

## Thermal conversion of solar radiation

The conversion of solar radiation into thermal energy happens in nature by absorption in earth surface, planetary ocean and vegetation. Solar collectors are utilized to manage this absorption and direct the thermal energy to consumers. This energy is conveyed from collectors to consumer by a liquid or gaseous heat carrier. The main parameter of this heat carrier, its temperature when leaving the collector, depends on:

- power density of the incident radiation,
- concentration coefficient of the radiation
- sun position tracking
- optical efficiency of the collector,
- thermal efficiency of the collector.

Photovoltaic panels may be connected in series to obtain a higher voltage or in parallel to obtain a higher current intensity. On the contrary, a higher temperature of the heat carrier cannot be obtained by series connection of some collectors, because the greater is the number of connected collectors, greater become the thermal losses. For this reason different types of collectors have specific field of interest.

A general classification of solar collectors can be made by the concentration factor point of view:

$$c = \frac{S_C}{S_R}$$

where  $S_C$  represents the entire area of the collector exposed to the sun

$S_R$  is the heated area of the collector.

In this respect, there are two categories:

- collectors without concentration of the solar radiation,  $c = 1$
- collectors with concentration,  $c > 1$ .

The first type of collector is intended for heat carrier temperature up to 100°C, while the second type collectors can reach a temperature level up to 3000-5000°C.

### Collectors without concentration

Because  $c = 1$ ,  $S_C = S_R$  or, with other words, the exposed surface to the sun and the heated surface are equal. This type of collector presents some advantages:

- both components of solar radiation, the direct and the diffuse ones are utilized;
- an accurate tracking of the sun path is not compulsory;
- simple structure, available materials;
- small investment and maintenance costs;
- large number of consumers for heat at low temperatures;
- good efficiency by comparison with the photovoltaic conversion.

The simplest type of collector without concentration is the flat collector (fig.1). Its operation is based on the so called "greenhouse effect" which consists in selective behavior of transparent bodies crossed by radiations with different wave lengths. Thus, the solar radiation, having short wave length, crosses glass and air without important attenuation while the infrared radiation emitted by the receiving plate, having much greater wave length, is strongly attenuated.

After crossing the colorless glass, the solar radiation is absorbed in the receiving plate, of black color, warming the plate until an equilibrium is reached between the entering solar energy, the delivered heat and the heat losses.

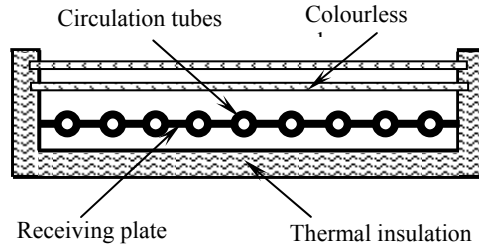


Fig.1 Solar collector flat type

**Optical efficiency of the flat collector**

The optical efficiency is defined as the ratio between the absorbed energy in the collector plate and the solar radiating power applied on the upper surface of the collector. The difference between these quantities represents the losses owed to the reflexion, refraction and absorption in the transparent layers and to the partial absorption of the light in the receiving plate.

Taking into account only one transparent layer and neglecting, for the beginning, the absorption of the light in this layer, can be determined the transmission coefficient,  $D_R$  [p.u.] owed to the reflexion and refraction processes (fig. 2).

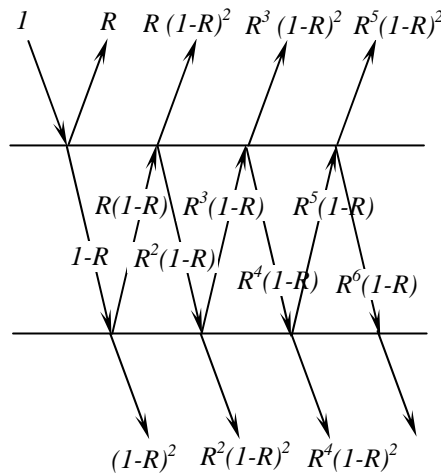


Fig. 2 Solar rays propagation across the transparent layer

The transmitted energy through the transparent layer can be evaluated by adding the successive transmitted components in fig.2

$$D_R = (1-R)^2 + R^2(1-R)^2 + \dots + R^{2n}(1-R)^2 = (1-R)^2(1 + R^2 + \dots + R^{2n})$$

By adding the terms between brackets, results

$$D_R = (1-R)^2 \frac{1 - R^{2(n+1)}}{1 - R^2}$$

Because  $R < 1$ ,  $R^{2(n+1)} \rightarrow 0$ ,

$$D_R = \frac{1-R}{1+R}$$

If there are  $s$  transparent layers, the transmission coefficient becomes, after a similar reasoning:

$$D_R = \frac{1-R}{1+(2s-1)R}$$

The reflexion coefficient  $R$  can be evaluated by the Fresnel equation for the reflexion process of an un-polarized radiation which propagates from a medium characterized by a refraction index  $n_1$  into another medium with refraction index  $n_2$ :

$$R = \frac{1}{2} \left[ \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} + \frac{\text{tg}^2(\theta_2 - \theta_1)}{\text{tg}^2(\theta_2 + \theta_1)} \right].$$

