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Comparative efficiencies of solar energy collectors

M. Duban

Laboratoire de Technologie Optique
 Traverse du Siphon par Allée Pereisc, 13012 Marseille, France

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Résumé. — Nous avons comparé les efficacités géométriques de différents collecteurs en examinant la constance avec laquelle chacun d'eux recueille l'énergie solaire pendant une journée ou un an, indépendamment de leurs dimensions, de l'énergie reçue, de la concentration, et de l'utilisation ultérieure du flux capté. Nous avons pour cela choisi l'*heure équivalente* comme unité d'énergie.

Nous avons considéré 5 types fondamentaux :

- collecteur asservi sur le soleil,
- collecteur fixe,
- miroir cylindrique fixe à facettes,
- collecteur mobile autour d'un axe (miroir cylindro-parabolique par exemple),
- miroir sphérique fixe.

Nous avons tenu compte de l'absorption différentielle de l'atmosphère, en considérant une atmosphère moyenne, sans nuages, et nous avons estimé que le rayonnement direct n'est utilisable que pour des hauteurs solaires d'au moins 20° .

L'énergie captée a été calculée pour toutes les latitudes entre 0 et 50° , par pas de 5° , le 21 de chaque mois, et pour les deux seuils $K = 0$ et $K = 0,5$ (K étant le rapport entre l'énergie minimum nécessaire pour un fonctionnement correct de l'installation, et l'énergie maximum, obtenue quand le collecteur est dirigé vers le soleil au zénith).

Nous donnons un classement global de ces 5 capteurs, fondé sur les efficacités moyennes annuelles.

Si l'on dispose de données climatiques, il est facile de déduire de ces résultats théoriques l'énergie effectivement captée ; nous donnons deux exemples d'un tel calcul.

Abstract. — We have made a comparison of the geometric efficiencies of basic collectors, by examining the constancy with which each of them collects the solar energy during a day or a year, independant of their dimensions, the amount of energy collected, the concentration, the use of the energy once collected. For this purpose, we have chosen the *equivalent hour* as a unit of energy.

We have considered five fundamental types :

- a sun-tracking collector,
- a flat plate collector,
- a fixed stepped cylindrical mirror,
- a collector rotating about an axis (such as a parabolic trough mirror),
- a fixed spherical mirror.

We have taken into account atmospheric differential absorption, assuming a mean atmosphere without clouds, and we have estimated that the direct sunshine is usable only if the sun's elevation is more than 20° above the horizon.

Collected energy has been calculated for all latitudes from 0 to 50° by 5° intervals, for every month, and for the two thresholds $K = 0$ and $K = 0.5$ (K being the ratio of the minimum power necessary for a correct utilisation of the installation to maximum power, which is obtained when the collector is pointed towards the sun at the zenith).

A global comparison of these collectors is given, taking into account annual averages of efficiency.

If climatic data are available, it is easy to correct theoretical monthly efficiencies, thus obtaining the energy actually collected.

Two examples of such a calculation are given.

1. Introduction. — It is difficult to make a comparison between the different kinds of solar collectors : for instance, a paraboloid with an equatorial mount receives more energy, with an higher concentration,

than a flat plate collector ; but its fabrication and its maintenance are more expensive.

Nevertheless, it is possible to examine the collection efficiency of the same collector at different lati-

tudes and under different climates, or to choose, in a given place, the best inclination for a fixed collector : the calculation of the collected energy, during each month or over a year, is fundamental.

But it is possible to go further, and to compare the efficiencies of entirely different collectors, by examining the constancy with which each of them collects the solar energy during a day or a year, independent of their dimensions, the amount of energy collected, the concentration, and the use of the energy once collected.

The reference being the sun-tracking collector, it will be possible to give a *merit factor* to each type, and to evaluate the loss or the gain given by different designs, or under different assumptions about climate or energy needs.

We must point out that this calculation is a *purely geometrical one* (taking however into account atmospheric absorption and climatic data).

It must be completed, in each particular case, by considering numerous factors, such as reflection, transmission, receiver shadow, window and thermic losses, thermodynamic efficiency, complexity, ease of operation, sophistication, reliability and technology level, etc...

