Optimum layout of heliostat field when the tower-top receiver is provided with secondary concentrators

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Report for SFERA, WP.13, Task2, April 2012

ABSTRACT

The experience gained during the last three decades in developing applications of concentrated solar energy shows that higher conversion efficiency of solar energy to electricity can be achieved only at high temperatures (more than 1100 K). At these temperatures, the radiation emitted from the receiver at the working temperature becomes the main mechanism of thermal losses depending on the size of the receiver aperture. It is obvious that, in order to increase the receiver efficiency, the solar energy must be introduced into the receiver at higher concentrations. To reach high concentrations at the receiver aperture it is not sufficient to improve the performance parameters of the primary concentrator (the field of heliostats), but a secondary concentration is often required. The receiver coupled with its secondary concentrator (receiver concentrator, RC) becomes a combined unit. Introducing the secondary concentrator has a substantial effect on the optimal shape, size and arrangement of the primary concentrator. In this paper it is searched the existing correlations between RC and the boundary layout of the heliostat field.

1 INTRODUCTION

The efficient use of solar energy for high temperature processes, such as conversion to electricity via Brayton cycle or various thermochemical processes requires its concentration to a high level. The main reason is that, at high temperatures, the radiation becomes a major mechanism for the thermal losses from the receiver. The radiation losses are proportional to the aperture size of the receiver.

Decreasing the size of the aperture requires higher concentrations; otherwise the optical spillage losses around the receiver's aperture are increased. Improving the performance parameters of the primary concentrator is one of the important ways to increase the concentration level, but often this is neither sufficient nor economical, and a secondary concentrator is required. The secondary concentrator intercepts most of the energy directed to it by the primary concentrator and concentrates it further, in order to meet the level required by the specific process.

However, introducing an additional optical device involves additional optical losses. These optical losses are: absorption, rejection, and some spillage around the entrance aperture of the secondary concentrator. This secondary concentrator is physically attached to the opening of the receiver, and therefore it is referred to in this paper as the Receiver Concentrator (RC). The optical losses of the RC are considered in this paper as a part of the receiver losses alongside of reradiation and convection.

Introducing the RC has a substantial effect on the optimal shape, size and arrangement of the primary concentrator (the heliostat field). As described in the present study, have been obtained interesting results connected with the optimization of the geometrical dimensions of the RC and the receiver's aperture, in order to meet the requirements of the process (maximum power into receiver at a specific working temperature). The computer calculations were performed used partly the **WISDOM** computer package [1], the accepted error for all calculations presented here being less than 1%. Newly developed solar receivers can presently operate at temperatures above 1200K and therefore it is necessary to analyze their performance and optimize their geometrical parameters with their associated optics.

The present report focuses on the implications of using RC connected with a receiver placed in a solar tower to the heliostat field layout. The conclusions resulting from the presented analysis are exemplified in few cases designed in our Unit.

2 EFFICIENCY OF A SOLAR RECEIVER PROVIDED WITH RC

The average primary concentration obtained with a conventional heliostat field and a central tower is not sufficient to reach high temperatures (above 1100K) with maximum receiver efficiency. Therefore, a secondary stage of concentration with a Receiver Concentrator (RC), usually Compound Parabolic Concentrator (CPC) [2], is used to further concentrate the primary level. The receiver and the RC then becomes a combined unit where both the thermal and the additional optical losses have to be analyzed and considered. The receiver and the RC unit are placed on a solar tower (*Tower-top*), as in the conventional central solar plant. The RC is tilted towards the center of a heliostat field section. There is a need to redefine the efficiency of the combined receiver/RC unit. The *receiver efficiency,* η_{rec}, is defined as the net power absorbed in receiver reported at the total power arrived at the RC's entrance plane. Therefore, in this definition is included both the optical and thermal efficiencies of the ensemble consisting of the receiver and the RC in front of the receiver.

