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Linear Beam-Down Solar Field Demonstrator: First Results and Validation

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Abstract. Linear beam-down solar fields consist of two stages of reflections that allow to concentrate solar irradiance at ground level. This approach seems promising for coupling with certain industries that require process heat, such as in mining and asphalt industries, in order to reduce their carbon emissions. In this work, the design and construction of a first of its kind linear beam-down Fresnel prototype is presented. First tests show that for the current solar field configuration, concentrations of up to 4.53 suns are achieved for a summer day at around 4 PM local time (UTC +2). Simulation projections show that this result could be enhanced to obtain up to 11.5 suns under the same solar conditions, by improving the mirror aiming system.

Keywords: Concentrated Solar Power, Linear Fresnel Reflectors, Prototype Experiments.

Introduction

Considering the goal of reducing carbon emissions, Concentrated Solar Power (CSP) is a technology with great potential. CSP is based in harnessing the heating power of concentrated solar irradiation, this way, using multiple mirrors, the solar heating power is multiplied and can be used for electric power generation or supplying process heat. Linear Fresnel reflectors concentrate solar power using low-curvature long mirrors, redirecting the solar irradiance linearly above the mirror level, parallel to the ground. Including a secondary beam-down reflector has been considered in previous studies, initially using a hyperbolic-cylinder mirror [1], then using several flat mirrors [2]. Incorporating this modification allows the solar field to concentrate the solar irradiance at ground level as displayed in Figure 1, which enables the direct use of this concentration to heat heavier products, such as aggregates for the asphalt industry or bio-wastes, to temperatures between 150 and 250ºC [3]. A prototype that incorporates this technology has been built, and it is expected to achieve concentrations of up to 11.5 suns throughout the year, which would facilitate the integration of this solar technology into asphalt production industry. In this communication the first heat flux measurements obtained with the constructed beam-down prototype will be presented, as well as the comparison with the expected results from the simulations, as well as the necessary measures to fix the problems encountered during the experimental campaign of this first version of the prototype.

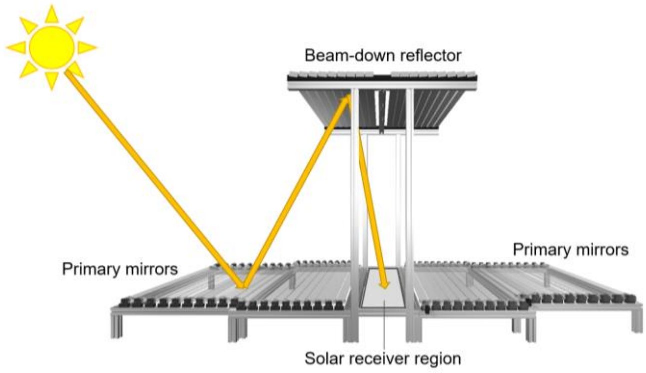

Figure 1. Beam-down linear Fresnel reflector working principle.

Solar field

A beam-down linear Fresnel reflector prototype has been designed and constructed, and is displayed in Figure 2. The designed solar field is composed of 3 different stages: the first one is the primary mirror field located near the ground, the second one is the secondary reflector placed above the first stage, and the last stage is the solar receiver, where the solar irradiance is concentrated. The followed philosophy when designing the prototype was to obtain a cheap lab-scale beam-down linear Fresnel reflector, which could be easily constructed and moved around in order to safely store it and take it outside to take solar measurements. The general dimensions of the solar field are displayed in Figure 2-A, while a picture of the prototype in the storage location is presented in Figure 2-B.

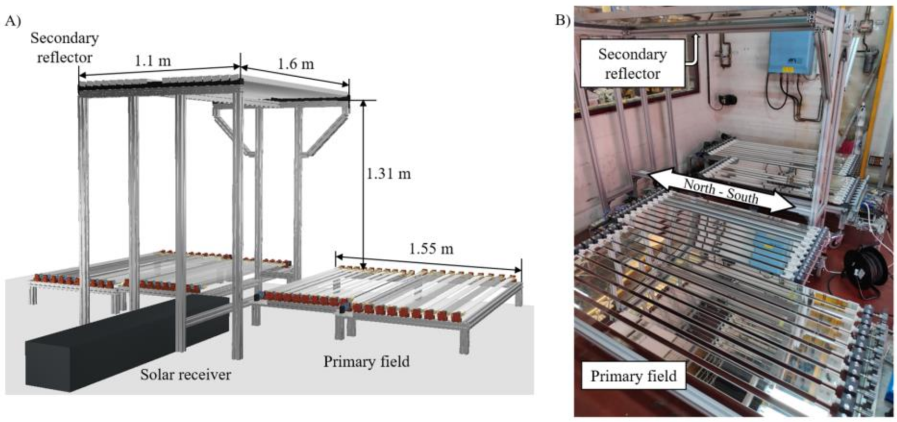

Figure 2. Proposed solar field. A) Design. B) Prototype.

