



Improving the concentration ratio of parabolic troughs using a second-stage flat mirror



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HIGHLIGHTS

- A secondary flat reflector is added to commercial parabolic troughs.
- Theoretical derivations and ray tracing used to size and position the absorber.
- Concentration ratio increases up to 80% can be achieved for current collectors.
- New flux distributions around the absorber are calculated.
- The use of flat secondary reflector will increase the plant efficiency.

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ABSTRACT

Increasing the concentration ratio of parabolic troughs is one of the challenges to make this technology economically competitive against fossil fuels. Parabolic troughs with large concentration ratios face several problems such as difficulty capturing all the solar direct radiation and structural issues associated with thermal expansions and wind resistance amongst others. For larger mirrors it may be necessary to use a bigger absorber in order to capture all the radiation, thus increasing the thermal losses. A second stage reflector helps to increase the concentration ratio without increasing the primary mirror size. In this work, a theoretical analysis of a parabolic trough with a secondary flat reflector is developed and ray tracing is conducted in order to validate the equations obtained. A flat reflector will have a minimal economic impact in the cost of a parabolic trough and it allows larger concentration ratios for identical primary mirror areas compared to a standard parabolic trough. Increases of concentration ratio up to 80% are observed when a secondary flat reflector is inserted in a commercial system, while the shadow area introduced in the primary mirror is usually less than 15% of the primary mirror area. The increase in pumping power is offset by the increase in system efficiency.

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1. Introduction

Out of all the concentrated solar thermal power technologies, parabolic trough collectors (PTC) are the one most mature, and the closest to being competitive in the electrical market. There are some commercial examples running now for more than 20 years, such as the SEGS plants in the Mojave desert [1]. Thus PTCs are a reliable technology, especially when compared to other concentrating solar technologies [2] which is why most of the worldwide solar concentrating power plants are built with this technology. As an example, in Spain, the country where most solar

concentrating power plants are built, 94% of the already installed power and most of the projected plants use this technology [3]. Nevertheless, a cost reduction is mandatory for PTC plants in order to be a competitive alternative for cheaper production methods such as fossil fuel, hydroelectric or nuclear power plants. Even photovoltaic and wind energy are currently cheaper energy sources [4–7].

Geometrically, a parabolic mirror is a reflective surface obtained from the extrusion of a parabola along an axis. An interesting property of these mirrors is that they concentrate the sun's rays into their extruded focus if its aperture area (A_p) is perpendicular to the solar radiation. A typical PTC plant is composed of several rows of parabolic mirrors that concentrate the beam radiation into a cylindrical absorber placed along the focus line of the mirrors while tracking the sun. Normally, inside this tube, there is a heat

Abbreviations: CPC, Compound Parabolic Concentrator; PTC, parabolic trough collector; PV-T, PhotoVoltaic-thermal.

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Nomenclature

a	distance from the secondary reflector to the centre of the absorber (mm)	$r_{x,y}$	radius of the absorber needed to capture rays x and y (mm)
b	distance from the centre of the absorber to the imaginary intersection of the reflected ray and the symmetry axis (mm)	X	half aperture width of a parabolic mirror (mm)
A_{absorber}	absorber's area (m^2)	W	aperture width of the parabolic mirror (mm)
A_p	aperture area of the parabolic mirror (m^2)	W_s	width of the projected shadow (mm)
A_x	half aperture of the parabola (mm)	W_{s1}	shadow projected by a secondary mirror formed from the parabola's edge ray with a deviation of $-\theta$ (mm)
C	concentration ratio of a classic PTC (–)	W_{s2}	shadow projected by a secondary mirror formed from the parabola's edge ray with a deviation of $+\theta$ (mm)
C'	concentration ratio of a PTC with secondary flat mirror (–)	x_i	horizontal distance of a point of the parabola to the focal line (mm)
d	diameter of the absorber for a classic PTC (mm)	y_i	vertical distance of a point of the parabola to its focus (mm)
d'	diameter of the absorber for a PTC with secondary flat mirror (mm)	Y	height of the parabola ($Y = F$ for the origin point of the parabola) (mm)
$d_{m,f}$	distance of ray m to the focus of the parabola when it goes through the symmetry axis of the parabola (mm)	<i>Greek characters</i>	
$d_{mr,f}$	distance of reflected ray m to the focus of the parabola when it goes through the symmetry axis of the parabola (mm)	α	sun's shape semi-angle = 0.266°
F	focal distance (mm)	θ	half acceptance angle ($^\circ$)
k	constant	σ	scattering ($^\circ$)
L	length of the collector (mm)	ψ	rim angle ($^\circ$)
r	radius of the absorber for a classic PTC (mm)	ρ	reflectivity (%)
r'	radius of the absorber for a PTC with secondary flat mirror (mm)	<i>Subscripts</i>	
		x	ray
		xr	reflected ray