$\theta_1$  and  $\theta_2$  are the angle of incidence and respectively the angle of refraction, governed by the refraction law:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 .$$

If the incident radiation is perpendicular to the surface of the transparent layer,

$$\theta_1 = \theta_2 = 0 .$$

Thus

$$R = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2 .$$

The transmission coefficient  $D_R$  depends on the angle of incidence  $\theta_1$  according to the graph in fig. 3. An important conclusion resulting from this figure is that the optical efficiency of the flat collector maintains quite unaffected when the angle of incidence changes within  $\pm 40-45$  degrees from the right orientation to the sun.

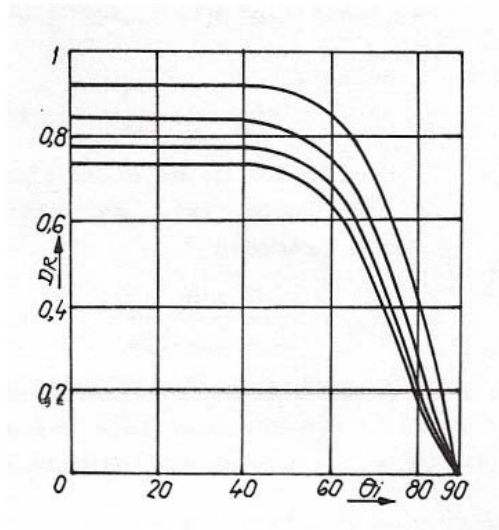


Fig. 3 - Transmission coefficient  $D_R$  dependence of the incidence angle

The incident radiation is partially absorbed in the glass, so that the transmitted power,  $D$ , depends on the path,  $d$ , length through glass, upon the exponential law:

$$D = D_R e^{-kd} .$$

$k$  is the attenuation coefficient, which depends on the chemical composition of the glass. For example, a glass with very low content of Fe has  $k = 0,04 \text{ cm}^{-1}$ , while a reprocessed glass can reach a value  $k = 0,32 \text{ cm}^{-1}$ .

Subtracting the transmitted power  $D$  from  $D_r$ , the result is  $A$  which represents the absorbed power, having as consequence a warming of the glass:

$$A = 1 - e^{-kd}.$$

Considering a glass sheet of 0,5 cm thick, the light attenuation represents 7,5% for the best quality glass and 52% for the poorest quality one.

Further, the transmitted solar radiation is partially absorbed by the receiving plate, depending on the absorption coefficient  $A_p$ . A new series of repeated absorption and emission processes take place, like that presented in fig. 4.

The incident radiation on the receiving plate will be considered as directional one, like it comes from the sun. The emitted radiation from the plate is diffuse, because the plate, which must absorb the radiation as much as possible, has a lusterless surface.

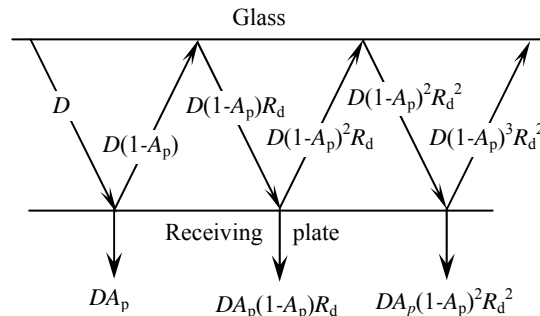


Fig. 4 Entering the solar radiation in the absorbing plate

A new reflexion coefficient  $R_d$  is introduced to evaluate the diffuse radiation reflected from the glass, which value depends on the number of glass layers. For example,  $R_d = 0.16, 0.24, 0.29$  if the number of glass layers,  $s$ , is 1, 2 or 3 respectively.

By adding the power components entered in the receiving plate, the result represents the optical efficiency of the collector.

$$\eta_{opt} = DA_p + DA_p(1 - A_p) + DA_p(1 - A_p)^2 R_d^2 + \dots + DA_p(1 - A_p)^n R_d^n + \dots$$

$$\eta_{opt} = DA_p \left[ (1 - A_p) R_d + (1 - A_p)^2 R_d^2 + \dots + (1 - A_p)^n R_d^n + \dots \right]$$

$$\eta_{opt} = DA_p \frac{1 - [(1 - A_p) R_d]^n}{1 - (1 - A_p) R_d}.$$

Because  $1 - A_p < 1$  and  $R_d < 1$ , too, the second term of the nominator can be neglected, so that the optical efficiency becomes

$$\eta_{opt} = \frac{DA_p}{1 - (1 - A_p) R_d}.$$

### Thermal efficiency of the flat collector

The heat developed in the absorbing plate can be divided in three main components:

- the heat transported by the cooling fluid to the consumer,
- the heat accumulated in the collector materials, which are warming up,

- the heat losses from collector to the ambient space.