Primary mirrors

The primary field is composed of a total of 40 flat mirrors 5.5 cm wide in order to reduce costs. These mirrors are divided in 4 independent sets of 10 mirrors each, where the two sets closer to the center of the field are 1.35 m long, and the other two are 1.6 m long. Each set is equipped with a set of wheels to easily move it around and locate it in the desired position.

Every mirror of each set is reinforced with an aluminum T-profile, and properly placed in the design position by anchoring it to the structure with a support system that can be coupled to a tracking device. Since the relative angle between the mirrors is constant, a tracking rack-and-pinion system has been implemented for each set to move the mirrors to the desired angle according to the solar position. This movement is controlled using an Arduino board. All of these components are displayed in Figure 3.

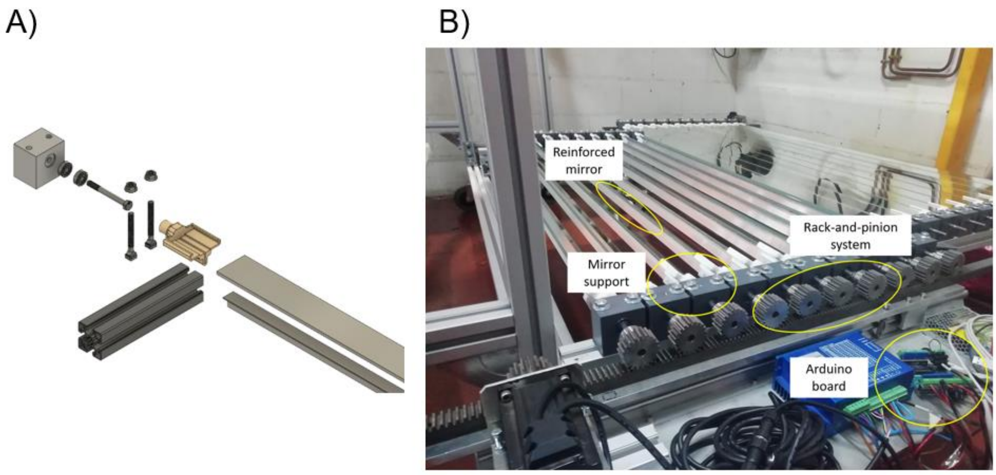

Figure 3. Primary mirror field details. A) Support system. B) Prototype result.

This rack-and-pinion tracking system did not end up working with the required precision, and ended up inducing aiming and tracking errors, as it will be seen in the results section of this communication. With the current system, the procedure to lock up the mirrors in their proper relative angle goes as follows: once the correct placement of the mirror in the field is obtained, the support system is locked up in a way that maximizes the contact between the rack and the pinion, after that, with the rack blocked, the mirror is tilted to the correct angle and then it is locked up to the pinion by using a special metal cap that connects the pinion to the bolt that acts as support of the mirror and using a nut to block this cap, this way the mirror angle can be fixed to a specific position of the rack. The main problem arises when tightening multiple nuts to the same rack, as the torque induces slight movements on both, the rack and mirror, and the system ends up with slight divergences from the desired relative angles.

The second problem comes from the usage of the system itself, as constantly moving the mirrors may induce an untightening of the nuts, and consequently a loss of the relative angles. Additionally, the inherent hysteresis of the system and the clearance between the rack and pinions means that sometimes the mirrors do not move to the desired tilt as determined by the Arduino board. This is especially worse when changing the direction the motor is turning.

Secondary reflector

The beam-down reflector is located 1.31 m above the primary field, and it is composed of 18 fixed mirrors 5 cm wide and 1.6 m long, 9 for each side of the solar field. These mirrors are also reinforced with an aluminum T-profile and are located in the correct position and with the desired angle using a special support to anchor them to the structure. In Figure 4 the design of the secondary reflector, as well as the prototype result are presented.

