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Characterization of a photovoltaic-thermal module for Fresnel linear concentrator

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ABSTRACT

An advanced solar unit is designed to match the needs of building integration and concentrating photovoltaic/thermal generation. The unit proposed accurately combines three elements: a domed linear Fresnel lens as primary concentrator, a compound parabolic reflector as secondary concentrator and a photovoltaic-thermal module. In this work the photovoltaic-thermal generator is built, analysed and characterized. Models for the electrical and thermal behaviour of the module are developed and validated experimentally. Applying a thermal resistances approach the results from both models are combined. Finally, efficiency electrical and thermal curves are derived from theoretical analysis showing good agreement with experimental measurements.

1. Introduction

The combination of concentrators based on Fresnel lenses with photovoltaic-thermal modules is a viable technology for solar generation in buildings. Concentrating photovoltaic systems can present higher efficiency than standard ones; this is achieved effectively by keeping the photovoltaic cells' temperature as low as possible. The uniform distribution of the concentrated solar radiation and temperature on the photovoltaic cells and the suitable cooling method contribute to an effective system operation and the achievement of high electrical output. Therefore, photovoltaic-thermal modules allow optimization of electrical output in concentrating generators.

The integrability on buildings of a concentrator depends on its concentration ratio, C (defined as the proportion of incident solar energy within the collecting angle that emerges from the exit concentrator aperture). Low concentrating systems can be stationary devices [1] when the concentration ratio $C < 2.5\times$ (though the concentration ratio is dimensionless magnitude the symbol $\times$ is commonly used to facilitate the texts understanding). Higher concentration ratios require sun tracking but concentration ratios $C < 10\times$ remain of particular interest because they can offer linear geometry and thus one axis tracking operation [2]. Currently, a concept which attracts much interest is the architectural integration of solar generators, to which most of photovoltaic-thermal developments are ill suited. Solar photovoltaic-thermal systems are only suitable for installation on flat roofs. CHAPS from the Australian National University [3] and BiFres from the University of Lleida [4] are some examples.

A static concentrator in which solar tracking is achieved by movement of the receiver seems to be a feasible option for integration in buildings of solar generators with concentrating ratios between $2.5\times$ and $10\times$. This configuration may be easily installed on either flat or inclined roofs. The application of linear Fresnel lens in such concentrator has been studied in [5,6]. Linear Fresnel lenses have a number of attractive features in this application: They are produced in large amounts and sizes, their aspect ratio can be adapted leading to compact concentrating units, they are very thin reducing the mechanical load on the structure and are made of reliable and durable material. The capability of linear Fresnel lenses to separate the beam from the diffuse solar radiation makes them useful for illumination control in building interior space [2].

The idea of combining a static Fresnel lens with a solar thermal-photovoltaic generator is not groundbreaking but further development of some interesting details is needed. The objective of this work is to build, simulate and characterize the electrical and thermal performance of a linear solar photovoltaic-thermal generator suitable for coupling with a static concentrating optical unit. The main requirements for the device are (a) optimization of the optical performance (maximum concentration ratio and homogeneous illumination conditions), (b) module thermal and electrical design adapted to the optical conditions and (c) integrability on buildings (the use of encapsulating elements, low weight, watertight and impermeable to dust and transparent to diffuse radiation).

This paper discusses aspects of a novel solar concentrating photovoltaic-thermal module that has been designed to produce both electricity and hot water. The motivation for its development is, in the long term, to produce photovoltaic power and solar hot water at a cost which is competitive with other solar energy technologies. To be capable of achieving this aim, the photovoltaic-thermal modules must have an inherent advantage over other photovoltaic and

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thermal technologies. The primary advantage is that concentrating light allows a significant reduction in the area of solar cell coverage, the main cost driver in a flat plate system. The thermal energy generated could be considered as a byproduct due to the necessity to cool the cells, but in appropriate applications the thermal energy is equally valuable. It is well known that photovoltaic cells efficiency is affected by temperature; therefore the best way to improve electrical production is to cool solar cells producing hot water at useful temperatures for applications such as building heating, as well as many commercial and agricultural applications that require low-grade heat. A secondary advantage is the efficient use of space inherent in combining electrical and thermal energy generation, which is advantageous on building applications where space is commonly limited. The challenge in the development of the photovoltaic-thermal module for a Fresnel linear concentrator is to design a robust unit with a clear pathway to optimize the performance within the cost constraints. A secondary advantage is the efficient use of space inherent in combining electrical and thermal energy generation, which is advantageous on building applications where space is commonly limited. The challenge in the development of the photovoltaic-thermal module for a Fresnel linear concentrator is to design a robust unit with a clear pathway to optimize the performance within the cost constraints.

The work is structured in the following sections. After introductory Section 1, the photovoltaic-thermal generator is described in Section 2. In Sections 3 and 4 electrical and thermal characteristics of the photovoltaic-thermal absorber are studied numerically and experimentally. Based on the experimental results shown, Section 5 proposes the efficiency curves for the hybrid device. Finally, the work is concluded in Section 6.