It is assumed that the RC has a circular entrance with a radius R that intercepts an amount P_{ap} from the total power P_t reflected from the heliostats and reaches the plane of the RC's aperture. The difference between P_{ap} and P_t is the spillage around the RC. The definition of the receiver efficiency, η_{rec} can be formulated as:

$$\eta_{rec} = \left(\alpha_{eff} \cdot (P_{ap} - P_{rej} - P_{abs}) - P_{rad} - P_{nc}\right) \Big/ P_t \qquad (1)$$

where α_{eff} is the effective receiver absorptance, P_{ap} is the power intercepted by the RC's aperture, P_{rej} is the amount of power rejected from the RC, P_{abs} is the power absorbed by the RC surface, P_{rad} is the amount of power lost by reradiation from the cavity, P_{nc} is the power lost by natural convection and P_t is the total power arriving to the plane of the RC's aperture. It is assumed that the receiver is well insulated and the losses by conduction can be neglected. An ideally insulated, isothermal receiver, without a transparent window at the receiver entrance, can be considered as a blackbody with the effective emissivity $\varepsilon_{eff} \approx 1$. When a window is added, a spectral discrimination must be performed and ε_{eff} (<1) will be a function of the average temperature of the receiver.

Studying the dependence between the previous components from the Eq. (1) we obtained [3], for a receiver without window, the efficiency given by:

$$\eta_{rec} = \alpha_{eff} f_{ap}(R)\eta_{CPC} - \frac{\sigma T_{rec}^4 \pi R^2 \sin^2\theta}{P_t} - \frac{C_H A_r (T_{rec} - T_a)^{1.25}}{P_t} \qquad (2)$$

where: $f_{ap}(R)$ is the fraction of P_t enclosed within a circle having radius R with $f_{ap}(R_{max}) = 1$, R_{max} being the radius in this plane which collects all the power P_t, η_{CPC} is the RC's efficiency (it is assumed that the concentrator is a perfect CPC having the acceptance angle ?, the entrance radius R and the exit radius $R \sin\theta$ [2]), σ is the Stefan - Boltzmann constant, T_{rec} is the representative (average) receiver working temperature, T_a being the ambient temperature, C_H is a coefficient depending of geometrical receiver parameters and physical air characteristics and A_r is the typical area of the receiver implied in the natural convection process. The concentrator efficiency is given by:

$$\eta_{CPC} = [\rho^{n(\theta)} - f_{rej}(\theta)] \qquad (3)$$

where $\rho^{n(\theta)}$ is the average reflectivity depending on *n*, the average number of reflections in RC , ρ being the reflectivity of the RC surface and $f_{rej}(?)$ is the fraction of the power entering the RC which is rejected by the RC. This fraction as well as the average number of reflections in the RC is strongly dependent on the acceptance angle and, relatively, weakly dependent on the position *r*.

When a window protects the receiver, the natural convection losses can be reduced substantially although some *window loss* is introduced.

3 DESIGN OF A PRACTICAL LARGE RC (CPC)

The design of a practical large 3D CPC is a compromise among performance, ease of manufacture, and cost. Thus the overall dimensions and the number of reflections must be kept at a minimum, and the shape of the device should be as simple as possible. Here we consider concentrators composed of either plane facets or facets with one-dimensional curvature, which can be manufactured more easily.

Three approximations have been considered: 1. CPC made by a number of truncated pyramids (fig.1a); 2. CPC made by a number of truncated cones (fig.1b); 3. CPC made by a number of sheets [4] bended so that the cross section will be a regular polygon and the edges will belong to the CPC's mathematical profile (fig.1c). In the case when the 3D CPC is approximated by truncated cones, the essential requirement is that each cross section of the basis of each truncated cone will be on the mathematical CPC profile. In the case when the CPC is approximated by truncated pyramids, the basis of each truncated pyramids having a polygonal cross section will have each corner on the mathematical profile. In this approximation, the CPC is composed by a number of facets that give a considerable reduction in the manufacturing cost. It can be observed that the approximation by truncated pyramids arrived, at the limit of infinite number of such pyramids, at the third case.

