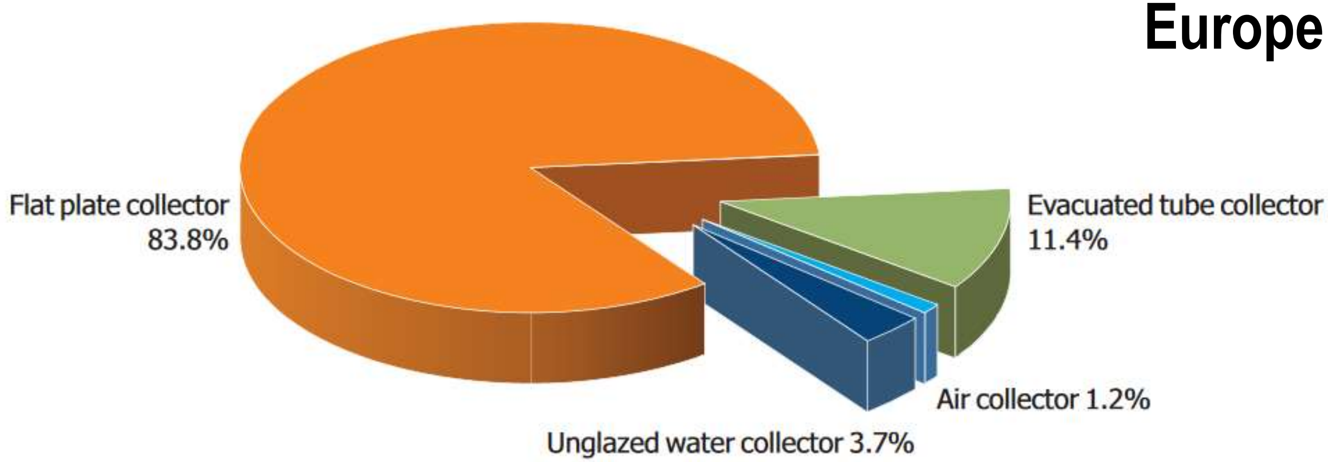
Sub-Sahara Africa:	Lesotho, Mauritius, Mozambique, Namibia, South Africa, Zimbabwe
Asia w/o China:	India, Japan, Korea South, Taiwan, Thailand
Latin America:	Barbados, Brazil, Chile, Mexico, Uruguay
Europe:	EU 28, Albania, Macedonia, Norway, Russia, Switzerland, Turkey
MENA region:	Israel, Jordan, Lebanon, Morocco, Palestinian Territories, Tunisia

Solar collectors installed (valid for 2015)