If the density of the solar radiation and the heat carrier mass flow are constant, the absorbing plate temperature is constant, too. As consequence, for this stationary operating mode, the accumulated heat in the collector materials can be neglected in the equation of energy balance.

The heat losses take place through all the outer surfaces of the collector. Because the walls structure differs on the side and back surfaces from the upper one, the basic heat transfer mechanisms have different weight on these directions. On the upper side prevails the heat losses by radiation and convection. On the other sides of the collector, the conduction mechanism is dominant, because the temperature of the external surfaces is low enough to allow neglecting by radiation and convection losses.

To calculate the whole heat losses, the next equation may be considered:

$$Q_p = K_t S (t_p - t_a),$$

where

$K_t$  is the whole heat transfer coefficient,

$S$  is the area of the upper surface of the collector, equal with the receiving plate area

$t_p$  is the average temperature of the receiving plate

$t_a$  is the temperature of the surrounding air.

Because the global heat transfer coefficient is difficult to evaluate, an electrical similarity of the heat transfer can be suggested. Considering a potential difference  $U_1 - U_2$  applied to a resistor  $R$ , the current intensity, may be written

$$I = \frac{U_1 - U_2}{R}.$$

Similarly, the heat transmitted, per the unit of surface, between two parallel plates, having different temperatures  $t_1 > t_2$  and the transfer coefficient  $k$ , is

$$q = k(t_1 - t_2) = \frac{t_1 - t_2}{R_t}.$$

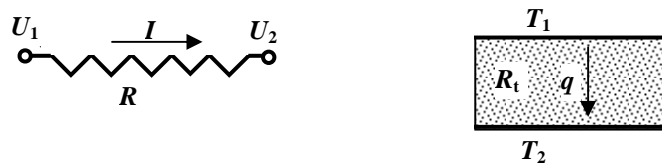


Fig.5 The analogy between the electric current and the heat transfer

Thus, the thermal resistance is similar to the electric resistance, the temperature gap is similar to the electric voltage and the heat flow is similar to the electric current.

For example, the diagram in fig. 6 represents the equivalent electric circuit for the flat collector in fig.1, having two transparent layers of glass.  $t_p$  is the temperature of the receiving plate,  $t_a$  is the air temperature,  $t_{g1}$ ,  $t_{g2}$  are the temperatures of the two glass layers and  $t_c$  is the temperature on the side and back surfaces of the collector.

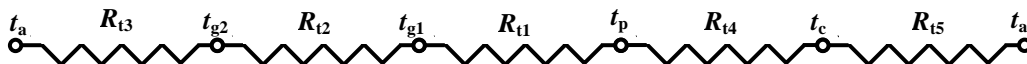


Fig.6 The equivalent electric circuit of the heat losses in the flat collector

The electric analogy allows expressing the global thermal resistance,  $R_t$ . On the upper side of the collector, the three thermal resistances are connected in series so that:

$$R_{upp} = R_{t1} + R_{t2} + R_{t3}.$$

On the others sides of the collector, the thermal resistances are connected in series, too:

$$R_b = R_{t4} + R_{t5}.$$

The global thermal resistance  $R_t$  will be:

$$R_t = \frac{R_{upp} R_b}{R_{upp} + R_b},$$

thus the global heat transfer coefficient,  $K_t$  is

$$K_t = \frac{1}{R_t}.$$

To calculate the heat resistances, it must be analyzed the heat transfer processes. From theoretical point of view, the upper structure of the collector can be modeled like parallel surfaces having infinite sizes and different temperatures. Considering a pair of surfaces with the temperatures  $t_1$  and  $t_2$ , the heat transfer between them, by radiation and convection, obeys to the next equation:

$$q_{12} = \alpha_C(t_1 - t_2) + \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}.$$

The first term in the right part of this equation represents the transfer by convection, while the second term, the radiation process. The significance of the symbols in the previous equation is:

- $\alpha_C$  is the heat transfer coefficient by convection,
- $\sigma$  is the Stefan-Boltzmann constant ( $5.67 \cdot 10^{-23} \text{ W/m}^2 \text{ } ^\circ\text{K}^4$ ),
- $\varepsilon_1$  and  $\varepsilon_2$  are the emission coefficients by radiation from the two surfaces.

By extracting the term  $(T_1 - T_2)$  as a common factor in this equation, results:

$$q_{12} = \left[ \alpha_C + \frac{\sigma(T_1 + T_2)(T_1^2 + T_2^2)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \right] (T_1 - T_2) = (\alpha_C + \alpha_R)(T_1 - T_2).$$

This way, two heat resistances in fig.1 can be written as:

$$R_{t1} = \frac{1}{\alpha_{C1} + \alpha_{R1}}, R_{t2} = \frac{1}{\alpha_{C2} + \alpha_{R2}}.$$

For the heat resistance  $R_{t3}$ , the model structure is different, the atmosphere being one of the two surfaces. Thus, for the heat transfer by radiation to the atmosphere, the heat transfer coefficient is:

$$\alpha_{R3} = \varepsilon_g \sigma (T_{g2} + T_a) (T_{g2}^2 + T_a^2).$$

For the heat transfer by convection to the atmosphere, an empirical equation is recommended:

$$\alpha_{c3} = 5.7 + 3.8v_t$$

where  $v_t$  is the air speed parallels with the upper surface of the collector.