An important question, that appears approximating the concentrator in the first two approximations, is what will be the optimum partition of an ideal CPC in a fixed number of truncated cones/pyramids. The problem was solved by Segal [5] and consists in choosing those points of the CPC profile satisfied the condition that

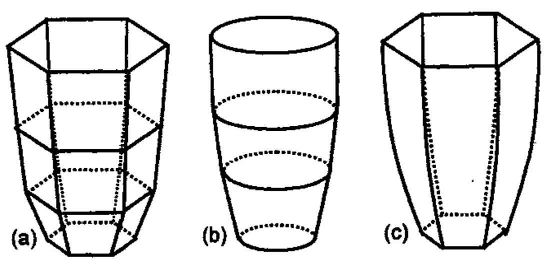

Fig.1 Various CPC approximations

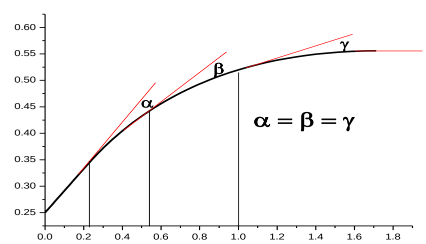

Fig.2 CPC optimum partition

difference between consecutive slopes remains constant (fig.2).

4 SIZE OPTIMIZATION OF A TOWER-TOP RC

The secondary concentrator which is provided in order to improve the efficiency of a tower-top central receiver is closely tailored to a matching heliostat field layout. This means that the field of heliostats must be circumscribed within the view cone of this concentrator because only the heliostats situated inside these boundaries will give useful contribution to the receiver (fig.3). However, because the ideal sun image is dispersed by tracking and surface errors of the heliostats, not all the rays originating from these heliostats will be transmitted by the concentrator into the receiver. Supposing that the field of heliostats has a known elliptical boundaries, for each concentrator acceptance angle, θ, there is a certain fraction of rejected rays, $f_{rej}(\theta)$. This fraction together with the collected fraction $f_{ap}(r)$ and the average number of reflections inside the concentrator, $n(\theta)$, should be considered when the receiver efficiency is evaluated, based on relation (2). Varying *r* and θ one can find these fractions and optimize the size of the receiver aperture and the concentrator dimensions. Ray tracing method (the codes **TRASOL** and **ASTRAC** from the package **WISDOM** [1]) is used to calculate the distributions of $f_{ap}(r)$, $f_{rej}(\theta)$ and $n(\theta)$ for a specific field. Using the above distributions, a simple method for numerical optimization can be applied based on relation (2) in order to find the best RC dimensions (i.e. acceptance angle and concentrator radius) which give a maximum for the receiver efficiency.

4. 1 Application at small fields

In a small field, the heliostats are placed north of the tower. As an example of a typical small field (a few megawatts thermal into the receiver) is described in [6]. Here is considered a tower having the height 100m, provided with a single receiver with RC (having clean surface reflectivity of 95%) facing north (in the northern hemisphere) and a field of heliostats with a typical heliostat having the area 36m^2 and high optical performances (total tracking and surface errors of about 2mrad and a reflectivity of 95%. The nearest heliostat is situated at a distance 50m north of the tower base (fig.3). The field is optimized following the method described in [8].