2. Basic parameters. — The energy received by a collector (during a day, for example) will be measured by its *equivalent hours*, such a unit being the energy which the collector would receive in an hour if pointed towards the sun, the sun being fixed on the vertical (at an elevation of 90°) for that hour. (The conversion into kWh is of course easy if the geometrical parameters of the collector are known.)

The use of such a unit allows to make a direct comparison of the efficiency of varied collectors, in any way we want.

The second basic parameter will be K , the ratio of the minimum power necessary for a correct utilisation of the installation to the maximum power $P_{\max}$ (that which is obtained when the collector is pointed towards the sun at the zenith).

Peak day performance can seem to be a more realistic reference ; in fact, if the same plant must be utilized in the intertropical area and at high latitudes, the effective maximum power to be considered is that we have chosen.

If the installation can function whatever energy is available (for example, with photovoltaic cells), K will be equal to 0.

But we have also developed calculations for ratios $K = 0.25$ and $K = 0.5$.

3. Calculation assumptions. — Very complete results about available or collected energy have already been published [1], but they generally neglect the atmosphere's influence.

As a terrestrial sun power plant cannot avoid this, we believe it useless to base calculations on geometri-

cal considerations alone : so, we have carried out the major part of this study assuming a mean atmosphere, defined by a gaseous absorption of 1.5 cm of water and a turbidity coefficient of 0.1, corresponding to a relatively clean blue sky [2].

Figure 1 gives the normalized transparency of such an atmosphere as a function of sun elevation.

Fig. 1. — Normalized transparency of a mean atmosphere.

For our calculations, we have approximated it by a 3d degree polynomial based on the method of least squares, the variable being the sine of the sun's elevation h :

$$T = -0.1429 + 3.24822 \sin h - 3.52997 \sin^2 h + 1.42465 \sin^3 h$$

(useful only for $20 \leq h \leq 90$).

Besides, we have estimated that the direct sunshine is usable only if the sun's elevation is more than 20° above the horizon (this principally because of shadows : shadows cast by vegetation around the installation, by one collector on another).

So, for our calculations, the hour to start putting a power plant into operation will be either H , when the sun's elevation is 20 degrees, or $H(K)$, generally later in the day, when collected power attains the fraction K of the maximum power $P_{\max}$ (defined above).

4. **Method of calculation.** — For a given collector, at a given place, on the 21st of each month, we first compute H , and the power received at this time, P_0 (by means of : 1) a more or less sophisticated formula, 2) integration over the whole area of the collector, 3) counting rays which effectively fall on the collector, but always taking the atmosphere into account; we will come back to this later).

If $P_0/P_{\max} \geq K$, we retain the hour H .

Otherwise, we compute P_1 , power received at noon (which is always the maximum power available that day) :

— If $P_1/P_{\max} < K$, the system cannot function this day, and the calculation is terminated.

— Otherwise, we calculate the hour $H(K)$ for which $P = K \cdot P_{\max}$, $H(K)$ being calculated by dichotomy between the two extreme values H and noon.

The energy collected during the day will be therefore :

$$2 \int_{H(K)}^{\text{noon}} P(t) \cdot dt, \quad t \text{ being the time.}$$

This integral is evaluated by computing $P(t)$ at 15 or 30 points, with parabolic smoothing between (which gives at least one more significant value than the trapezoidal method).

Such a calculation is made for every month, from December to June, in the northern hemisphere (the other months being symmetrical give the same results).

For the other hemisphere, the results are the same but set back six months (we neglect the eccentricity of terrestrial orbit, which can result in 6 % difference on some months, but *differential* effects of which, for our final comparison, are much smaller).

An ultimate integration using parabolic smoothing gives the annual mean.

For all types of collectors studied, these calculations have been made for all latitudes from 0 to 50°, by 5° intervals, for $K = 0$ and $K = 0.5$.

It is possible to go further if climatic data are available. The fundamental information here is the mean monthly number of hours of sunshine.

With this information and the maximum number of hours of sunshine possible, we can correct the equivalent hours calculated as if there were no clouds.

To make this work easier, we have computed the number of hours of sunshine possible, for each day, between the latitudes of 5 and 50° by intervals of 5° (for latitude 0°, there are always 12 hours of sunshine).

