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Design and optical performance of a nonimaging Fresnel transmissive concentrator for building integration applications

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ABSTRACT

A transmissive Fresnel reflector is designed to match the needs of building integration for concentrating photovoltaic (PV), thermal (T) or hybrid photovoltaic/thermal (PVT) generation. The device concentrates radiation toward a static receiver by means of an array of reflectors which rotate collectively. All rotation axes are coplanar and parallel. A deep analytical ray tracing study has been made of the design characteristics and concentrator performance, thus determining the configuration which optimises efficiency. Numerous ray tracing numerical simulations have been performed which contrast and support the analytical results.

1. Introduction

At present, use of solar concentrator systems is mainly limited to large installations with devices of considerable size. Most of the manufacturers of solar concentrators are focusing their developments to these huge solar plants and there are very few examples in the market of middle or small scale installations. The medium or small scale installations would allow for a feasible integration of the concentrating solar systems into the buildings, leading to more distributed energy production scheme. Building Integrated Concentrating Photovoltaics systems may be installed either on the building façade or on the roof (which may be flat or sloped) producing in each case a different visual impact. Depending on the type of device, the system may be integrated in such a way that it is unseen, plays some role in the architectural aesthetic or that it constitutes in itself an architectural concept [1].

The integrability of a concentrator, being it reflective or refractive, depends on its concentration factor, C (defined as the ratio of the entrance aperture width to the exit aperture width). Concentrating systems with $C > 2.5X$ use a system to track the sun, whereas systems with $C < 2.5X$ can be static. However, in the long term static concentrators with higher ratios which make use of luminescence and photonic crystals may appear. Low concentrating ratio systems ($C < 10X$) are of particular interest for as they are of linear geometry and thus one tracking axis is sufficient for efficient operation [2].

Furthermore, concentrating photovoltaics is a feasible method to reduce the high initial cost of photovoltaic solar energy. Concentrating the solar radiation onto solar cells implies that the area of semiconductor devices is diminished by replacing part of it with a cheaper element (the concentrator). Considering that a higher concentration factor results in higher cost reduction, it can be seen that within the concentration range where single axis tracking may be used, the most desirable concentration factor is that which approaches the upper limit.

For the aforementioned range of concentrations, good versatility is offered by systems which work using Fresnel reflection.

The technology which groups the great majority of the Fresnel solar concentrators is the one in which the tracking is achieved by the movement of the individual reflectors whilst the receptor remains static opposite them. These systems are designed for power generation on an industrial scale, and in consequence this leads to a difficult direct building integration. By considering the elements sizing to be architecturally incorporated, this option may be easily installed on either flat or inclined roofs. Installation on façades however presents certain problems: the reflectors prevent light from passing into the building and the receiver must protrude outward from the building creating strain on the building structure and an anaesthetic appearance. The most important design within this group is the Compact Linear Fresnel Reflector (CLFR). The CLFR system is used for the direct steam generation. Similar systems to the CLFR have been developed, being an example the solar collector Solarmundo [3]. The University of Lleida has constructed another such system with a PVT receiver in 2009 in collaboration with *NUFRI* corporation and Trigen Solar S.L.

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Another type of Fresnel reflective concentrators make the tracking functions by movement of the entire system using 2-axis actuators, such as the BiFres system developed at the University of Lleida (equipped with a photovoltaic-thermal – PVT – receiver), whose integration in buildings would be restricted to flat (horizontal) roofs [4].

A new concept in the field of Fresnel reflection systems is the so called Non-Imaging Reflective Lens (NIRL) concentrator, of which there are two types: the axially symmetric Ring Array Concentrator (RAC) and the linearly symmetric Slat Array Concentrator (SAC). These operate by using reflectors to direct and concentrate light onto a receiver behind the optical element thus emulating a lens. The high concentration, RAC, requires two axis tracking, whereas the medium concentration SAC can be employed with either one or two axis tracking. This type of concentrator combines the high optical efficiency achievable by mirrors with the flexibility of design which is characteristic of lenses [5]. The principle drawback of these systems is that solar tracking is achieved by movement of the whole system, incurring the aforementioned restrictions with regard to architectural integration.