To apply this algorithm is necessary to know the temperatures of the parallel surfaces that are difficult to obtain. As consequence, simpler methods are utilized for the collector designing:

- nomographs based on the analytic equations, valid for specific collector structure or materials;
- empirical equations, experimentally proved as valid for specific structure and materials.

A heat transfer by conduction produces through the thermal insulation on the back and side walls of the collector, according to the next equation:

$$q_{is} = \frac{\lambda_{is}}{\delta_{is}}(t_p - t_a),$$

where

$\delta_{is}$  represents the thermal insulation thickness,

$\lambda_{is}$  is the coefficient of thermal conduction of the insulating material.

Thus,

$$R_{t4} = \frac{\delta_{is}}{\lambda_{is}}.$$

From the side and back surfaces of the collector, the heat losses to the atmosphere, through radiation and convection can be neglected because the both temperatures are very close. As consequence,  $R_{t5} \rightarrow \infty$ , respectively,  $k_5 = 0$ .

### The efficiency of the flat collector

In order to calculate the collector efficiency, some energy quantities can be defined:

- the incident energy on the upper surface of the collector

$$W_1 = ESf,$$

where  $E$  is the power density of the sun radiation,  $S$  is the area of upper surface of the collector and  $f$  is it's orientation factor;

- the energy developed in the receiving plate

$$W_2 = ESf\eta_{opt};$$

- the energy losses in the optical system of the collector

$$W_3 = (1 - \eta_{opt})ESf;$$

- the whole heat losses

$$W_4 = K_t S(t_p - t_a).$$

Two possibilities to define the collector efficiency are relevant:

- the general efficiency

$$\eta_g = 1 - \frac{W_3 + W_4}{W_1}.$$

By replacing the above defined energy quantities, results

$$\eta_g = \eta_{opt} - \frac{K_t(t_p - t_a)}{Ef}.$$

- the inner (thermal) efficiency

$$\eta_t = 1 - \frac{W_4}{W_2} = 1 - \frac{K_t(t_p - t_a)}{E_f \eta_{opt}}$$

These two efficiencies are linked by the equation

$$\eta_g = \eta_{opt} \eta_t,$$

so that  $\eta_g < \eta_t$ .

The collector efficiency depends on more factors like sun power density, collector orientation, the temperature of the receiving plate, the air temperature etc. For a good quality collector, in a normal regime of operation, the energy losses have the average values:

Type of losses	Loss weight
<i>optical losses</i>	
by reflexion	2 x 4%=8%
by refraction	2 x 3.5%= 7%
<i>thermal losses</i>	
convection	17%
radiation	12%
conduction	3%
<i>energy losses, total</i>	47%

The global efficiency results to be 53%, much greater than that of the photoelectric cells. However, the temperature gap between the receiving plate and the air influences the global efficiency, like fig. 7 shows. The nonlinear dependence is owed to the heat losses through radiation because those depend on the 4<sup>th</sup> power of the temperature. The highest temperature of the plate is reached when the heat carrier does not circulate, while the collector is exposed to the sun. At this temperature all the energy losses from the collector equalize the received sun power. Is very important to know how great this temperature for an adequate designing of the collector is so that it could operate in every regime without damages.

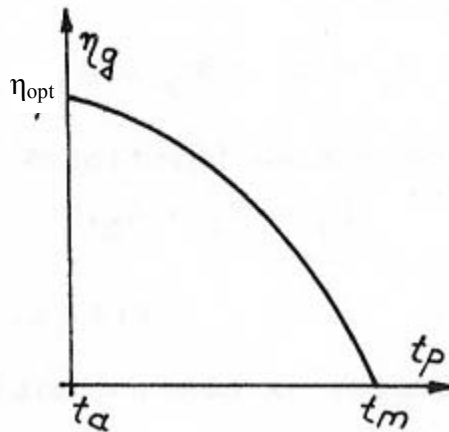


Fig.7 The flat collector efficiency versus absorbing plate temperature

An example of flat collector design is shown in fig.8.