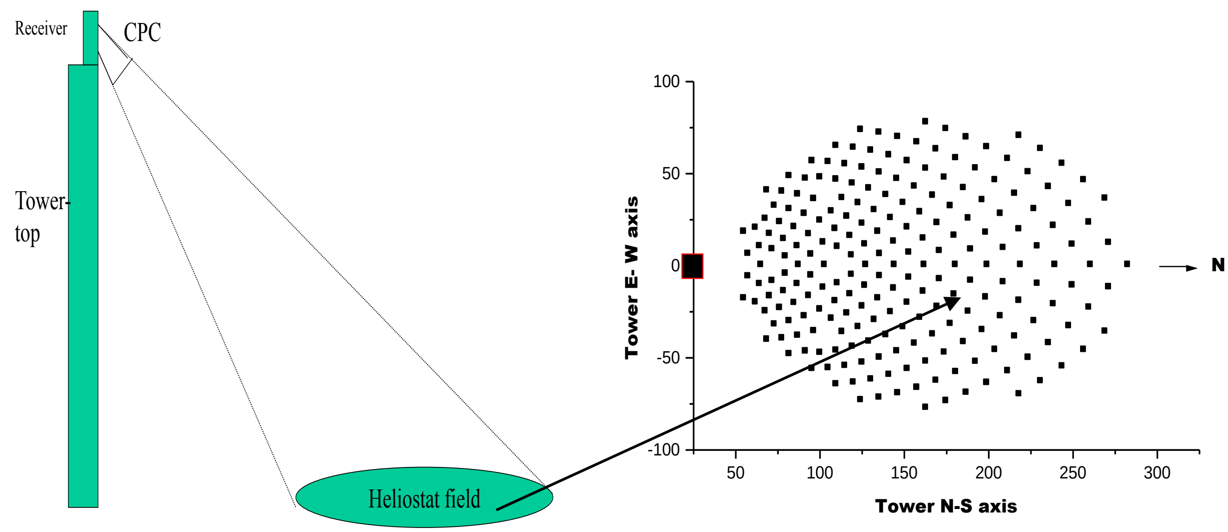

Fig.3 Boundary of heliostat field correlated with tower-top RC; at right, the layout of the heliostat field

The boundary of heliostat field shown in fig. 3 is function of tower height and CPC geometry (acceptance angle, entrance diameter, tilted angle to the ground. This boundary is an ellipse having the semi-axes **a** (South-North) and **:** (West-East):

$$a = \frac{h\, tg\theta \left(1 + tg^2\theta\right)}{1 - tg^2\beta\, tg^2\theta} \tag{4}$$

$$b = \frac{h\, tg\theta}{1 - tg^2\beta\, tg^2\theta}\sqrt{(1 + tg^2\beta)(1 + tg^2\beta\, tg^4\theta)} \tag{5}$$

where h is tower height (measured from the heliostat level plane to the center of receiver aperture), θ is the CPC acceptance angle and β is the CPC tilted angle measured between the tower axis and the CPC axis.

4. 2 Application at large fields

Larger heliostat field with typical rating of about 100MW$_{th}$ having a tower-top optics cannot use a single receiver concentrator (RC) because increasing the field dimension will increase the acceptance angle of the RC

and reduce its effectiveness. Therefore, a cluster of RCs, connected to the same receiver with multiple apertures, or with multiple receivers has to be used. Each one of these RCs is facing its matching elliptical section of heliostats on the ground. Such an arrangement is shown in fig. 4 for a north field and in fig. 5 for a surrounding field (six sections in a "*butterfly*" arrangement) [6]. These sections, having a radial staggered array, are not necessarily equal in size. In figure 4 the south part of the field has three smaller sections then the north part because of lower efficiency of south heliostats (in the northern hemisphere). This partition to six field sections permits different optimum density of the heliostats in each section. In fig.5 is represented a heliostat field composed by six sections: north-1200 heliostats, north-east/west: 2*1000heliostts, south east/west: 2*700 heliostats, south: 300 heliostats, total 4900 heliostats 36 m^2 each. A similar layout is presented in [7].
But the design for a heliostat field must be adapted to thermal requirements (nominal power needed and receiver working temperature) and to geometrical conditions (aperture(s) dimension, concentration needed). One design example is presented in the next section.

