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A novel Compound Elliptical-type Concentrator for parabolic primaries with tubular receiver

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ABSTRACT

The Parabolic Trough (PT) is the most used concentrator in CSP (Concentrated Solar Power). However, this concentrator technology is facing a significant challenge to increase its overall efficiency and cost-effectiveness. Meanwhile, other low-cost solutions such as Fresnel concentrators are also being perceived as potentially attractive. In order to achieve the lower cost goal, new optical solutions can be considered, in parallel with improvements coming, for instance, through the use of new materials or manufacturing solutions. But conventional PTs can still be improved to yield, for instance, higher concentration values, a possible starting point for higher conversion efficiency. These new solutions, in turn, can also be useful for other technologies and applications (Fresnel Concentrators, Central Tower Receivers, etc.). However it is easier to develop and test these solutions in conjunction with parabolic primaries (continuum primary). And that is the topic of this paper: to present a new Compound Elliptical-type Concentrator for a parabolic primary with a tubular receiver. A comparison is made between this new concentrator and two other concentrators (a conventional PT concentrator and a XX SMS (Simultaneous Multiple Surface) concentrator), as well as a calculation of the total amount of collected energy (kW h) for a particular location, Faro (Portugal). The paper ends with a discussion of the results obtained, their impact and possible applications in the future.

1. Introduction

Recently new optical solutions for tubular receivers were proposed (Canavarro et al., 2013a, 2013b, 2014), based on the Simultaneous Multiple Surface (SMS) method (Chaves, 2016; Winston et al., 2005). These solutions, designed for Parabolic Trough like primaries and Fresnel primaries, have potential; they have as little optical losses as possible, while approaching as much as possible the limit of $CAP = C\sin(\theta) = 1$, where CAP is the Concentration Acceptance-Product (Benítez, 1998), θ is the half-acceptance angle of the concentrator (Chaves, 2016; Winston et al., 2005) and the receiver is in vacuum or air (refractive index $n = 1$).

In practice, for the same acceptance angle, a higher CAP really means a larger aperture area for the same receiver (higher concentration) when compared with the conventional Parabolic Trough (PT) concentrators and with most Linear Fresnel (LFR) concentrators present on the market nowadays. If non evacuated receivers were to be used this could also mean a smaller diameter tube for the same aperture area and thus smaller thermal losses, thereby enhancing the energy delivered by the concentrator by a significant amount.

Nevertheless these solutions have some drawbacks. Firstly, the SMS method is a powerful but complex design method. The simultaneous design of all the optical parts of the concentrator using the SMS chains (Chaves, 2016; Winston et al., 2005) is far from being trivial. Plus, practical experience showed that this method can be somewhat unstable during the optimization process of the optic (adjustments of design parameters), being very sensible to little variations of the values of the input parameters (resulting in distortion of the concentrator). Another problem of these concentrators is the size of the secondary mirror. In fact, by achieving a much higher CAP than the other concentrators for the same acceptance-angle and tubular receiver, the result is a significant increase of the size of the secondary mirror, which "increases" the apparent size of the tubular receiver "seen" from the primary field. That, by the way, is the reason why these SMS concentrators can increase their aperture size without penalizing the acceptance-angle. As an example, Fig. 1 shows a comparison between the sizes of the secondary mirrors of a conventional Fresnel concentrator

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Nomenclature

Latin characters

[**A**, **B**]	Euclidean distance between points **A** and **B**
A_C	area of solar collector field (m^2)
A_L	aperture length (m)
A_G	gap between two consecutive rows (m)
C	geometric concentration (×)
CAP	Concentration-Acceptance Product
CEC	Compound Elliptical Concentrator
CPC	Compound Parabolic Concentrator
CPV	Concentrated PhotoVoltaics
CSP	Concentrated Solar Power
DNI	Direct Normal Irradiance
E_R	energy captured by the receiver
E_P	energy captured by the primary
H_R	receiver linear heat losses (W/m)
H_P	connecting pipes linear heat losses (W/m)
HTF	Heat Transfer Fluid
K	Incidence Angle Modifier
L_P	total length of connecting pipes (m)
LFR	Linear Fresnel Reflector
n	refractive index
N_R	number of rows of a solar field
P_L	pipe length (m)
P_W	pipe width (m)
PT	Parabolic Trough
q_{elec}	instantaneous electric energy produced
R	circular receiver
r	radius of the circular receiver
SMS	Simultaneous Multiple Surface
T_{in}	temperature of the HTF at the entrance of the receiver tube (°C)
T_m	mean temperature of the HTF (°C)
T_{out}	temperature of the HTF at the exit of the receiver tube (°C)
T_w	working temperature (°C)
U	etendue
w	wave front

Greek characters

η_S	steam conversion efficiency
η_T	turbine conversion efficiency
η_{opt}	optical efficiency
θ	half acceptance-angle (°)
θ_Z	solar zenith angle (°)
φ	rim angle (°)
φ_S	solar azimuth angle (°)

(smaller CPC secondary) and a Fresnel XX SMS concentrator (large secondary).