Figure 2 gives a summary of this work.

These general curves are completed by those of figure 3 — which give the hours during which the sun is higher than 20° —, and those of figure 4, which take into account differential atmospheric absorption, and thus give the solar radiation actually available, expressed in equivalent hours for a sun-tracking collector (with $K = 0$).

Fig. 2.

Fig. 3.

Fig. 4.

5. **Types of collectors studied.** — We have chosen 5 fundamental types for study :

- a sun-tracking collector
- a flat plate collector
- a cylindrical fixed stepped mirror
- a collector rotating about an axis (such as a parabolic trough mirror)
- a fixed spherical mirror.

We will successively examine the results obtained for each type.

6. **Sun-tracking collector.** — For $K = 0$, results have already been given in figure 4; they represent the maximum amount of energy which can be collected.

One can notice that the two annual maxima, occurring at the equinoxes for the equator, joint together into a single maximum at the summer solstice (June 21 in the northern hemisphere), as soon as we go outside the tropics.

This maximum increases less rapidly than the minimum decreases for the winter solstice : therefore, the annual mean decreases with increase in latitude (Fig. 5).

For $K = 0.5$, the results are the same, in conformity with figure 1 which shows that the atmosphere transmits more than 60 % of the maximum sunshine as soon as the sun elevation is above 20° .

7. **Fixed collector.** — The basic type is a flat plate collector (panel of solar cells, ...).

It is obvious that the most effective orientation

Fig. 5. — Annual mean of a sun-tracking collector.

will be perpendicular to the meridian plane (except if climatic conditions are not symmetrical during the day), with an inclination i near that of the latitude.

It should be noted that a flat plate collector can make an appreciable use of diffused light, not taken in consideration here.

Figure 6 gives the results for $K = 0$, and for latitudes $\varphi = 0, 20^\circ$ and 40° , i being approximately equal to the latitude.

Fig. 6. — Efficiency of a fixed collector.

We again find that the two maxima of the collected energy, which are at the equinoxes for the equator, join at the summer solstice in the zones beyond tropics, and that the winter minimum is more noticeable.

We also find that we can attain a better annual mean if the panel is tilted by an angle i slightly less than φ when φ increases ($\varphi - i$ being about 7.5° when $\varphi = 40^\circ$, for $K = 0$, and about 3.5° for $K = 0.5$). (This effect being largely due to 20° cutoff.)

As for all collectors studied here, one can see that it is possible, inversely, to minimise the annual variations by choosing i greater than φ ($i - \varphi > 10^\circ$) : more energy is thus collected during the winter, but at the expense of a decrease in the annual mean.

The conclusions are the same for $K = 0.5$.

Figure 7 shows the decrease in the annual mean with latitude.

Fig. 7. — Annual mean of a fixed collector ($i = \varphi$).

8. Fixed cylindrical collector with faceted mirror. —

The purpose of this collector is to ensure a *focalisation* on a linear receiver which moves along the cylinder itself, a motion which is easy to obtain with a simple mechanical mounting.

Since this collector is fixed, one would think that its orientation and performance would be the same as for the case already described. This is not at all the case, because a part of the incident or reflected light is lost (Fig. 8).

These losses disappear when the sun is in the plane of symmetry (of the useful part of the cylinder) containing the axis : the maximum efficiency will be the same as for a fixed collector, but the mean efficiency will be lower.

The calculation of the energy collected at a given time is somewhat difficult, because a part of the collector may be in shadow, and, for the lighted part, we must distinguish the area without losses and the area with losses, and then, for the latter case, perform a secondary integration in α to find the useful reflected energy.

For this purpose, it is convenient to consider the ideal case where facets are infinitely narrow, and plane.

We must also know their exact shape : we choose the basic one of figure 9.

If s is the angle between the plane of incidence (containing the sun and the axis) and the plane of symmetry, and 2ω the aperture of the useful part of the cylinder (Fig. 8), we find three possibilities :

- 1) if $s \geq 90 - \omega/2$, no energy is available (the focal point being on the reflecting part of the cylinder);
- 2) if $\omega/4 \leq s < 90 - \omega/2$, the loss coefficient,

Fig. 8. — Geometry of a faceted fixed cylindrical collector.

