Enhancement of SunDial Optical Performance Handling Cosine and End Losses

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Abstract. A new low-cost collector has been conceived for solar heat for industrial processes: the SunDial. This collector seeks cost reduction by means of an innovative design that must carefully address the important effects of cosine and end losses. An in-house Monte Carlo Ray Tracing code is used to assess these effects for different configurations. It results that a low tilt of the field might help to reduce importantly cosine losses, whereas in order to reduce end losses fields with higher length/width ratio are required. This study leads to a design methodology that will be used in the construction of two prototypes that will be built for two different end-users in the framework of the H2020 project ASTEP (GA 884411).

INTRODUCTION: SUNDIAL CONCENTRATOR

Solar concentrators for industrial processes should be simpler than those designed for power generation. Indeed, heat transfer fluid temperatures are normally lower and, thus, lower concentration factors are required [1]. Therefore, collectors should prioritize low capital and maintenance costs of the concentrator. Concentrators for solar heat for industrial processes (SHIP) generally include non-imaging concentrators (for relatively low temperatures), linear Fresnel collectors and parabolic troughs (for higher temperatures). The two latter are able to achieve temperatures well above 150 ºC, but they are systems adapted from power generation with high maintenance cost.

In the framework of the H2020 project ASTEP (GA 884411), an innovative solar technology concept is proposed: the SunDial. This concept seeks the reduction of installation, maintenance and operation requirements. It is the result of four Spanish patents and two international patents belonging to Universidad Politécnica de Madrid (UPM) and Universidad Nacional de Educación a Distancia (UNED). The SunDial consists on a short Fresnel collector installed on a rotary platform that tracks the sun so that it is always within its symmetry plane, see Fig. 1. As a result, mirrors are fixed on the platform, which leads to lower costs.
Preliminary tests [3] have warned two main issues. First, cosine factor leads to important flux intensity variations along the day and, therefore, the receiver must be able to work with low and high mass flows. Second, end losses become very important when the collector is short compared to the receiver height. The present study is focused on the latter problem.

**METHODOLOGY**

An in-house Monte Carlo Ray Tracing (MCRT) code has been developed to quantify annual losses depending on the field tilt and the specific design of the SunDial. This code, validated with commercial software Soltrace [4], has been adapted to SunDial configuration with multitube receiver. The outputs of this code are the optical efficiency, the energy losses—classified in cosine losses, lateral losses, end losses, mirror absorption, blocks between mirrors and shadings, and the flux intensity along the receiver—including circumferential and longitudinal distribution-. Fig. 2 depicts a preliminary simulation of SunDial collector.

In the present study, a characterization of both cosine and end losses for different SunDial configurations is carried out for Corinth, location of one end-user in ASTEP project. Special attention is paid to the effect of length/height ratio, the optimum location of the receiver and the tilt of the field towards the south. Also, the effect of a transversal mirror at the end of the receiver to reduce end losses is studied.

In the present work, the annual optical efficiency is obtained both globally (for the collector), $\eta_g$, and locally at each receiver location, $\eta_l$. The latter is defined as follows:
\[
\eta_l = \frac{\sum_{t=Time} \sum_{i= Tubes} 2r_i}{\sum_{l=Mirrors} w_l \sum_{t=Time} DNI_t} 
\]

where \( I_t \) is the local flux intensity (power input per length unit and per tube diameter), \( r_i \) is the tube radius, \( w_i \) is each mirror width and \( DNI_t \) is the direct normal irradiance. The global annual optical efficiency considers both the length of the receiver and the length of the mirrors:

\[
\eta_g = \frac{\sum_{l=length} \sum_{t=Time} I_t \sum_{i= Tubes} 2r_i}{\sum_{l=Mirrors} w_l L_i \sum_{t=Time} DNI_t} \]

where \( l_{rs} \) is the longitudinal distance between two consecutive measures at the receiver and \( L_i \) is the length of each mirror.

Meteorological data from www.satel-light.com (1996-2000) has been used. Data is available every 30 mins and only instants when \( DNI > 100 \text{ W/m}^2 \) are considered. For each simulation, 100,000 beams are traced.

Regarding the solar field, four cases have been considered. All of them have the same transversal non-dimensional design, i.e. the ratio between any two lengths in the transversal plane is the same for the four configurations. The primary solar field consists of twelve mirrors and the receiver is a multitube receiver with 4 tubes. The four configurations are as follows:

- One field 8 m wide and 8 m long (60.5 cm wide mirrors and tubes with diameters of 3 cm), where the receiver is 4 m above the primary mirrors, with no tilt.
- One field 8 m wide and 8 m long (60.5 cm wide mirrors and tubes with diameters of 3 cm), where the receiver is 4 m above the primary mirrors, tilted 10 deg.
- Two parallel fields 4 m wide and 8 m long (30.2 cm wide mirrors and tubes with diameters of 1.5 cm), where the receiver is 4 m above the primary mirrors, with no tilt.
- Two parallel fields 4 m wide and 8 m long (30.2 cm wide mirrors and tubes with diameters of 1.5 cm), where the receiver is 4 m above the primary mirrors, tilted 10 deg.