These large secondary mirrors have two major drawbacks: (1) they produce a lot of shading over the primary field and (2) it may be more difficult to manufacture and use them in practice. Point (1) above is especially true for LFR concentrators with SMS second stage concentration (Canavarro et al., 2013b), since, in this case, the secondary mirror is fixed and, therefore, as the sun moves in the sky the shading of the secondary will go over the entire primary field, hence decreasing the efficiency of the concentrator. In PT-type concentrators this may not be particularly problematic, since in this case all the optical elements track the sun as a whole, but, on the other hand, it might cause some mechanical-tracking problems due to size of the secondary.

A possible alternative is to use the Winston–Welford design method, also known as the flow-line method (Chaves, 2016; Winston et al., 2005) (smaller CPC secondary in Fig. 1). The optics generated with this method can be more compact but with lower *CAP* values than the SMS ones. Therefore, a possible solution is to combine the two methods and design a "hybrid" concentrator, an in-between solution aimed for higher *CAP* values than the flow-lines concentrators and with less shading losses that the SMS concentrators.

One possibility is to design a CEC-type (Compound Elliptical Concentrator, CEC for short) concentrator for a continuous primary (parabolic-type). The reason for a continuous primary is mainly related with the design process. It is usually easier to design new optical solutions for a continuous primary than for other configurations, such as Fresnel primaries. Plus, since PT is the most common technology for CSP (Concentrated Solar Power) today (Crespo, 2011) it makes sense to start with the design of a concentrator of that type and compare its performance with the conventional configurations.

Given that all linear concentrators for CSP, of whatever type, are designed for the same 70 mm diameter receiver tube within a glass envelope (a sort of practical market imposed standard), for the sake of comparison, the choice in this paper is to develop a new CEC concentrator for the same evacuated tube with the same acceptance angle as in Canavarro et al. (2013a, 2013b, 2014) and compare the new concentrator both with a generic PT concentrator representative of present day PT technology (Kearney, 2007) as well as with the XX SMS concentrator (Canavarro et al., 2013a). The comparison will be made in terms of several different param-

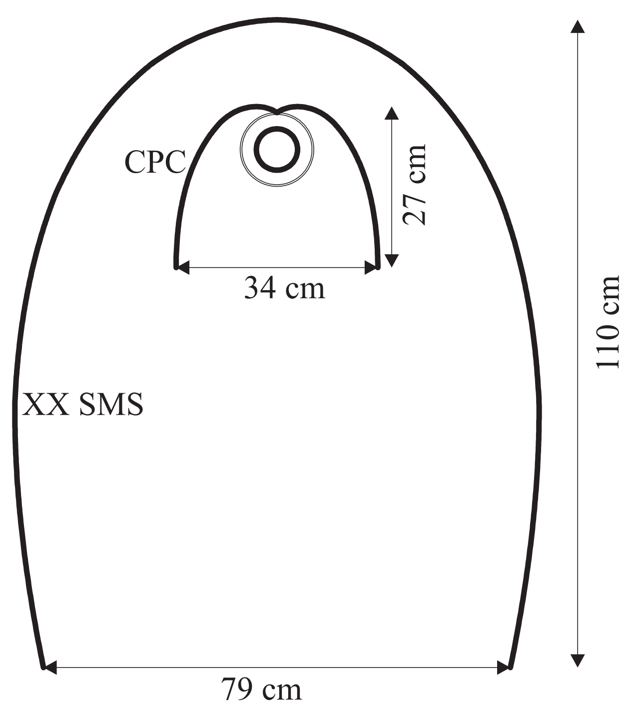

Fig. 1. Comparison of dimensions between a CPC secondary and a XX SMS secondary for a Fresnel primary and a tubular receiver of 70 mm. Both optics have an acceptance-angle of 0.44° but different concentration (*CAP*) factors: 73.71× and 50.13× for Fresnel XX SMS and Fresnel CPC, respectively.