Fig. 9. — Shape of facets.

compared to a flat collector of the same useful aperture, is

$$k = [\sin(s + \omega) + 2 \sin(s + \omega/2) - 3 \sin s] / 2 \sin \omega \cos s;$$

3) if $0 \leq s \leq \omega/4$, the loss coefficient becomes
 $k = 1 - [3 \sin s - \sin 3s]/2 \sin \omega \cos s$.

Another difficulty results from the fact that two arrangements are possible : the mirror being placed as a fixed plane collector, facets may be horizontal East-West, or parallel to the meridian plane (Fig. 10).

Fig. 10. — Two possible arrangements for a faceted fixed cylindrical collector.

We consider $\omega = 60^\circ$ (calculations for $\omega = 55^\circ$ and $\omega = 50^\circ$ give nearly identical results : $\omega = 55^\circ$ is about 0.5 % better, and $\omega = 50^\circ$ about 1 % better, than $\omega = 60^\circ$).

East-West mounting appears better, the one with the axis in the meridian plane giving only about 85 % of the annual energy of the East-West arrangement, for latitudes between 0° and 40° , when $i = \varphi$. (82.8 % for $\varphi = 0^\circ$, $K = 0.5$, and 87 % for $\varphi = 40^\circ$, $K = 0$.)

This results from the fact that in the East-West type, losses are lower, for the sun does not move out of the plane of symmetry more than 23.45° (at the two solstices), while it moves much more, with the meridian arrangement, at sunrise and sunset.

The annual mean of energy, for the East-West arrangement, is 92.2 % (if $K = 0$), and about 88.7 % (if $K = 0.5$), of that for a fixed collector : losses are therefore moderate (they even vanish at the equinoxes), and nearly independent of the latitude.

This result shows that our hypothesis of infinitely narrow facets cannot be far from correct, and will be sufficient in practice as a first approximation

(we must however notice that end effects are neglected).

As for a fixed collector, the annual energy increases slightly if i is a little less than latitude ($\varphi - i$ will be about 7.5° for $\varphi = 40^\circ$, if $K = 0$, and 3° if $K = 0.5$).

Figure 11 (to be compared with figure 6) sums up these results for $K = 0$, $\varphi = 0, 20^\circ$ and 40° .

The annual mean *versus* the latitude is the curve of figure 7, reduced by affinity in the ratio 0.922 for $K = 0$, and about 0.887 for $K = 0.5$.

9. Collector rotating about an axis. — The interest of such a collector is to allow a partial tracking of the sun with a simple mechanical device.

The basic type is the parabolic-cylinder mirror, movable around its focal axis parallel to its generators.

As in the case of the fixed faceted cylindrical mirror, two mountings are possible (Fig. 10) : East-West axis, or meridian axis (with a tilt angle $i \sim \varphi$).

But we have come here to an opposite conclusion : *the meridian axis mounting is better*, because it tracks the sun during the whole day, and weakens a little only at the solstices, while the East-West mounting would track the sun well according to the seasons, but would give poorer results at the rising and the setting of the sun.

The efficiency will be high, and close to that of the sun-tracking collector : at the equinoxes, in particular, the sun will be perfectly tracked (if $i = \varphi$).

Calculations confirm these results : the East-West type reaches, in annual mean energy, only 85 to 85.7 % of the meridian type for $K = 0$, and 76 to 76.4 % for $K = 0.5$ (between $\varphi = 0$ and $\varphi = 40^\circ$).

The meridian type reaches 96 % of the sun-tracking collector, which is a considerable value.

The curve of the annual mean as a function of latitude is given by figure 5, reduced by affinity in the ratio 0.96.

As for the other meridian collectors, i will be chosen slightly less than φ ($\varphi - i$ reaches 5° for $\varphi = 40^\circ$).

It is interesting to notice that as soon as the elevation of the sun is above 20° , more than half of the maximum power is available (as for a sun-tracking collector) : efficiency is thus the same for $K = 0$ and $K = 0.5$.

Figure 11 gives this efficiency for $\varphi = 0, 20^\circ, 40^\circ$, $K = 0$ or 0.5 , and $i = \varphi$.