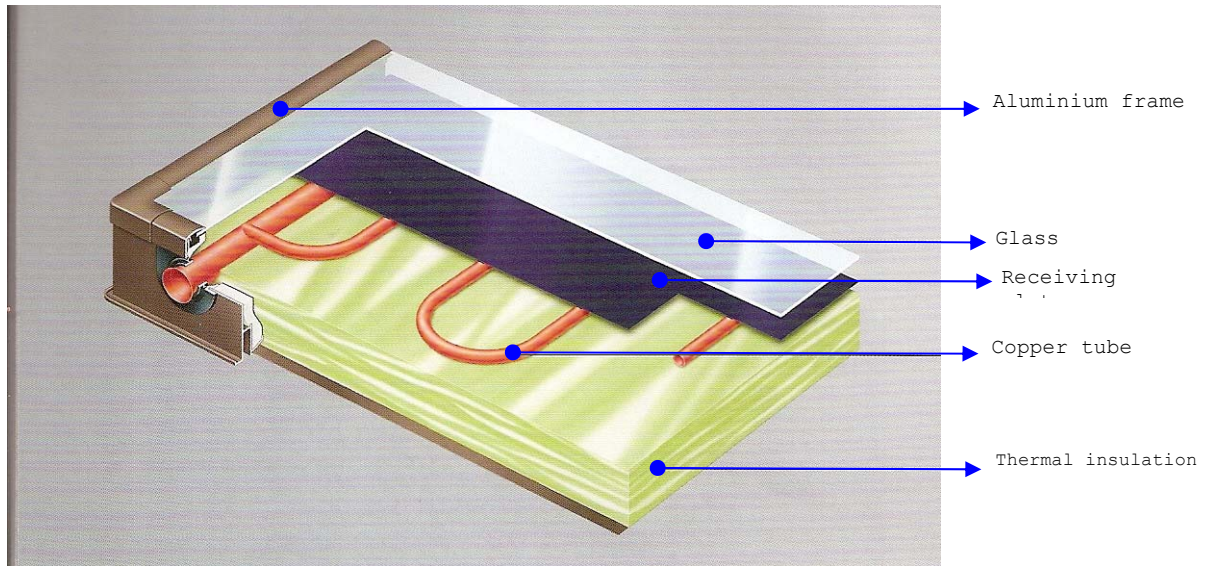


Fig. 8 The flat collector

### The cylindrical collector

A cylindrical collector consists in two tubes: the inner, metallic tube having a dark surface in order to absorb the solar radiation, surrounded by a transparent tube, fig. 9. Through the inner tube flows the heat carrier fluid.

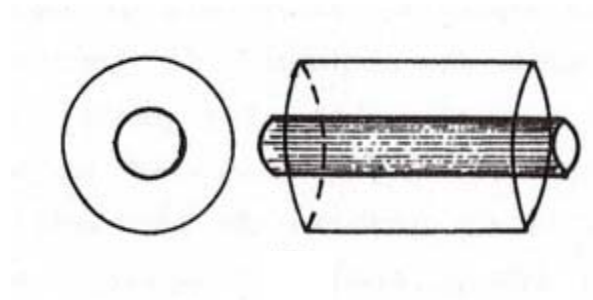


Fig. 9 The cylindrical collector

This structure of collector presents some advantages by comparison with the flat collector:

- the illuminated surface area of the inner cylinder remains unaffected if the sun position on the sky changes;
- if the space between tubes is empty (advanced vacuum) the convection and conduction heat losses are avoided, so that the whole efficiency can be much improved.

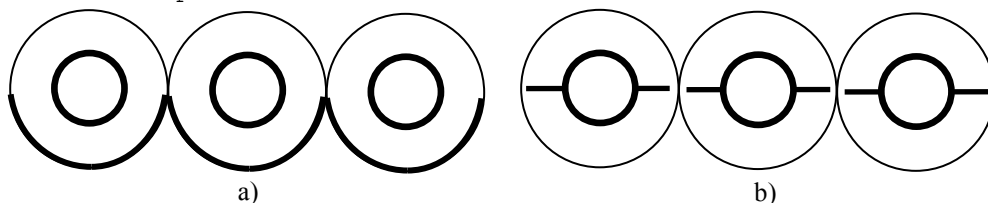


Fig. 10 Different structures of cylindrical collectors

To increase the received sun power, the absorbing surface must increase. However, this growth is limited because as the inner tube diameter

grows, the quantity of the fluid grows too, as well as the thermal inertia of the collector.

More cylindrical collectors can be connected in parallel and arranged on a plate surface like a flat collector. To utilize the solar radiation which passes between tubes, the inner surface of the outer tube can be covered with a mirror layer. Thus, the reflected radiation reaches the absorbing surface (fig. 10, a).

Another solution is to add an absorbing flat surface to the inner tube (fig. 10.b). In this manner, the entire solar radiation reaches the absorbing surface, but the independence regarding the sun position on the sky will be lost. However, remains the main advantage of heat losses diminution.