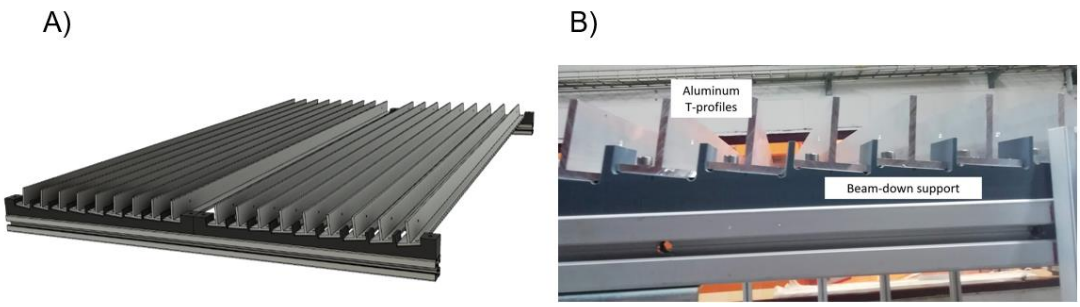

Figure 4. Secondary reflector details. A) Design. B) Prototype result.

Solar receiver

For this experiment, the solar receiver consists of a Lambertian target, which diffusely reflects the incident radiation. This target is located at the same height as the primary mirrors and can be moved in two directions parallel to the ground level. It also allows the coupling of the irradiance sensor. This Lambertian target is displayed in Figure 5.

Figure 5. Lambertian target.

Methodology

Experimental measurements will be compared with SolTrace simulations. These experiments were carried out at Carlos III University of Madrid, in Spain, located 40.33º North and 3.77º West. By using a Hukseflux HFS01 radiometer (thermopile water-cooled sensor) that measures between 0 and 20 kW/m^2, and that is coupled to the Lambertian target, the concentrated heat flux is measured. Additionally, a CCD Basler scA1300-32 gm camera, fixed to the beam-down, is aimed towards the Lambertian target in order to obtain the irradiance distribution by combining it with the radiometer results. Two pyranometers, one for measuring the total irradiance (model SR05-D1A3), and another for measuring diffuse irradiance (model SR15-D2A2), are used to obtain the direct irradiance, which combined with the radiometer measurements allows to obtain the total concentration of the solar field. The complete prototype setup, prepared to take measures, is presented in Figure 6, with the mirrors in their correct position, the motors connected to the Arduino board. In Figure 7 a detail of the Lambertian target with the incident concentrated sunrays is depicted.

Figure 6. Solar prototype setup.

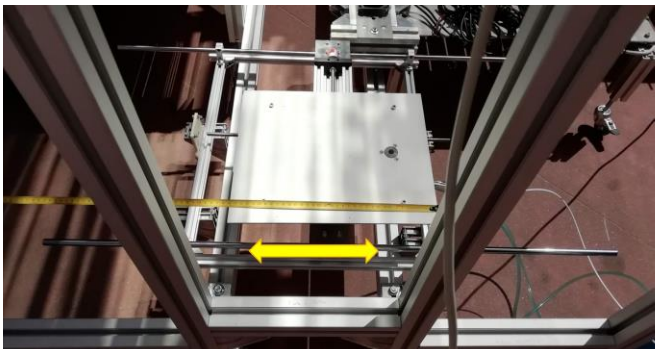

Figure 7. Concentrated solar irradiance that reaches the target.

The experimental procedure started with the orientation of the primary mirrors. Once the measurement time was determined the angle of the mirrors for said time was calculated, and the different mirror sets were set up by adjusting the closest mirror to the midfield for the closest sets, and the furthest mirror for the external sets, to the desired angle. Since all the mirrors move together due to the rack-and-pinion system, all the mirrors should be properly angled. Once the mirrors were tilted, their inclination was measured and the Lambertian target was slowly moved in the direction of the arrow in Figure 7, starting and ending in a similar position, to measure the obtained heat flux and to characterize the concentration profile observed by the CCD camera.

With the measured angles, SolTrace simulations are performed. With these results the simulated irradiance distribution can be compared with the experimental one, as well as the heat flux, as it will be observed in the next section, the obtained experimental results were not particularly close to the desired ones. By adjusting the simulation parameters to best match the experimental results, a realistic approximation can be obtained for a more precise version of the prototype, by adjusting the encountered errors in the current version.

Results and discussion

Once the prototype was properly set-up, we started quantifying the different relevant parameters. These measurements were taken on July 18th, 2022 (day number 199 of the year) at 4:06 PM CET. The irradiance results for all sensors are displayed in Figure 8.