Fig. 11. — Efficiency of faceted E-W mirror ($i = \varphi$) and parabolic cylinder mirror.

10. Fixed spherical collector. — The value of this collector is to give a geometrical concentration which is variable, but *much higher than that of the previous collectors* (except the sun-tracking paraboloid type), by moving only a linear boiler, movable around the center of the sphere, and always pointed in the direction of the sun [3].

In the device studied and built in the L.A.S. of Marseille (France), the *high concentration* part corresponds to a $2 \times 28.5^\circ$ aperture cone, the *low concentration* part collecting the rays of first reflections up to $2 \times 60^\circ$, of second reflections up to $2 \times 72^\circ$, etc...

(Fig. 12). This results in two independent receivers : the *high concentration* (a) and the *low concentration* (b) ones.

Fig. 12. — Geometry of a fixed spherical collector.

The relative complexity of such a device conduces us to a more detailed study.

The calculations have been carried on in two different ways :

- by exactly computing the areas of all ellipses, or parts of ellipses, which represent the different collection areas (normal to incident flux),
- by taking into account a very high number of rays (many thousands) equally spaced, falling on the mirror, and by counting those which fall on useful areas.

The first way is fast, but analytically rather difficult (in particular, we must take in account the eventual shadow of the rim of the mirror, which leads to the consideration of many elliptical arcs).

The second needs more computer time (especially for $K \neq 0$), but the program is easy to write.

These two methods of course have given the same results (with a relative accuracy better than 0.1 %).

We have considered 3 different variations (Fig. 13) :

- a portion of sphere with vertical axis, and with a semi-angle aperture $\omega = 50, 55, 60, 65$ and 70° (a),
- this same reflector with axis tilted by an angle β in the meridian plane (b),
- the first reflector, improved by the addition of a sector (called a visor), characterised by its elevation α as seen from the sphere's center, and pointing towards the sun (its aperture is about 120°) (c).

Fig. 13. — Variations of a fixed spherical collector.

For our basic calculations we considered, in a first step, only the rays of the first reflection.

Two reflections increase the collected energy by approximatively 10 %. Multiple reflections being, however, less efficient (owing to the high reflection angles on a slightly dusty mirror), one can estimate that if all reflections are taken into account, the energy obtained here from one reflection will improve by approximatively 10 %.

Different considerations having decided us to prefer $\omega = 60^\circ$, this value has been chosen for the calculations now developed.

For $K = 0$, figure 14 gives, for $\varphi = 0, 20^\circ$ and 40° , the overall efficiency for $\alpha = 0, 10^\circ, 20^\circ$ (with $\beta = 0$), and for β around φ (with $\alpha = 0$), referring again to the curves of figure 4 (sun-tracking collector).

Fig. 14. — Efficiency of a spherical mirror ($K = 0$).

Figure 15 gives the annual mean, as a function of φ , for $\alpha = 0$ and 20° , for $\beta = \varphi$, and recalls the curve of the sun-tracking collector.

For $K = 0.5$, the same results are given in figures 16 and 17. We can see that the basic device ($\alpha = \beta = 0$) is poor. (Of course, it would be better with $\omega = 65^\circ$ or 70° ; in addition, we have considered here only the first reflections.)

Fig. 15. — Annual means of different spherical collectors ($K = 0$).

The improvement is clear with a tilting angle $\beta \sim \varphi$ ($\varphi - \beta$ reaching 3° for $\varphi = 40^\circ$, if $K = 0$, and 1.5° if $K = 0.5$), and is obvious on figure 16, for $K = 0.5$ and $\varphi = 40^\circ$, during the winter.

Fig. 16. — Efficiency of a spherical mirror ($K = 0.5$).

But the improvement becomes very great with a sun-tracking visor (and $\alpha = 20^\circ$, for instance).

This results from the fact that such an arrangement, defined by ω and α , collects all the energy falling on a mirror of semi-aperture angle $\omega + \alpha$, while avoiding a great part of the shadows of such an arrangement : efficiency is greater, while reflecting area is smaller.

Fig. 17. — Annual means of different spherical collectors ($K = 0.5$).

