Energy Conversion and Management 78 (2014) 676–683

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Parametric analysis of the curved slats fixed mirror solar concentrator for medium temperature applications

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ARTICLE INFO

Article history:
Received 8 August 2013
Accepted 22 November 2013
Available online 18 December 2013

Keywords:
Solar concentrator
CSFMSC
Ray-tracing
Heating process
Moving receiver

ABSTRACT

The Curved Slats Fixed Mirror Solar Concentrator (CSFMSC) is a solar concentrator with a static reflector and a moving receiver. An optical analysis using ray-tracing tools was presented in a previous study in function of three design parameters: the number of mirrors N, the ratio of focal length and reflector width F/W, and the aperture concentration C_a. However, less is known about the thermal behavior of this geometry. In this communication, the integrated thermal output of the CSFMSC has been determined in order to find the optimal values for the design parameters at a working temperature of 200 °C. The results were obtained for three different climates and two axial orientations (North–South, and East–West). The results show that CSFMSC can produce heat at 200 °C with an annual thermal efficiency of 41, 47, and 51%, dependent of the location considered (Munich, Palma de Mallorca, and Cairo). The best FMSC geometries in function of the design parameters are exhibited for medium temperature applications.

1. Introduction

The Curved Slats Fixed Mirror Solar Concentrator (CSFMSC) is a solar concentrator with static reflector and moving receiver that can produce thermal energy in medium temperature range [1]. The CSFMSC is made up of a set of curved mirrors arranged with their respective central lines positioned along a circular path (called a generating circle) and oriented such that the rays reflected by the curved mirrors intersect upon a small area on the same base circle. The CSFMSC geometry is an evolution of the Fixed Mirror Solar Concentrator (FMSC) that emerged in the seventies [2–4] where flat mirrors are replaced by curved mirrors (for more details on the optical behavior of the FMSC, see the study presented by the authors in 2012 [5]). Therefore, the CSFMSC has the same sun tracking properties as FMSC, so receiver sun tracking can be done simply by positioning the receiver at a certain angle over the circle path without moving the reflector. Fig. 1 gives an example of each geometry: Fig. 1(a) for the diagram of the FMSC with focal length and reflector width ratio $F/W = 1.5$, and Fig. 1(b) for the diagram of the CSFMSC with focal length and reflector width ratio $F/W = 1$.

These geometries have several advantages when compared to other designs, namely it is one of the best geometries for collector integration onto building roofs. The main exponent of this technology [6] is the Concentrating Collector with Stationary Reflector (CCStaR) prototype, developed by Tecnologia Solar Concentradora S.L. (www.tsc-concentra.com) in close collaboration with the University of the Balearic Islands [7–9]. The CCStaR collector is a CSFMSC with one parabolic mirror ($N = 1$).

An optical study of CSFMSC geometry was presented in [10,11] for the number of curved mirrors: 1, 3, 5, and 7, that form the reflector. The optical efficiencies were analyzed in function of three design parameters: the number of mirrors N, the ratio of focal length and reflector width F/W, and the aperture concentration C_a (in order to represent different receiver widths). The results show that the CSFMSC has better optical behavior than the FMSC, which results in a solar concentrator with fewer reflector segments for the same concentration and optical efficiency [11]. A standard evacuated tube with a flat fin was used as a receiver; see Fig. 2 for the receiver configuration. The receiver tube design considered was based on a commercial evacuated tube collector tested at TÜV [12].

In the optical analysis [11] the practical interest of the geometry was shown, and a set of candidate parameters with high optical efficiencies was determined. Nevertheless, in practical applications, the best optical efficiency does not necessarily produce the highest thermal efficiencies, since other factors like the concentration factor also have a large influence on the collector output, especially at high working temperatures. Therefore, to find the more practical parameters, a thermal analysis has been conducted using

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http://dx.doi.org/10.1016/j.enconman.2013.11.032

Nomenclature

A_a	mirror aperture area
a_1, a_2	thermal losses coefficients
C_a	aperture concentration ratio (mirror aperture/absorber aperture)
d	day
E_b	annual beam energy per unit area
E_{DNI}	annual direct normal energy per unit area
E_{Hb}	annual horizontal energy per unit area
E_T	annual total energy per unit area on 15° tilted surface
E_{Tb}	annual beam energy per unit area on 15° tilted surface
F	focal length
F_{av}	collector heat removal factor
G_{Tb}	direct irradiance on 15° tilted surface
h	hour
$K_{\gamma\rho\tau\alpha}$	incidence angle modifier referred to the collector aperture
$L_{\alpha\beta\gamma}$	transformation matrix
N	total number of mirrors
$\dot{Q}_g$	net energy gained per unit time
$Q_{g,a}$	annual net energy gained
T_a	ambient temperature
T_{av}	arithmetic average of the fluid inlet and outlet temperature
$\vec{u}_s$	sun position vector in local coordinates
$\vec{u}'_s$	sun position vector in CSFMSC coordinates
W	reflector width
α_c	angle rotation (see Fig. 4)
β_c	angle rotation (see Fig. 4)
γ	intercept factor
γ_c	angle rotation (see Fig. 4)
η_a	annual average efficiency
θ_f	focus angle position (see Fig. 1)
ρ	reflection coefficient
τ	transmittance