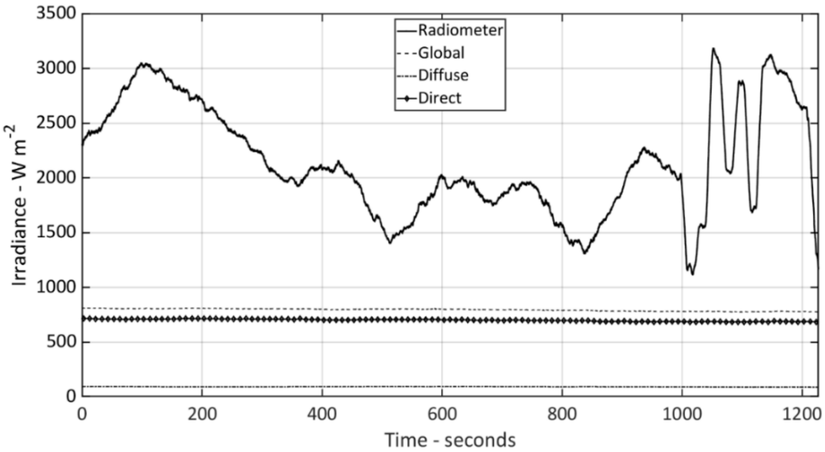

Figure 8. Irradiance measurements for July 18th.

As it can be observed, the total measurement time was 1200 seconds (approximately 20 minutes). Note that during this time, there was no solar tracking so the position of the mirrors remained fixed while the sun kept moving. The solar motion can be noticed in Figure 8 by the slight decrease of the global solar irradiance (from 809 to 778 W/m^2). Near the end of the measuring process the radiometer was slowly moved to different positions in the focal range to characterize the CCD camera image, ending up in a similar position to the one in which the measurement started, and the measured irradiance varied between 1000 and over 3000 W/m^2. At about 1050 seconds the maximum irradiance recorded was around 3150 W/m^2, which corresponds to a local concentration of approximately 4 suns. However, it is important to note that this is not the maximum irradiance obtained on the receiver. To know the maximum irradiance was necessary to calibrate the grayscale images obtained with the CCD camera by applying a linear regression between the grayscale and the radiometer measures.

By measuring the angles of each mirror during the experimental data acquisition process, different SolTrace Monte Carlo Ray-Tracing simulations are executed until the obtained simulated result fits the experimental one, both in maximum and minimum measured heat flux and in the solar concentrated profile. Considering a direct irradiation of 695 W/m^2 as obtained from the pyranometers, a reflectivity of 0.81, and a slope and specularity error of 3.15 mrad for the mirrors, a peak heat flux and a minimum flux of 3142 W/m^2 and 1145 W/m^2 respectively are obtained which, match the range displayed in Figure 8, while an average of 2069 W/m^2 is achieved. In Figure 9 the concentration profiles of both the simulation and the experiment are displayed side by side, as it can be seen, both are very similar.

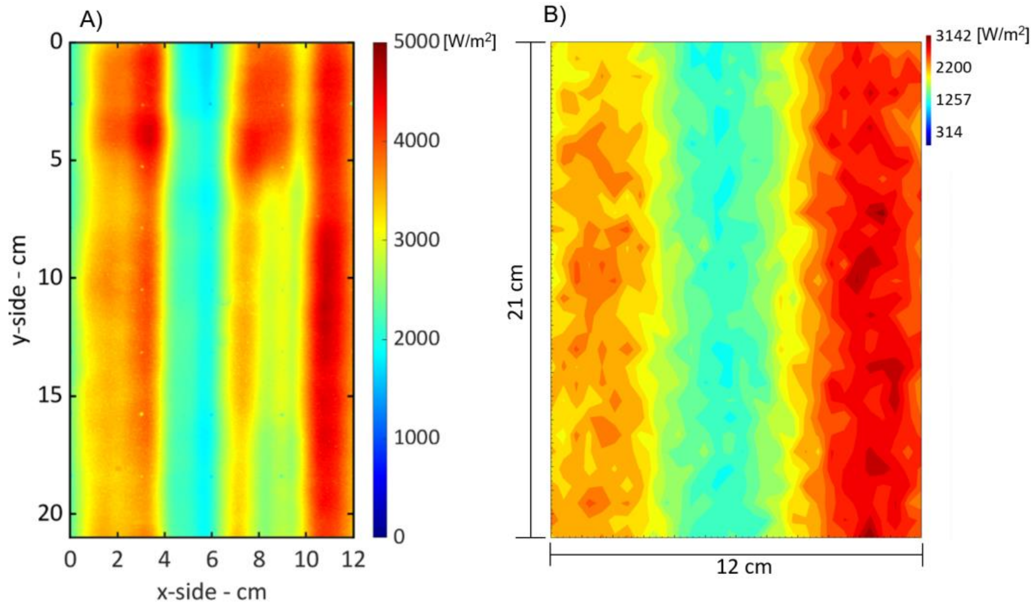

Figure 9. Solar concentration distribution. A) Experimental. B) Simulated.