This advantage clearly appears on figure 18, where we have given the minimum sun elevation necessary to work properly with a given threshold-coefficient K ; one can see that for a given ω , improvement is great if α increases from 0 to 20° ; one can see also that curves ($\omega = 60^\circ$, α_0) are better than ($\omega = 70^\circ$, $\alpha_0 = 10^\circ$) : for instance, curve (3) (60° , 20°) is better than curve (b) (70° , 10°).

The final comparison of all the collectors will bring out this quality.

It is interesting to examine the efficiency for the *high concentration* area alone, which can result in a high thermodynamical efficiency, and can be used independently. (Of course, the entire spherical dish is required as the *high concentration* area moves in time.)

Fig. 18. — Minimum solar elevation necessary to work with a given K , for various spherical collectors.

We see that when α is around 20° , the mirror is in sunlight early in the morning over the whole useful area ($2 \times 28.5^\circ$) : as atmospheric absorption is somewhat high with a low sun elevation, the efficiency over a whole day will be very close to that of the sun-tracking collector.

On figure 19, for example, we have added, for the

Fig. 19. — Energy collected on the March 21st by a spherical collector.

March 21, for $\varphi = 20^\circ$, $\omega = 60^\circ$ and $\alpha = 18^\circ$, the energy (in kWh) collected by the *high concentration*, *low concentration with one reflection*, and *low concentration with two reflections* areas, as a function of the time of day (the collection area of the mirror $\omega = 60^\circ$ being one square meter).

The useful hour of sunrise is 7.42 hours, that of full high concentration lighting, 8.91 hours : one can see that after this time, the *high concentration* curve becomes *sun-tracking*, and, so, remains flat, thus allowing the plant to work satisfactorily without need for storing energy (unless one desires to operate on partly cloudy days).

Over the whole day, the efficiency, for this high concentration part, reaches 95.3 % of that of the sun-tracking collector, which is a very good value.

Figure 20 gives some daily efficiencies, compared with that of the sun-tracking collector, at $\varphi = 20^\circ$, for $\omega = 60^\circ$, $\alpha = 0$ and 18° , on Dec. 21, Mar. 21 and June 21.

$(\varphi=20, \omega=60, K=0)$			
	21/12	21/3	21/6
Sun-Tracking	100 (6.2 hours)	100 (8.1 h.)	100 (9.1 h.)
1 Reflexion ($\alpha=0$)	51.6	64.9	70.3
1 and 2 Reflexions			
$\alpha=0$	58.2	72.2	76.7
$\alpha=18$	69.1	84.4	88.3
All Reflexions ($\alpha=0$)	60.5	74.7	78.6
High concentration			
$\alpha=0$	63.5	81.5	83.5
$\alpha=18$	93.6	95.8	96.2

Fig. 20. — Comparative efficiencies of different parts of spherical collectors.

We can see that, for $\alpha = 0^\circ$, the rays twice reflected increase the collected energy by about 10 % (9.1 to 12.8), and that the entire range of reflections give a total improvement of 11.7 to 19 %.

In fact, as previously mentioned, the total energy actually collected by a slightly dusty mirror will be approximatively the same as that given theoretically by the rays reflected 1 and 2 times.

It gives an efficiency of 58.2 to 76.7 %.

The visor greatly increases this global efficiency, which reaches 69 to 88 % (the reflecting area increases by 19.5 % for a visor aperture of 120°).

Without a visor, the efficiency of the high concen-

tration area remains between 63 and 83 %. With a visor, it reaches 94 to 96 %, which is considerable (the improvement is between 15.7 and 49 %).

11. **Global comparison of the different collectors.** — Taking into account only the annual averages of efficiency, figure 21 gives a classification, compared with the sun-tracking collector, between $\varphi = 0$ and $\varphi = 40^\circ$ (the value for $\varphi = 0$ has been underlined), for $K = 0$ and $K = 0.5$.