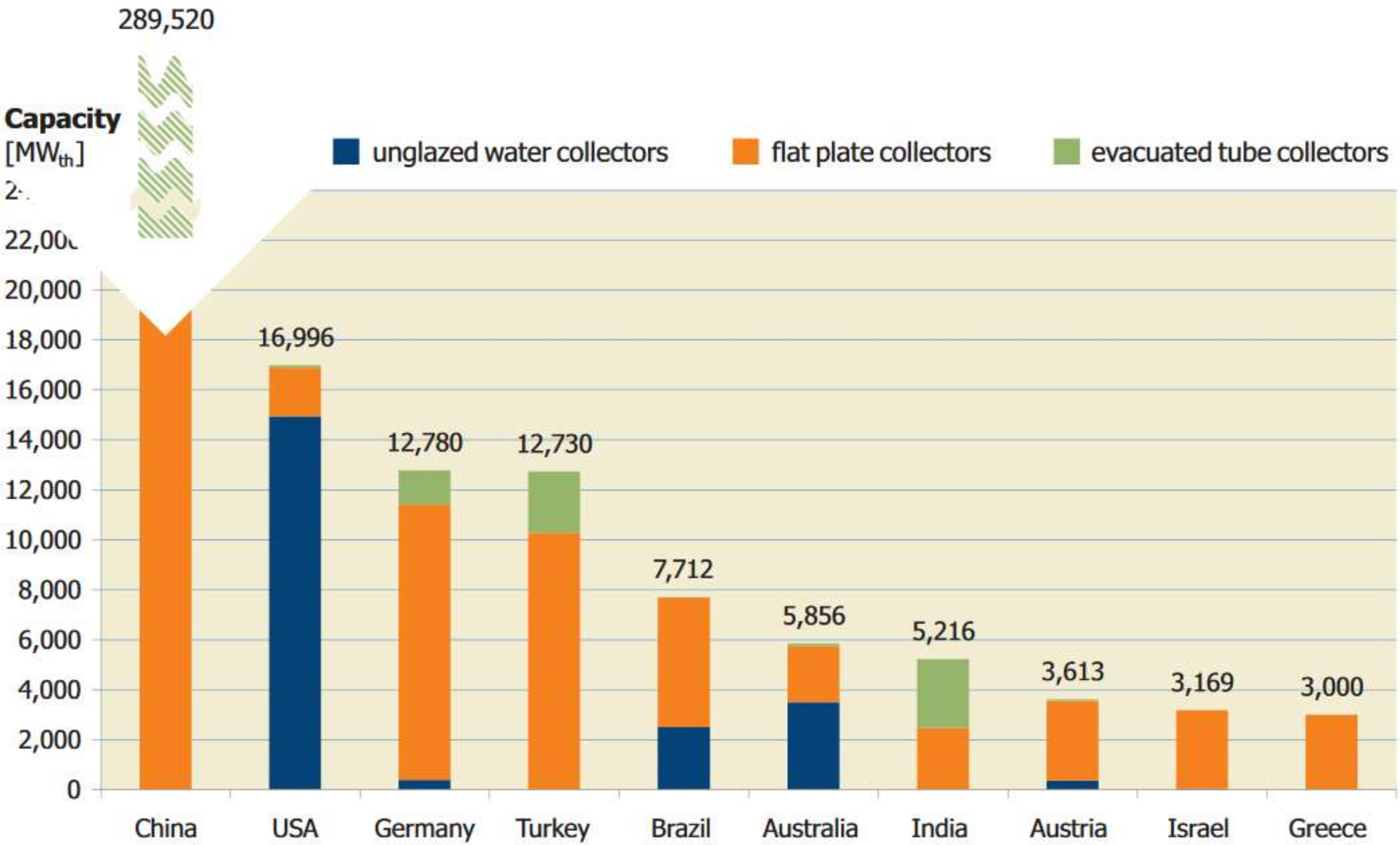
world



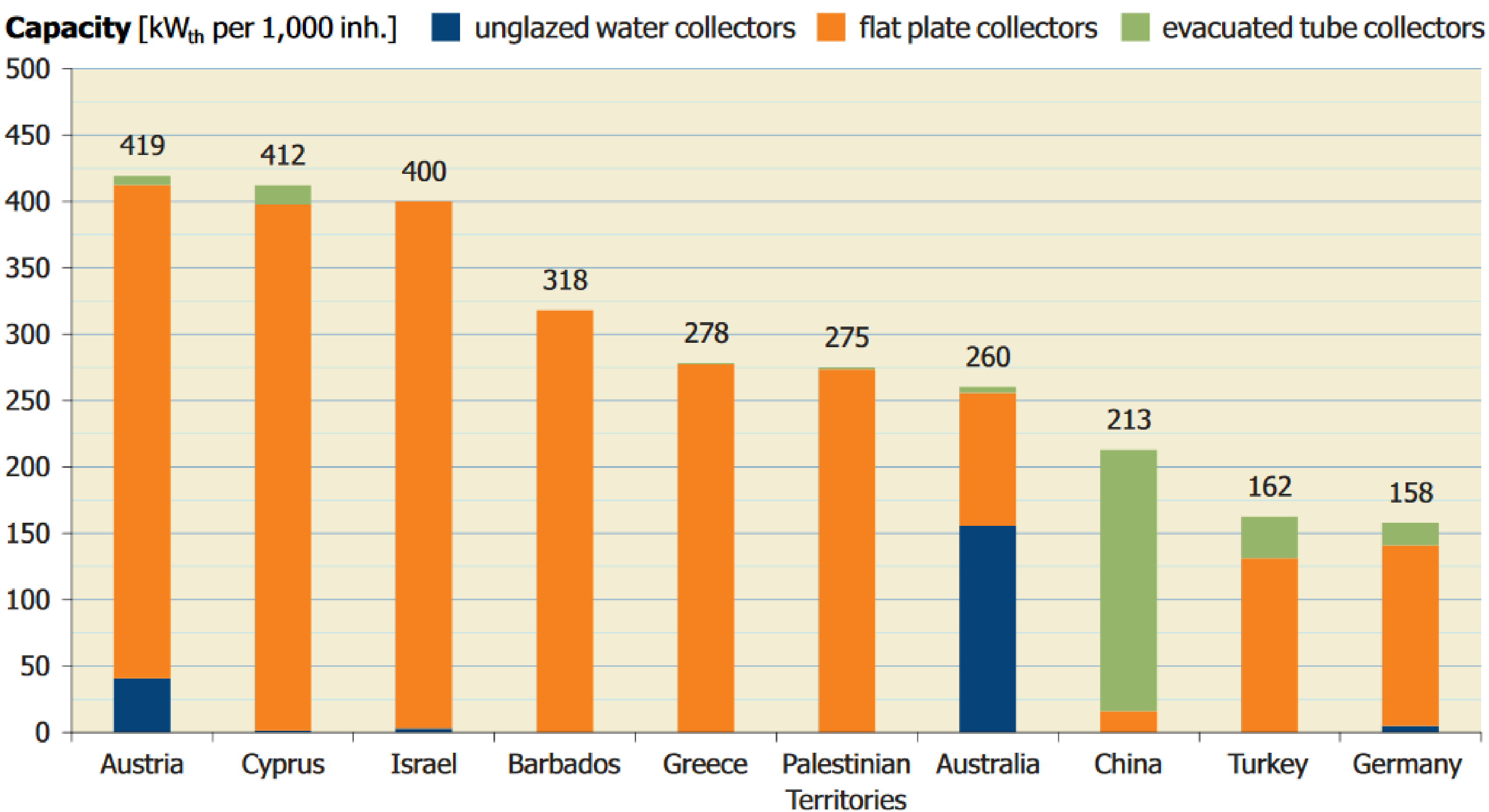
Europe



Solar collectors installed (valid for 2015)

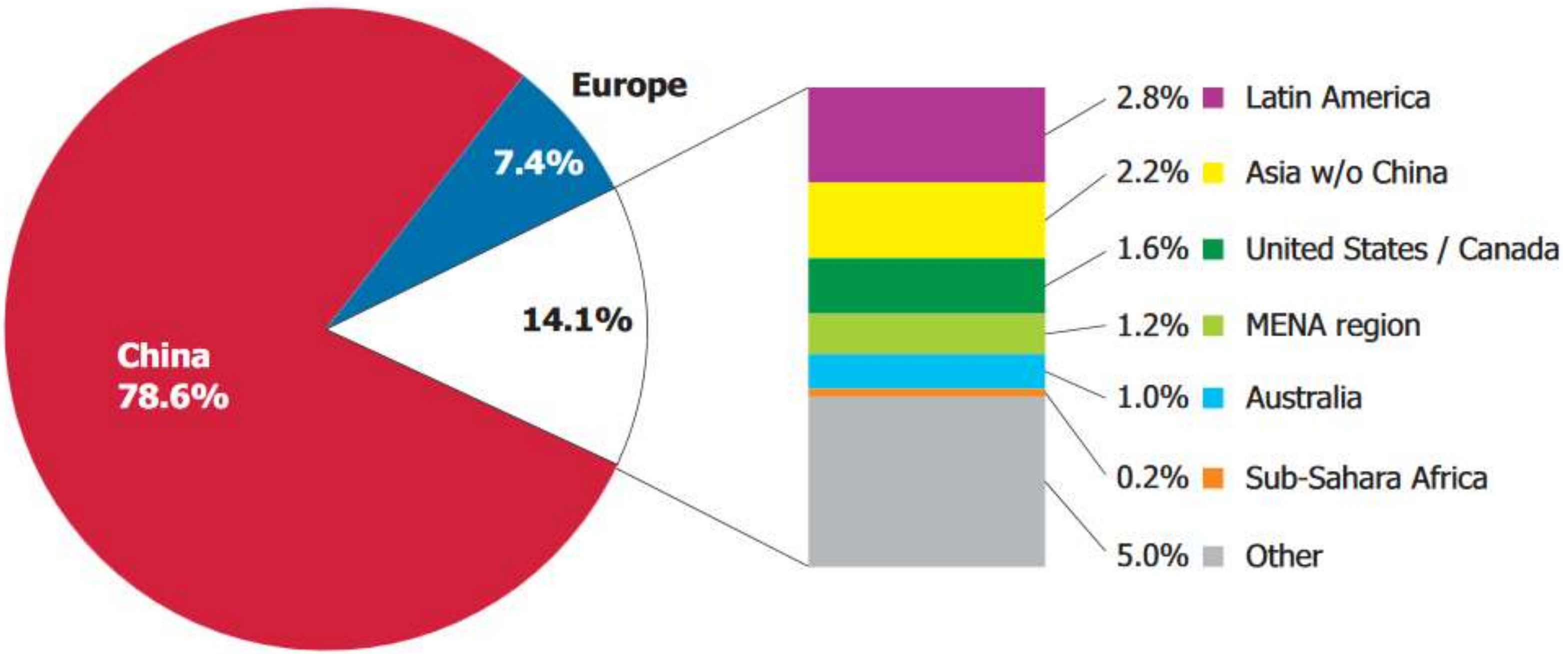


Solar collectors installed (valid for 2015)



per 1000 inhabitants

Solar collectors new installations (2015)



Sub-Sahara Africa:	Lesotho, Mauritius, Mozambique, South Africa, Zimbabwe
Asia w/o China:	India, Japan, Korea South, Taiwan, Thailand
Latin America:	Brazil, Chile, Mexico, Uruguay
Europe:	EU 28, Albania, Macedonia, Norway, Russia, Switzerland, Turkey
MENA region:	Israel, Jordan, Lebanon, Morocco, Palestinian Territories, Tunisia