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Impact of heliostat curvature on optical performance of Linear Fresnel solar concentrators

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A B S T R A C T

The present paper gives a numerical investigation of the effect of mirror curvature on optical performance of a Linear Fresnel Reflector solar field installed recently in Morocco. The objective is to highlight and discuss the effect of mirror curvature on the flux density distribution over the receiver and the system optical efficiency. For this purpose, a Monte Carlo-ray tracing simulation tool is developed and used to optimize the optical design taking into account the curvature degree of the heliostat field. In order to assess the accuracy of the numerical code developed and the validity of simulation results, a set of verification tests were developed and detailed within this article. Then, the optical performance of the system is evaluated as a function of mirror curvature and receiver height. The major challenge of this study is to find a trade-off between heliostat curvature and receiver height since lower and smaller receivers may reduce the system cost. It has been found that the flux distribution over the receiver and the optical efficiency of the system are relatively sensitive to the mirror curvature. We have demonstrated quantitatively how the use of curved mirrors can enhance the optical performance and reduce the required receiver size.

1. Introduction

Nowadays, due to geopolitical circumstances in the MENA region, the energetic situation in Morocco has become one of the most critical ones. Currently, the kingdom imports about 96% of its required energy. Energy consumption has risen at an average annual rate of 5.7% from 2002 to 2011 where petroleum represents nearly 61% of the overall national energy consumption [1]. This situation made Morocco one of the most extremely dependent Northern African countries on energy imports and fossil fuels. The kingdom therefore became highly threatened by increases in international fuel prices, a situation that may increase the burden on the government budget.

However, the country has abundant renewable energy resources such as wind and solar energy. Solar energy is one of the most abundant and valuable renewable energy alternatives in the country. Solar technologies convert solar radiation directly into electrical energy by using photovoltaic systems or to thermal energy by using CSP systems [2].

The current Moroccan government's energy strategy has set sustainable development as one of the most relevant priorities at the national level. The adopted green economy strategy aims to face the current energetic challenges by ensuring energy security, sustainable development and encouraging investment in the renewable energy sector. In this context, an ambitious renewable energy project has been launched for the period 2009–2020 which aims at having 42% of the total power installed capacity from solar, wind and hydroelectric sources by 2020. A big interest is given to solar energy due to the fact that the country has a great solar potential characterized by an intensive solar radiation with an average radiation amount of 5.3 kW h/m^2 under annual sunshine of 2700–3500 h [3]. The objective of the solar plan is to reach 2000 MW from photovoltaic and CSP power plants [4].

A series of measures have been taken to accompany this program including the establishment of renewable energy and

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Nomenclature

Φ	Total power (W) attaining the receiver surface
C	Solar cone
Ω	Solid angle of the solar cone
H	Total reflecting surfaces of the reflector
$\vec{\omega}_{in}$	Incident sun rays directions into a given point on the reflector and which reach the receiver
θ	Sun rays incidence angle
$I(\theta)$	Solar radiation intensity corresponding to the incidence angle θ of sun rays directions
$\vec{n}$	Normal vector on the incidence point of the reflector
ρ_k	Reflectivity of the solar field components
τ	Transmissivity of the solar field components
dS_H	Elementary surface on the reflector (heliostats)
k	Total number of reflections
X_0	Randomly sampled ray position point from the heliostat surface
$\vec{\omega}$	Random variable associated to the direction of the ray from the solar disk
$P_X(X)$	Probability density function of the random variable X associated to the position X_0 on the mirror
$P_\Omega(\vec{\omega})$	Probability density function of the random variable $\vec{\omega}$
ψ	Monte-Carlo weight (W)
ε_r	Relative error (%)
U	Uniformity of the distribution
σ_{flux}	Standard Deviation (W/m2) of the flux density distribution
DNI	Direct normal irradiation (W/m^2)
CSP	Concentrating Solar Power

efficiency agencies, legislations and the engagement of different domestic and international stakeholders. The renewable energy program will create a structural change in the energy supply mix [5]. However, even with these assets, enhancing R&D infrastructure, building up local capacity and investments in the knowledge formation will be essential conditions for reaching the renewable energy targets [6]. This explains why scientific research axes have started to turn to a strategy where the ecological variant is omnipresent while several renewable energy research projects have emerged. CHAMS-1 is one of the R&D projects on Solar Energy supported by IRESEN (Institute of Research on Solar and New Energy-Morocco) [7]. The project aims to design and implement a new low cost CSP system based on a new generation of Linear Fresnel technology [8], taking into account the local solar and climate conditions, cost reduction, material enhancement and efficiency gain.