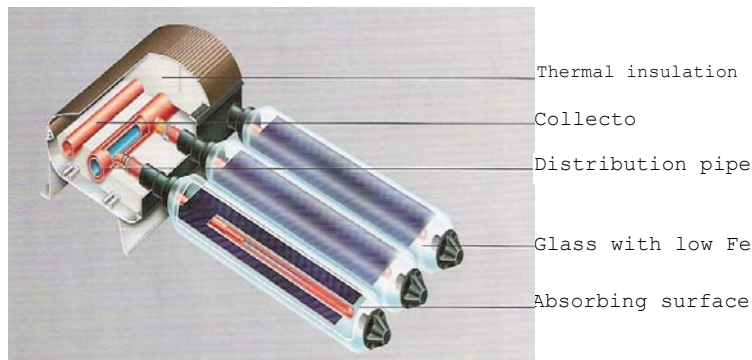


Fig. 11 Cylindrical collector design

Despite it is more expensive than the flat collector, the cylindrical one are nowadays much more asked because it's higher efficiency.

### Solar radiation concentration

To obtain a concentration coefficient greater than 1, an optical system must be added between the sun and the absorbing surface (the receiver). This optical system is based either on the reflexion or the refraction phenomena of the solar directional radiation. The diffuse radiation can not be concentrated.

Depending on the mirror geometry, the concentration coefficient may vary between 2 and  $10^4$  that mean a similar growth of the power density on the absorbing surface. Some losses however, appear owing to the quality of the optical system.

As the concentration coefficient greater is, an accurate solar position tracking is necessary in order to preserve an efficient operation of the collector. This orientation must be permanent and needs an independent energy source.

The solar collectors with concentrating systems can be divided in two categories:

- collectors with motionless optical system
- collectors with mobile optical system

### Collectors with motionless optical system

*The flat collector associated with side mirrors*

The simplest way to concentrate the solar radiation is to add one or two side mirrors to a flat collector (fig.12). The solar radiation arrives at the flat collector surface directly and reflected from the mirrors.

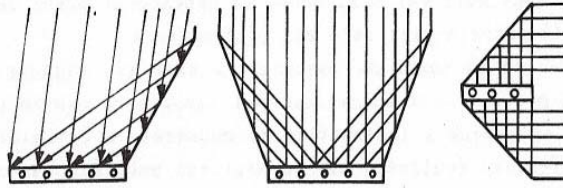


Fig.12 Flat collector associated with mirrors

The concentration coefficient is variable, depending on the sun position on the sky. Sometimes, the entire power reflected from the mirrors reaches the flat collector surface. Other times, only a part of the reflected radiation arrives at the collector surface, depending on the incidence angle on the mirrors.

*Flat collector associated with parabolic mirrors*

Two segments of parabolic mirrors,  $P_1$  and  $P_2$  are arranged to lean on the side ends of a flat collector; the axes of the parabolic surfaces are disposed symmetrically against the collector axis, under an angle  $\theta$  (fig.13). The both centers of the parabolic surfaces, points  $B$  and  $D$ , are located on the flat collector surface. The parabolic mirrors concentrate the incident rays towards the collector bottom, if that rays are parallel with the mirrors axes. So that, if the incidence angle between the collector axe of symmetry and the incident rays are smaller than  $\theta$ , all the solar power what enter the collector arrive at the absorbing surface. If that incidence angle is greater than  $\theta$  the solar radiation is partially or totally reflected from a mirror towards another mirror and then back to the atmosphere. Depending on the size of angle  $\theta$ , the collector can operate 5-7 hours daily.

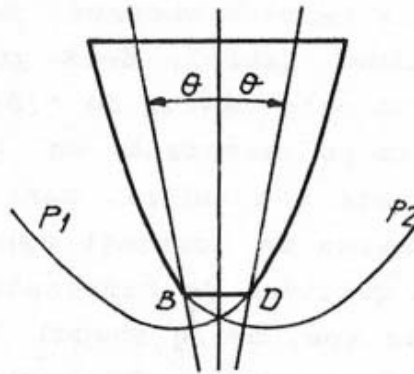


Fig.13. The double-parabolic mirrors collector

The geometrical concentration coefficient is

$$c = \frac{1}{\sin \theta}.$$

Actual values of this coefficient vary from 2 to 10.

*The spherical concentrator with mobile receiver*

A spherical mirror reflects the directional radiation towards a linear focus, parallel with the incident rays (fig.14). While the mirror is fix, the receiver must perform a motion with two degree of freedom in order to follow the sun position on the sky. The receiver movement needs smaller power consumption than the mirror orientation.

The concentration coefficient becomes highest if the mirror angle is  $120^\circ$ . For a perfect mirror surface, this maximum is 187.

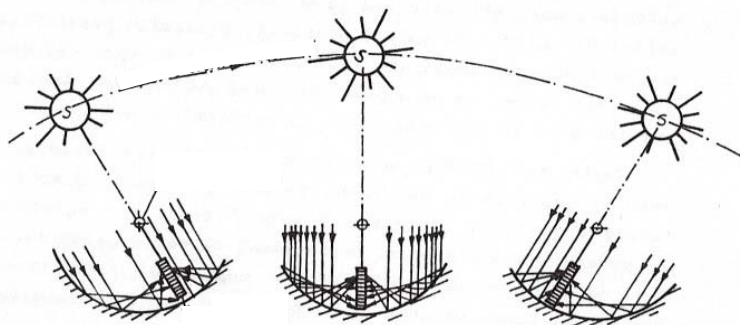


Fig.14 The spherical concentrator

### Collectors with mobile concentrator

#### *The parabolic mirror*

A parabolic mirror is obtained by rotating a parabola around its axis. This mirror has the highest concentration coefficient among all other types. Fig. 15 shows the optical behavior of this mirror.