As it can be seen, the general shape of both distributions is overall similar. However there are certain discrepancies in both axes. In the longitudinal axis, the main difference is a higher concentration in the upper region of the experimental image, this is because of the distribution of the primary mirrors in the solar field, as some mirrors end up further away from the middle of the target. On the other hand, in the perpendicular axis, the discrepancies can be explained because the simulation result is a picture taken at a certain specific time, the experimental results take some time to acquire, and during this time sun keeps moving.

The next interesting result is the potential solar concentration obtainable by improving the prototype conditions. The most important parameter to improve is the relative angle of the mirrors. Because of the current design, the mirror inclination was defined manually, and was locked by tightening a nut against a custom-made cap. By constantly adjusting and moving the solar field mirrors, this system can be loosened, and the original relative angles are lost. When comparing the ideal angles with the measured ones, an average error of 5.24 mrad is obtained, with a maximum error of 64.58 mrad for certain mirrors. By adjusting the mirrors to their correct inclination, a maximum irradiance of 8027 W/m^2 with an average heat flux of 6116 W/m^2 is achieved. This means that the maximum irradiance increases in a factor of around 2.55, while the average heat flux increases in a factor of around 2.96. As it can be seen in Figure 10, the obtained profile presents a normal distribution, with the highest heat flux in the center of the receiver.

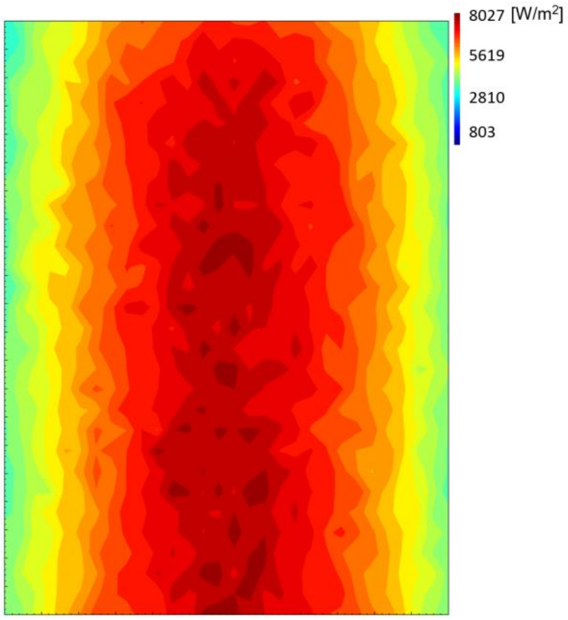

Figure 10. Solar concentration distribution with improved aim.

This result shows the potential of this presented technology: being able to concentrate up to 11.5 suns by using only flat mirrors.

It is evident that the desired result was not obtained in the experimental sessions. This campaign was the first approach to the construction and start-up of this kind of technology, and we encountered many unexpected setbacks and difficulties. The most influential problem was the set-up of the correct mirror tilts, since they are bound together in groups of 10 and their relative angles must be properly fixed. The main issue was fixing all the mirrors to their correct angle while being connected between them through the transmission system, so tightening one of the mirrors might affect the angle between said mirror and the adjacent ones. This is the main reason why the concentration profile obtained in the experimental campaign does not match the desired one.

Conclusions and future works

A first of its kind beam-down linear Fresnel reflector prototype has been designed and constructed. Experimental measurements have been obtained using this prototype, which have been compared with simulation results, where the maximum heat flux obtained is 3150 W/m^2, which corresponds to a concentration of 4.53 suns, with an average of 2069 W/m^2. Additional simulation results show that this prototype can be improved to obtain an average concentrated irradiance of 6116 W/m^2 or 8.8 suns, by just improving the aim of the mirrors.

Regarding future works, a new version of the prototype will be developed in order to improve the obtained performance. This includes reducing the number of mirrors and removing the rack-and-pinion tracking system, which will reduce the aiming errors and relative angle inconsistencies. Additionally, a closed system loop will be implemented to constantly check the mirror tilts and improve the aiming and tracking.

Data availability statement

The data obtained in the experimental campaign can be accessed through the following DOI: https://doi.org/10.21950/JWIRUU

Author contributions

- S. Taramona: Investigation, software, visualization, conceptualization, writing: original draft.
- A. Gallo: Investigation, software, visualization, writing: review and editing.
- E. LaTourrette-Ghez: Investigation, software.
- J. Gómez-Hernández: Conceptualization, supervision, funding acquisition, writing: review and editing.
- J.V. Briongos: Conceptualization, supervision, funding acquisition, writing: review and editing.

Competing interests

The authors declare no competing interests.

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