As commonly known, the Linear Fresnel reflector (LFR) solar concentrator is one of the most cost advantageous and promising solar thermal technologies. The main principle of LFR technology consists on using multiple rotating flat heliostats to reflect the sun rays onto a linear receiver at fixed position. Such kind of solar collector concentrators may have a lower efficiency than other concentrating geometries, but the likely reduced cost may well compensate that, providing a solution for cost-effective solar energy collection on a large scale [9]. This technology still in phase of development and represents a great promising research and development track for Morocco to achieve the solar plan goals. Enhancing the optical precision of the mirrors is one of the challenges to be achieved by the end of the decade. In fact, the geometrical configuration of LFR heliostats is originally flat. As commonly known, the focus width obtained using flat heliostats wouldn't be smaller than heliostats width. Consequently, using flat heliostats would offer a very limited concentrating capacity [10]. Recently, concave mirror strips with static curvature are proposed, based on the elastic deflection of the glass sheet [11]. The curvature would allow the heliostats to be more precise than in case of flat ones, and offer a higher concentrating capacity. But while applying curvature to heliostats, some minor factors have to be considered, including the simplicity and the cost of the control mechanism, the resistance to wind load, etc [10].

Unlike the LFR technology and among numerous technologies for utilizations on solar energy, the Parabolic Trough Collector (PTC) technology of concentrating solar power (CSP) systems is the most proven and lowest cost large-scale solar power technology available today ([11,12]). Moreover, it also has been the most mature and field-tested solar thermal electric technology up to now ([13,12]). In terms of concentration factor, PTC systems offer a higher one than the LFR systems. The fact of introducing PTC systems principle in a LFR system would represent an important advantages combination between these two technologies to enhance the optical efficiency and reduce the required costs. For this reason, we have chosen to study the curvature effect on the optical efficiency of Linear Fresnel reflectors by changing slightly the mirror curvature instead of using flat ones.

Generally, evaluating optical performances of a solar concentrator system is done using several simulation codes where the most reliable are those based on ray tracing method. Available ray-tracing software includes specialized codes for Concentrating Solar Power (CSP) applications such as SOLTRACE [14] and some general purpose commercial optical tools like ASAP (Breault Research Organization). Ray tracing generates a set of sun rays simulating the original or broadened/altered sun shape and lets them interact with various collector components with specified optical properties and mechanical aspects [15]. In CSP, the solar radiation is reflected by a multitude of heliostats and concentrated in the aperture of one or more receivers to be transformed into another form of energy in an associated thermodynamic process, which is subject to thermodynamic restrictions ([16] [17]). As clearly summarized by Garcia et al. [18], the solar power that is intercepted in the receiver aperture can be calculated sufficiently precise by a handful of well known tools [17], such as HFLCAL [19], HELIOS [20], MIRVAL [21], DELSOL [22], SOLTRACE [14], ENERTRACER [23], or RCELL [24].

The majority of existing ray tracing codes predict rigorously the optical behavior of a CSP system, but without flexibility in terms of use. Furthermore, in some cases, they are usually complicated or restricted for user's access. Generally, implementing personalized loop for the optimization procedure is very difficult.

In our study, we have developed new optical-geometrical libraries dedicated specifically to an optimization procedure of the linear Fresnel solar field. The developed simulation tool, named OPSOL, is based on two distinct models; an optical-geometrical model and a radiative transfer model. It offers new and large range possibilities for simulating the optical behavior of Linear Fresnel Reflector (LFR) systems, including the Curved Linear Fresnel ones. The code contains an optimization calculation loop that predicts the appropriate curvature radius for the parabolic through heliostats with its corresponding optical performances. In addition, OPSOL will be used to predict the total flux intercepted by the receiver aperture plan from solar radiations reflected by heliostats rows.