Collector	$K = 0$	$K = 0.5$
Sun-tracking	100	100
Parabolic cylinder	96	96
Spherical ($\alpha = 20$) high concentration	94.4- <u>97.2</u>	90.8- <u>95.4</u>
Spherical ($\alpha = 20$)	80.1- <u>87.6</u>	68- <u>82</u>
Spherical ($\alpha = 0$) high concentration	69- <u>82.4</u>	52.2- <u>73.6</u>
Fixed	76.3-77.4	66.1-66.9
Faceted E-W ($\omega = 60$)	70.4-70.7	58.7-58.9
Tilted spherical	67-68.1	52.5- <u>53.4</u>
Spherical ($\alpha = 0$)	56.4- <u>67</u>	32.5- <u>53.4</u>

Fig. 21. — Comparative efficiencies of different collectors.

One can see the excellent performance of the *high concentration* part of the spherical collector with a visor ($\omega = 60$, $\alpha = 20$), which even surpasses the parabolic cylinder collector sometimes, but also the good efficiency of this collector working globally (high and low concentration).

(When taking in account all reflections, and not only one, these values would be slightly improved.)

The fixed collector and the cylindrical faceted collector are clearly less efficient.

As to the spherical collector without visor, with $\alpha = 0$, with vertical or tilted axis, it has only poor efficiencies, thus showing the fundamental advantage of the visor.

Its relative efficiency would be of course worse by taking no account of atmospheric differential absorption [4].

One can notice also an unexpected result : the fixed collector, cylindrical faceted collector, and tilted spherical collector (for $K = 0$), are slightly improved (in comparison with the sun-tracking collector) when φ increases.

12. Examples of application of these results. —

A) It is our intention to equip food processing plants (jams, ...) in Provence (latitude 43° North) with steam generators capable of functioning during the working season.

An inclined spherical collector — therefore without a visor — would be an inexpensive solution worth thinking about.

To determine its angle of tilt i , we calculate the equivalent hours, at 15 days intervals, for $i = 20$, 25, 30, 35 and 40° ; an integration over the working

season gives the efficiency for each angle of tilt, making possible the determination of the optimal value for i .

If the plant operates between May 21 and October 21, the optimum is $i = 25^\circ$, giving an average of 6.4 equivalent hours/day, which is 76.3 % of the energy received by a sun-tracking mounting.

The choice of different dates leads to quite different tilt angles :

$i = 23^\circ 5$ for the period March 21 to September 21.

$i = 28^\circ 5$ for the period June 21 to October 21,

$i = 32^\circ 5$ for the period June 21 to November 21, for example.

But even in this last example, the use of $i = 25^\circ$ would entail a loss of only 1 % with respect to an optimum i and an efficiency of more than 76 % with respect to a sun-tracking mounting.

Therefore from an industrial point of view we could adopt this inclined spherical collector (120° opening angle) and choose $i = 25^\circ$ for all plants which function during the good season at latitude 43° and be assured of an effective operation.

B) Let us take as an example that we must use a cylindrical faceted mirror, working with $K = 0$.

1) Hawiyah, in Saudi Arabia, is at latitude 21° N (rounded here to 20°), and has a regular available sunshine (Fig. 22).

It is easy to correct theoretical monthly efficiencies, given by figure 11, by the available sunshine hours and the theoretical sunshine hours given by figure 2.

Fig. 22. — Hawiyah (Saudi Arabia).

We thus obtain the energy actually collected (given in figure 22).

The annual mean is 4.22 hours/day for $i = 10^\circ$, 4.27 for $i = 20^\circ$ and 4.13 for $i = 30^\circ$: we are in *normal* case, for which i will be chosen slightly lower than φ ($i = 18^\circ$). We so obtain an annual mean of 4.28 hours/day, that is to say 78.7 % of the theoretical maximum efficiency (reached without clouds).

2) Bombay, in India, is at latitude 18° N (rounded to 20° for this example), and its available sunshine presents a great deficiency in summer, during the rainy season (Fig. 23).

Fig. 23. — Bombay (India).

This leads us to believe, according to figure 11, that we must choose i greater than φ .

The results obtained show, effectively (Fig. 23), that the best annual mean (around 3.26 hours/day) is reached for $i \sim 25^\circ$, that is to say with $i = \varphi + 5$.

We thus obtain 60 % of the theoretical maximum efficiency.

If we intended to maximise the energy collected during the rainy season, and not the annual mean, we would, on the contrary, choose i between 0 and 10° .

These two simplified examples show that the general results we have found allow us to determine the actual efficiency of a given installation, and its optimum parameters.

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