Abbreviations

EW	East–West direction for axial orientation
IAM	incidence angle modifier
FMSC	fixed mirror solar concentrator
CSFMSC	curved slats fixed mirror solar concentrator
NS	North–South direction for axial orientation

the Incidence Angle Modifier (IAM) curves obtained in the optical analysis to determine the annual energy yields of the different designs at a set temperature of 200 °C.

The thermal analysis has been conducted for three different weather types at different latitudes: Cairo, Palma de Mallorca, and Munich. The cases analyzed in this paper are defined by the following design parameter values (792 cases were analyzed):

- $N = 1, 3, 5, 7$
- $F/W = 1.0, 1.25, \ldots, 3.0$
- $C_a = 3, 4, 5, 18, 20, \ldots, 30$

There is a great potential for the use of solar thermal collectors in industrial applications as well as other process heat uses such as solar cooling [13–18]. The CSFMSC thermal analysis was done because of the current interest in the integration of solar collectors into building surfaces that work inside the gap temperature between 100 °C and 250 °C [19]. Additionally, although many scientific studies of the parabolic trough and linear Fresnel geometries have been reported, (see for example [20,21] for a comparison of these technologies, or [22,23] for new designs of Fresnel concentrators, and [24] for a new kind of trough solar concentrator), less is known about energy output of the CSFMSC geometry. Therefore, in this paper we have presented a parametric analysis of the CSFMSC geometry to determine the best parameter set (N, F/W, C_a) for medium temperature applications.

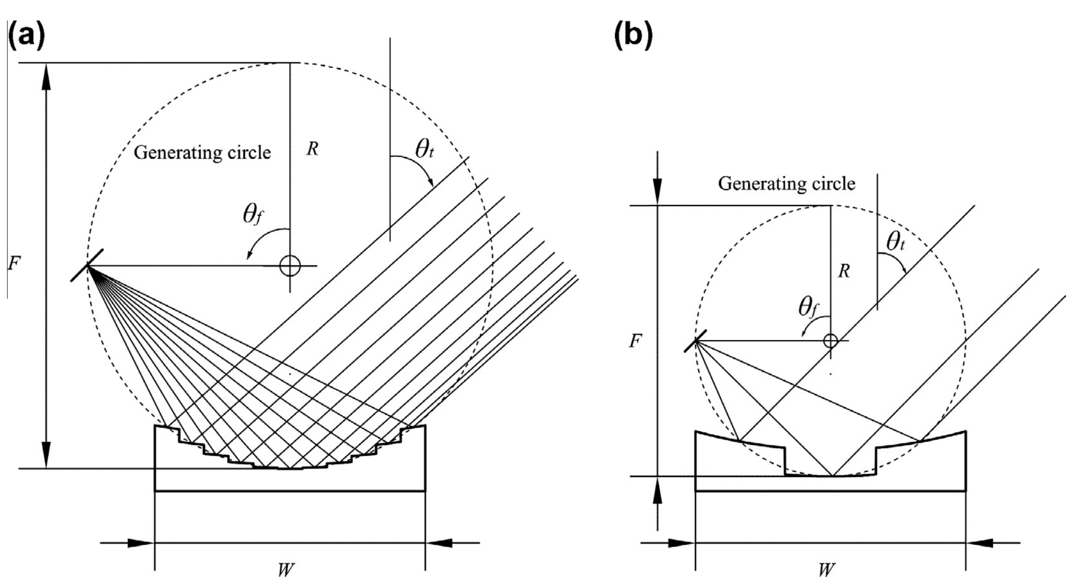

Fig. 1. Optical principle of the (a) FMSC with $N = 11$ flat mirrors and $F/W = 1.5$, and (b) CSFMSC with $N = 3$ parabolic mirrors and $F/W = 1$. In both cases the receiver is moving in a circular path on the generating circle. The generating circle has a radius R, the focal length of the concentrator is $F = 2R$, and the receiver is positioned by the θ_f angle. The position angle of the receiver is twice that of the transversal incidence angle ($\theta_f = 2\theta_t$). The reflector width is W. An image of the principal rays is shown for the transversal angle at 45°.