The sun disc is seen from the sun-earth distance as the base of a circular cone having the top angle of  $32'$ . The two side rays which arrive at the mirror top (point **A**) reflect maintaining the same angle between them, so that in the focal plane appears a circular light spot with diameter  $d_f$ .

The rays cone which arrives in point **B**, reflects, too and, crossing the focal plane, an ellipsoidal light spot appears, having the main axis  $d > d_f$ . Taking into account all the mirror points situated at angular distance  $\theta$  from the mirror top, the image in the focal plan becomes a circle with diameter  $d$ . If  $\theta = 90$  degrees, all the focal plane will be illuminated and if  $\theta > 90$  degrees, a concentrate light will appear on the surface exposed to the sun. These two last situations are not interesting for sun collectors because, obviously, the power receiver surface must be smaller than the mirror aperture in order to not shadow its surface.

Since as greater is the angle  $\theta$ , the focal spot diameter grows, the power reflected from the mirror surface spreads on a greater surface in the focal plane. Thus, the power density on the focal plane surface diminishes from center to edge. Theoretically, the power density changes as fig.16 shows; the curve **1** has a flat zone corresponding to the circle of diameter  $d_f$ . Because of deviations of the actual mirror from the geometrical shape, the power density changes as the curve **2** shows.

The diameter of the absorbing surface chooses according to the purpose that is intended for the mirror. That purpose can be:

- to obtain the higher possible temperature on the receiver;
- to collect the entire radiation reflected from the mirror surface.

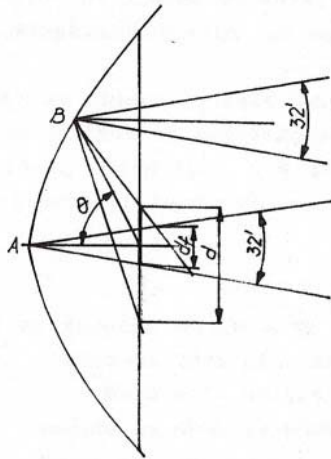


Fig.15 The parabolic mirror

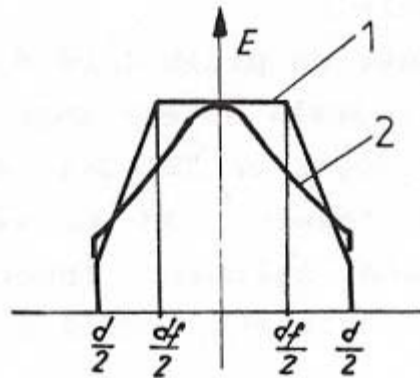


Fig.16 The power density on the absorbing surface

In the first case, the receiver diameter must be equal with  $d_f$ . The maximum concentration coefficient is reached for an aperture angle of  $90$  degrees and is equal to

$$c_{\max} = \frac{1}{\text{tg}^2 16'} \approx 46100 .$$

In the second situation the receiver surface chooses of diameter  $d$ .

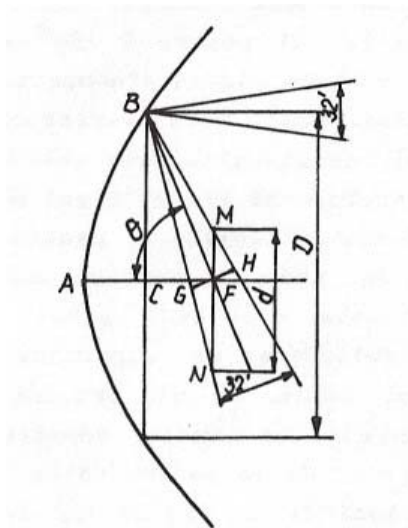


Fig. 17 Determining the concentration coefficient

The concentration coefficient is defined as

$$c = \frac{S_D}{S_d} = \left(\frac{D}{d}\right)^2$$

We note, in fig. 16,  $AD = f$  and  $BF = R$ . Considering the triangle  $BCF$ , results

$$D = 2BC = 2R\sin\theta .$$

From the triangles  $GFN$  and  $FHM$ :

$$d = MN = \frac{GH}{\cos \theta}$$

Since

$$GF = FH = R \operatorname{tg} 16'.$$

Results

$$d = \frac{2R \operatorname{tg} 16'}{\cos \theta}.$$

Finally

$$c = \left( \frac{\sin \theta \cos \theta}{\operatorname{tg} 16'} \right)^2 = \left( \frac{\sin 2\theta}{2 \operatorname{tg} 16'} \right)^2,$$

that means the concentration coefficient depends on the aperture angle  $\theta$ .