The optimal total length of the receiver is analyzed. Irradiance at the receiver is measured every 25 cm, i.e. \( l_{rs} = 0.25 \text{ m} \). Fig. 3 depicts a simulation with 50 beams in order to show the layout of the 4 m wide solar field.

**FIGURE 3.** A transversal representation of the 4 m wide layout for a 50 beams simulation.

**RESULTS**

First, the receiver is assumed sufficiently long so that the solar footprint of the reflected radiation is always on the receiver, i.e. end-losses are avoided. A length of 30 m is enough for all configurations. The local annual optical efficiency is obtained for all points of the receiver, see Fig. 4.
FIGURE 4. Local annual optical efficiency for a 30 m long receiver and for all configurations.

One can observe that a very slight tilt of the field (10 deg leads to elevation lower than 1.4 m) leads to important efficiency increases, 9.5 percentage points (+26%) for the maximum efficiency locations. This is only due to the cosine losses, which are very important for SunDial collectors. This leads to the conclusion that tilting the field is extremely important in terms of optical efficiency, so this variable should be studied very carefully from a cost and performance perspective.

Second, one can observe that, for a given field tilt, the use of two narrow fields leads to higher local efficiencies for the locations where its value is higher, i.e. in the part of the receiver that is located above the second half of the primary mirrors field. In this case, this performance increase is due to the higher length/width ratio that reduces the distance travelled by the reflected beams and, thus, lead to a solar footprint location that is less affected by the longitudinal impinging angle. For the horizontal configurations, the 4 m field lead to local efficiencies close to the maximum for around 2 m, whereas these efficiencies are not achieved at any point of the 8 m wide field. Differences are even higher in the case of tilted field, when narrow configurations achieve the maximum local efficiency for around 4 m length, whereas the maximum efficiency is not obtained at any point for wide configurations.

For a wider picture of the problem, the solar field annual optical efficiency is obtained for different receiver lengths, between 5 and 30 m, for the 4 configurations raised. For each receiver length and each configuration, the receiver optimal offset related to the primary mirrors field is obtained. Results are depicted in Fig. 5.
When tilted and horizontal solar fields are compared a similar trend is observe: the former configuration always achieve higher efficiencies, with a difference of 9.5 percentage points if the receiver is sufficiently large. For shorter receivers this difference is even higher. As expected, when the solar field is tilted the optimum offset is reduced due to the decrease of the apparent longitudinal incident angle.

Regarding the use of two narrow fields instead of a wider one, both configurations achieve the same efficiency if the receiver is sufficiently long. However, the length required is much longer in the case one wide field. If the receiver has a length equal to the field length, 8 m, then the efficiency increase due to the use of two narrow fields would be 4.2 percentage points for horizontal fields (+14.7%) and 4.6 percentage points for tilted fields (+12.2%). These differences are due to end-losses.

As a design criterion it can be decided that the length of the receiver should be the one that achieves an efficiency of 0.9 the maximum efficiency for the given configuration. That is to say, end-losses would imply less than 10% of the impinging energy for extremely long receivers. Results are shown in Table 1.

| Field configuration | Required length | Optimal offset |
|---------------------|-----------------|----------------|
| 1 horizontal field  | 11 m            | 2.25 m         |
| 1 tilted field      | 10 m            | 1.75           |
| 2 horizontal fields | 8.5 m           | 1.5 m          |
| 2 tilted fields     | 8 m             | 1.25 m         |

One can observe that the effect of using two parallel narrow fields on the required receiver length is more important than the effect due to the use of tilted fields. A receiver length reduction of 20% is achieved when fields are narrower. This is very relevant not only in terms of costs, but also in terms of receiver thermal efficiency: longer receivers imply higher thermal losses for a given power input.

Regarding the optimal receiver offset, it is lower for narrow fields, due to the shorter distance travelled by reflected beams, and for tilted fields, due to the longitudinal incident angle reduction.

**CONCLUSIONS**

This paper has analyzed the effect of the solar field tilt and its width/length ratio for innovative SunDial collectors. The following conclusions are withdrawn:

- The effect of the solar field tilt is extremely important in terms of efficiency due to the reduction of the cosine effect. A very low tilt of 10 deg, which implies a height increase of 1.4 m every 8 m length, leads to efficiency increases around 26%.
- The use of solar fields with lower width/length ratios lead to a reduction of the receiver length requirements. The same optical efficiency can be obtained if the receivers are sufficiently long.

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