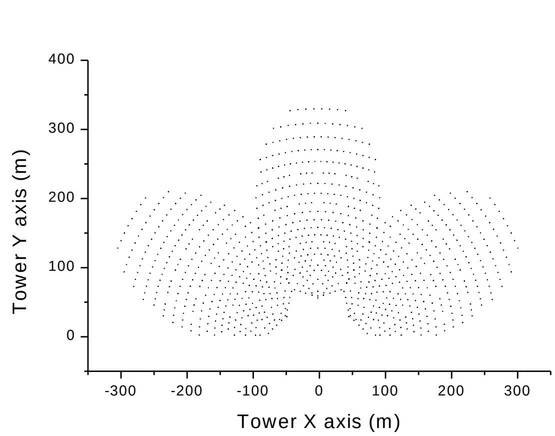

Fig.4 Large field dedicated to three RCs

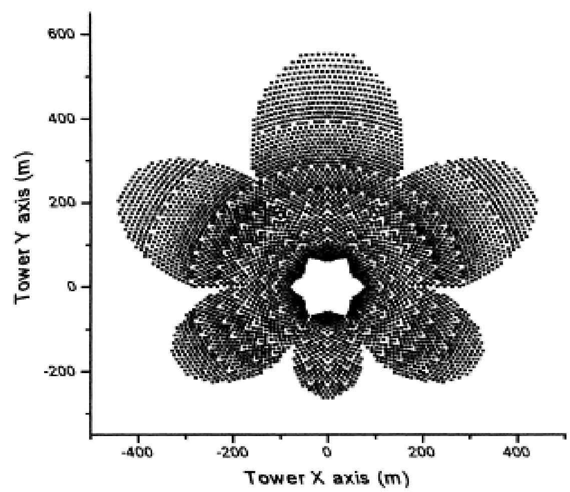

Fig.5 Large field (176,400m^2) dedicated to six RCs

4.3 Optical design for a central solar plant for $10MW_{thermal}$

Starting with the field resulting from the example given in Section 4.1, we will consider the direct solar insolation of 850W/m^2, a realistic $cos\varphi$=0.90, heliostat reflectivity 0.92, blocking, shadowing and attenuation 0.05, admissible spillage around the CPCs 0.03, optical efficiency of the CPCs cluster 0.94, we arrived at the value of about 16,500m^2 collector reflective surface needed. This calculus is valuable for ideal heliostats. In fact the total heliostat surface must be significant large, considering the real CPC and the inherent losses by spillage around the CPC entrance. Therefore, this calculated value can be an informative starting point only.
In order to made a real analysis we will impose a big restriction due to the maximum diameter of the window at the entrance into receiver (0.45m). In this case, it is necessary to use a RC composed by a cluster of seven CPCs having each of them the exit diameter 0.45m and an acceptance angle of 30^0. As a result we obtain an equivalent diameter of the target of about 2.2m. With these restrictions (target diameter, acceptance angle) it is obvious that a single field is inconceivable; the heliostats far from the tower will create so big spillage that the design will be impractical. Increasing the acceptance angle to 35^o is not a good solution because the last row of the heliostats will be closer to the tower, but the target diameter will be smaller and the spillage problem will be more acute. As a result we attempt to build three fields of heliostats so that the acceptance angle of the CPCs is no more than 30^o, based on heliostats having various dimensions (100m^2, 50m^2 and 25m^2). The field obtained in this concept, for a tower with 80m height, has the rear row at about 205m distant. But at this distance even an ideal heliostat gives quite large image on the target. The results obtained with the three types of heliostats are given hereafter for each field. I mention that with smaller heliostats these preliminary results seem to be better. (Moreover, recently it is a general trend to use small heliostats of 20m^2 – 10m^2 or even less).

You can see that the spillage is considerable large if we preserve the aim power of 10MW, but this value can be attained at least at the design point (Equinox, Noon), see Table 1.
The lateral fields will have a different behavior in the morning or afternoon e.g. the West field will be advantaged at the beginning of the day, and the East field will be advantaged afternoon (see Table 2, calculated for the hour 9:00, where the insolation has been preserved at the same value in order to illustrate the influence of the Sun position only).

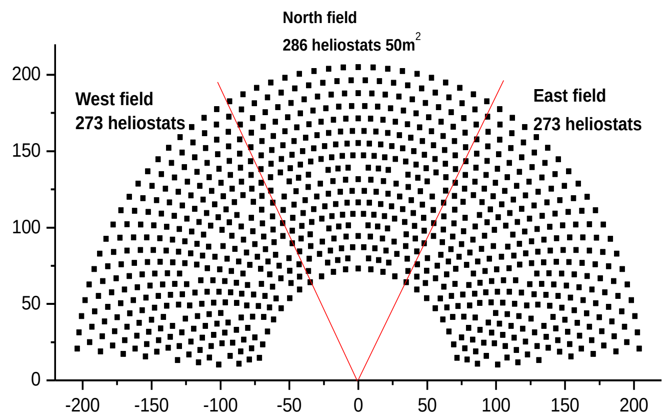

Fig. 6 Layout heliostat field 832 heliostats 25m^2 each

Table 1 Power into receiver at the design point (insolation 0.85kW/m^2)