The function  $\sin 2\theta$  has the maximum value equal to **1**, and that happens if  $2\theta = 90$  degrees, or  $\theta = 45$  degrees.

For  $\theta = 45$  degrees the concentration coefficient reaches the value

$$c_{\max} = \frac{1}{4 \operatorname{tg}^2 16'} \approx 11525.$$

In fact, the realized mirrors have deviations from the theoretical geometric shape so that the optimum aperture grows to **60** degrees. In this case the concentration coefficient can be only **8655**. Even this value can not be obtained; practical values are 4-5 times smaller.

The cylindrical parabolic mirror is obtained by translating a parabola along a straight line. The sun image on the focal plane is now a rectangular one, which length is equal to the mirror length. The geometrical concentration coefficient is

$$c = \frac{S_D}{S_d} = \frac{D}{d},$$

having the maximum value

$$c_{\max} = \frac{1}{2 \operatorname{tg} 16'} \approx 107.$$

Large parabolic mirrors are built with many small mirrors disposed to form a parabolic surface. The small mirrors may be flat or curved. Such a mirror will have a smaller concentration coefficient, of course, than a parabolic mirror. Two examples are shown in fig. 17 and fig. 18.

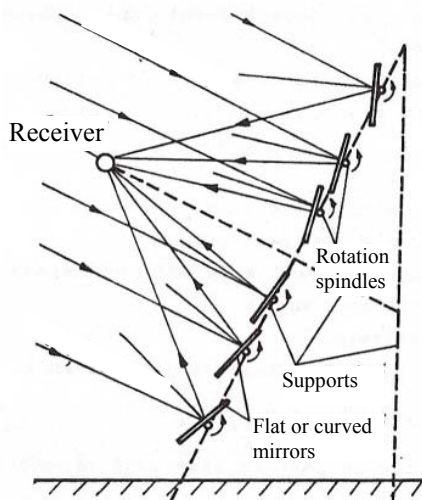


Fig. 18 Cylindrical parabolic mirror (Fresnel concept)

### Solar thermal power plant

Collecting the solar radiation with large mirror systems, a high steam temperature may be obtained to generate electricity through the conventional thermodynamic cycle. Two main types of such plant are built up.

a) *The plant with distributed collectors (fig. 19).*

Every collector has a mirror and a receiver where the heat carrier is warmed up. A pipe system collects the flows of heat carrier from all receivers and transports it to the steam generator. The size of such a plant

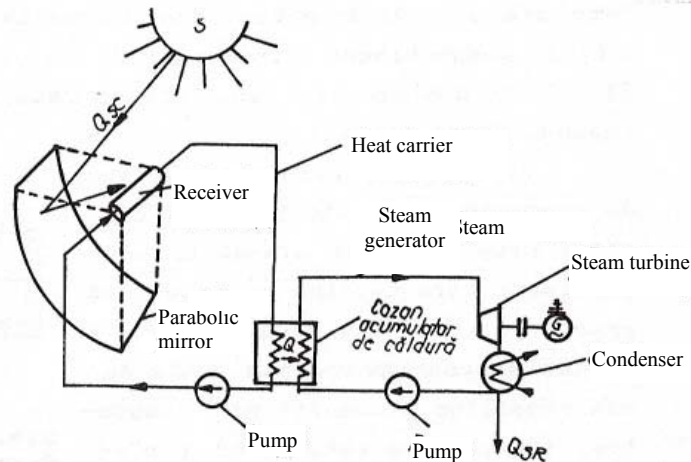


Fig. 19 Solar plant with distributed collectors

is limited, up to some hundreds of kW, because the heat losses in the collecting pipe system.

b) *The plant with field of mirrors and central receiver (fig. 19).*

The receiver is placed on a tower top where the reflected radiation arrives from a very large number of mirrors arranged around the tower. The energy losses are much smaller in this case because the absorption of the solar radiation is very small in air and the length of the high temperature pipes are limited to the tower height. Some realized plants have installed power up to tens of MW.

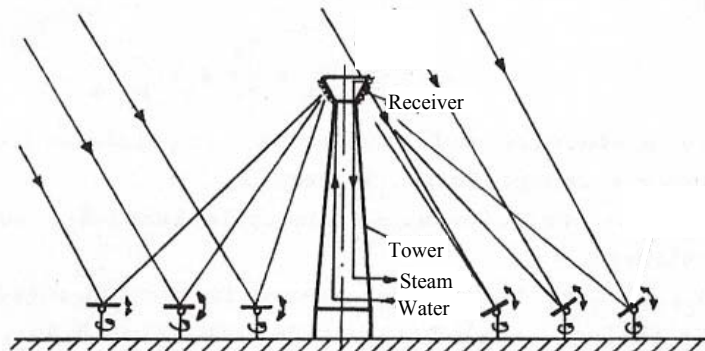


Fig. 20 Parabolic system with a field of mirrors