transfer fluid that absorbs the thermal energy. The heated fluid can be used in an industrial process; however more commonly it is used to generate steam that feeds a Rankine generator to generate electricity [8]. Some alternatives such as using CO_2 in the Rankine cycle have been attempted [8,9] and also air [10]. For all the applications it is desirable either to obtain the highest output temperature possible, although with higher temperatures the heat losses increase [11,12], or to achieve a fixed temperature for applications such as solar cooling. If the collector's efficiency is increased, a smaller mirror field could be sufficient to achieve the target temperature. In order to minimise the losses, the heat loss area of the absorber should be as small as possible. However, the pressure drop is higher in smaller absorbers with the same flow rate, and thus more pump energy is required. If the pressure drop increases too much, the pumping power required could influence the viability of the field. This effect, while not in the scope of this work, has been addressed and for the absorber diameter variations discussed in this paper it does not affect our conclusions. Details will be given in future publications. A secondary reflector placed somewhere near the absorber can be used in order to further concentrate the solar radiation. Several attempts of second stage reflectors for PTCs [13–17] have included complicated secondary mirror geometries that, while increasing the concentration ratio considerably, did not become practical solutions due to the difficulty for manufacturers in building them at a competitive cost. Recent work states the potential improvement of secondary reflectors in PTC and analyses geometries previously investigated [18].

A new method for the design of the secondary mirror has been carried out by [19]. They emphasise increasing the primary mirror area as much as possible while maintaining the receiver as small as possible. They also state that some of the present limitations of the second stage solutions are that the absorber sometimes touches the secondary mirror, increasing the thermal losses, or that they

can even introduce a new optical loss due to the necessity of accommodate the gap between the secondary reflector and the absorber (gap losses) [20].

In this paper, a flat secondary reflector is studied as a solution to increase the geometrical concentration ratio of several commercial PTCs maintaining the range of deviations and misalignments that the systems can handle. The flat second stage mirror could be a practical and cost-effective solution to increase the concentration ratio of the collectors. The cost of installation of PTCs can be decreased if the concentration ratio is increased but the ground usage and structures, tracking systems and primary mirrors remain the same. This method can be used for new designs as well. However, the objective of this work is to analyse the theoretical gain of using a secondary reflector. Further work will include a full cost analysis.

As an additional advantage, the secondary flat reflector helps to distribute the energy flux around the tube more evenly than with a classic PTC where all the concentrated flux falls on one side of the receiver tube. This better flux distribution could help to minimise the deflections and the stress of the absorber tube due to different thermal expansions [21] and could also stabilise internal two phase flow and pressure drop. Also, a reduction of the absorber dimensions and the local maximum temperature will reduce the thermal losses.

Unlike other studies using secondary reflectors in linear absorbers [15,19], in this work the absorber is not located on the parabola focus because the secondary reflector is placed on it. As a consequence, the absorber has to be located on a place near the focus, not on it. The new location of the absorber is chosen to ensure there is no thermal short-circuit between it and the second-stage reflector, while not producing gap losses due to the distance between these two components. In Fig. 1 a schematic of a PTC with a secondary flat reflector with gap losses is shown.

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