The system presented in this article consists of a linear Fresnel reflector which focuses radiation in a manner analogous to a lens. The receiver remains static and solar tracking is achieved in a simple and effective way by rotation of the individual reflectors. Thus overall movement is minimised facilitating incorporation into buildings and offering different possibilities for suiting the varied requirements of specific installations. In order to compare and to easily identify advantages of the system proposed, in comparison with the concentrators mentioned above, three indicators are described: the Characteristic Length, the Transparency Coefficient and the Shading Coefficient.

The Characteristic Length (CL) is defined as the quotient between the volume needed by the tracking system and the aperture area of the concentrator. When CL values obtained by the concentrator are low, building integration capabilities increase. In case of the design system, this parameter is highly decreased due to the rotational tracking, taking the same value than the mirror width. On the other hand 2-axis concentrators achieve CL levels equal to the square root of the concentrator area, practically disabling a proper integration.

The Transparency Coefficient relates the transparent surface to the light with respect to the aperture area of the collector. If the concentrator surface blocks a big percentage or totally the incoming radiation, the number of integrating possibilities of the concentrating systems is very limited. Compact Linear Fresnel Reflector systems and similar devices take low values of the CL indicator; however the structure of the concentrator hinders both good views from the interior of the building and an adequate lightening. The inclination of the reflectors (see Fig. 1) in the system described below facilitates to reach transparency coefficients guaranteeing comfort.

The last of the indicators is the Shading Coefficient, which is the ratio between the direct beam radiation passing through the system and the total direct radiation received on the aperture area of the concentrator. Concerning to the 2-axis Fresnel concentrators, this coefficient exactly coincides with the Transparency Coefficient and it is equal to 0. In Compact Linear Fresnel Reflectors these indicators are strongly dependent on the final structure of the concentrating device.

2. System design and mathematical model

The system design must aim to fulfil the following requirements: architectural integrability (environmental integration, appropriate materials, dimensions that fit the composition and harmony of the building, light weight), high compactness (this is the inverse of the aspect ratio, the aspect ratio being the ratio between the focal distance and the concentrator aperture), low mirror ratio (ratio between the surface area of the reflectors and the concentrator aperture), high optical efficiency and geometric concentration above 5*X*.

The mathematical model is formed as follows:

Let N be the total number of mirrors which form the concentrator, each being labelled with a subindex i. Cases with odd N are considered such that there exists a central reflector with subindex $i = 1 + (N - 1)/2$, although expressions described below can be extended for any case. The coordinate origin O is taken to be at the centre of rotation of the central mirror (Fig. 1). The axes of rotation of all reflectors lie in the XZ plane and are parallel to the Z axis. The receiver, of width d, sits parallel to the XZ plane at a distance f from the origin. The length of the receiver is considered equal to that of the mirror.

The distance of the centre of rotation of the ith mirror from the origin is defined to be x_i, and the angle subtended at the centre of the receiver by the reflector and the origin α_i, where:

$$\alpha_i = \tan^{-1}\left(\frac{x_i}{f}\right) \tag{1}$$

If θ_s is the angle of incidence of the solar radiation (positive clockwise) then to reflect the light onto the receiver each mirror must be inclined at:

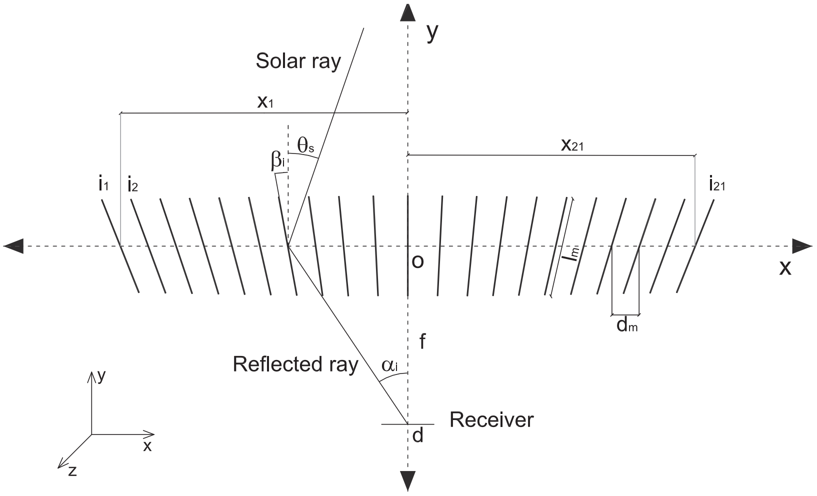

Fig. 1. Schematic showing parameters used in the mathematical model.