2. Photovoltaic-thermal generator description

The solar generator developed is composed of two clearly distinct but interdependent parts, the optical concentrator and the photovoltaic-thermal absorber (Fig. 1). The design and optimization of the optical unit was addressed at an early stage. The optical analysis presented in detail in [6] is briefly introduced in the following paragraph to facilitate the reading of the work.

2.1. Optical concentrator

The optical unit is based on a stationary wide angle optical concentrator which, whatever the location of the Sun, transmits the input radiation into a small moving focal area, which in turn is tracked by the solar absorber. To maximize concentration ratio and to obtain the best illumination of photovoltaic cells (mainly homogeneity in the focus area) it is concluded that the combination of a linear Fresnel lens (5×) with a secondary CPC reflector (2×) is preferable for achieving building integration for solar concentrating generators (Fig. 1). Therefore, this configuration of a domed linear Fresnel lens as a primary concentrator and a compound parabolic reflector as a secondary concentrator is adopted for the further developments presented in this paper.

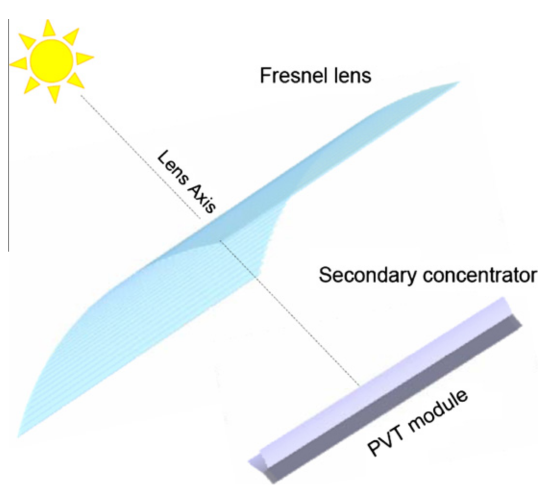

Fig. 1. Schematic draw of the optical concentrator elements.

The behaviour of the optical system was studied in detail giving the placement of the focal area and the optical concentration obtained for that area [6]. The optical behaviour of the systems was simulated using ray tracing software. While previous studies for linear systems were focused on the plane transverse to the lens, [6] demonstrated that a three-dimensional analysis is needed to characterize the system due to the influence of the longitudinal angle in focus placement and optical concentration ratio. Due to the optical design more than 85% of the annual direct radiation incident on the static Fresnel is concentrated onto the moving solar receiver. For a range of incidence angles close to paraxial conditions the concentration ratio reaches values above 9×. The optical concentration ratio was evaluated for a wide range of incidence angles and the data was used to adjust an empirical concentration function. Optical results and numerical equations derived from [6] are adopted in this work to evaluate the photovoltaic-thermal module performance. The linear Fresnel lens aperture width is 0.1 m × 1 m while the focal area in the CPC secondary concentrator is 0.01 m × 1 m.

2.2. Photovoltaic-thermal module

The optimized optical concentrator defines the constraints to be achieved in the design of the hybrid solar module: linear focal area, homogeneous illumination conditions and variable concentration ratios from 7× to 10×. While keeping in mind that the main requirement introduced in Section 1 for the whole device is building integrability. An extended review was done to find a solar unit which suits the needs. It was concluded that no adaptable hybrid generator was available. Therefore, in the following sections the solution developed is presented and analysed in detail.

In the development process, several photovoltaic-thermal configurations are studied. The hybrid module is constructed as a water channel one using concentrating silicon cells (Fig. 2). The solar energy converted into heat is removed by water flowing in a rectangular pipe to which solar cells have been adhered. The generator is composed of photovoltaic cells (0.1 m width) on top of the rectangular cross section aluminium heat sink.

The heat exchange properties of the aluminium sink improve on increasing the aspect ratio (A = channel height/channel width) of its cross section. However, a big aspect ratio makes mechanical procedures such as hydraulic connection and isolation more difficult. Moreover, it is necessary to mention that the main aluminium factories do not manufacture pipes with ten millimetres width and aspect ratios higher than 2.43. Following these considerations, the pipe selected for inclusion in the photovoltaic-thermal system under concentration have an external cross section of 0.2 m × 0.1 m (A = 2.43). These cost-effective arguments were decisive in the choice of final design.

The photovoltaic-thermal module consists of 26 series connected crystalline silicon cells optimized for concentrating systems (photovoltaic cells are manufactured by the British company NaREC®). Other essential elements of the module are: (a) an EVA film is applied to the cells and low reflectivity glass with low iron content is used as an outer shell; (b) the cells are attached to the heat sink, the adhesive used is a material with high heat transfer conductivity that is also resistant to extreme temperatures and is an excellent