	North Field			East Field			West Field		
Heliostat surface(m^2)	100	50	25	100	50	25	100	50	25
No. heliostats	68	144	286	66	136	273	66	136	273
Power to target (kW)	4,700	4,838	4,862	4,187	4,314	4,338	4,175	4,305	4,326
Spillage (kW)	737	675	650	867	711	610	862	705	598
Enter CPCs (kW)	3,963	4,163	4,151	3,319	3,603	3,728	3,313	3,600	3,728
Losses from CPCs (kW)	210	217	205	165	179	184	164	178	184
Power into receiver (kW)	3,753	3,945	3,946	3,154	3,424	3,544	3,149	3,422	3,544
Average flux at entr.rec.(MW/m^2)	3.37	3.54	3.54	2.86	3.08	3.18	2.83	3.07	3.18

Table 2. Power into receiver at Equinox hour 9:00 (insolation 0.85kW/m^2)

	North Field			**East Field**			**West Field**		
Heliostat surface(m^2)	100	50	25	100	50	25	100	50	25
No. heliostats	68	144	286	66	136	273	66	136	273
Power to target (kW)	4,278	4,494	4,448	3,188	3,280	3,272	4,364	4,429	4,414
Spillage (kW)	898	768	656	1,961	1,728	925	639	645	616
Enter CPCs (kW)	3,380	3,726	3,791	1,227	1,852	2,347	3,725	3,784	3,798
Losses from CPCs (kW)	168	195	188	61	92	115	186	188	188
Power into receiver (kW)	3,212	3,531	3,603	1,166	1,760	2,232	3,539	3,596	3,610

4.4 Alternative receiver concentrator shapes

As can be seen from section 4.1-4.2, choosing the CPC as part of the RC leads to characteristic heliostat field distributions that resemble ellipsis. These heliostat field distributions can be perfectly acceptable in many cases. However, for example when effective use of land is an issue, they might be disadvantageous. In these cases the desire for RCs which lead to and work with more compact heliostat field shapes grows. Moreover, it is a well-known fact that the CPC shape can be improved upon towards higher efficiency [2] – admittedly only marginally but nevertheless significantly.

Within the SFERA project it has been attempted to describe, test and design reflective surfaces using non-uniform rational B-splines (NURBS). In contrast to the CPC, NURBS surfaces offer a virtually unlimited number of degrees of freedom to define their exact shape, which makes them very flexible but in turn means they can only be treated numerically instead of analytically like the CPC. Their flexibility promises to allow more complex designs of the combined optical system – primary and secondary concentrators - with irregular shapes that may overcome these problems. Details about the NURBS design can be found in other parts of the SFERA project report ([9]).

In order to design a NURBS secondary reflector, a cost function has to be defined that quantifies the fitness of a particular reflector shape for the given setting. It is tempting now to define this cost function such that it includes not only the efficiency of the RC but also the heliostat field shape, i.e. one might want to design both primary and secondary reflector simultaneously. The problem with this approach is that it has way too many degrees of freedom to be computationally feasible nowadays (and most probably in the future, too). So one has to find some reasonable compromise.

In [9], a pre-calculated, fixed heliostat field has been used as a starting point. This field has been designed a-priori for usage without any secondary concentrator. The design process of the NURBS secondary concentrator, the parameter search, now can be based on trying to use as few heliostats of this field as possible to obtain an annual yield higher than some threshold value with maximum efficiency. This approach reduces the degrees of freedom to an acceptable level and can be considered as a co-design of heliostat field and secondary concentrator. Details and results can be found in [9].

CONCLUSIONS

An analysis of correlation between using of tower receiver provided with a concentrator type CPC and heliostat field layout is performed. The use of a concentrator in front of receiver improves the receiver efficiency but imposes few conditions in boundary layout of the heliostat field. In this report are presented methods for obtaining the best correlation between tower height, receiver aperture and geometrical data for the receiver concentrator and heliostat field in case of small fields and large fields.

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