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New optical designs for large parabolic troughs

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Abstract

The potential for cost reduction in parabolic troughs (PT) large collector fields is real and can be achieved by a variety of different ways. One problem certainly contributing to the costs of PT-STE fields is certainly the fact that large fields have a significant quantity of receiver lines and pipes bringing the heat transfer fluid to and off from them. The very large pipe length in large collector fields (for instance the 50MW fields in Spain) is a source of heat losses and parasitic losses due to significant pumping power, but also a source of other costs related to the number of pumps, to the amount of (costly) circulating fluid) etc. In any given large field, receiver length and pipe length are determined by the aperture size of the PTs and one way to reduce these impacts on cost would be to increase aperture size. This has been the idea behind developments like the Ultimate Trough [1]. In this paper we present and propose new optical solutions to obtain much larger troughs, using the same standard evacuated 70mm inner radius tube, which in fact amounts to a substantial increase of concentration [2], but without sacrificing the acceptance angle of the optic. The SMS method [3,4] is used and practical solutions are obtained for apertures nearly close to twice the present standard of ~ 6m width.

The solutions developed minimize transmission losses due to the glass cover and in that sense are an improvement on previous work [5].

They also achieve a higher optical performance than other second stage solutions, because they are designed to eliminate optical losses through large gaps, something that is associated with the fact that the outer glass envelope has a much larger diameter than the inner – receiver – tube.

The paper will explain the first concept and present examples, together with the energy collected on a sunny location (Faro, Portugal) in comparison with that of a standard PT, as for the fixed receiver concept.

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1. Introduction

Perhaps the major concern with STE technologies today is the drive towards lower kWh production costs. This objective can be achieved in a variety of ways, for each one of the main existing technologies.

The most used today is still based on parabolic troughs (PT) – 94% of all STE power solar already installed in Spain are of the PT type [6]. Cost reduction in PT fields can be achieved on the collectors, the balance of the field (investment cost – Capex) but also on O&M (Opex cost). In the following paper, we propose and discuss solutions which have a potential for cost reduction in all of these fronts, using larger troughs. Perhaps the main drive for larger troughs can be appreciated by the fact that, for the same amount of total field installed power, they would significantly reduce the number of receiver tubes, connecting pipe length, number of pumps and heat transfer fluid volume (see Fig.1). Pipes are directly associated with heat losses, pumping power losses, i.e. a string of operating and maintenance aspects that will also be reduced by a reduction of the necessary pipe length. Receiver tubes are a costly item and have failures, whose impact will also be reduced if their number is smaller.

Fig. 1. View of pipes in a 50 MW PT field (Spain).

Larger troughs have already been proposed [1], but without taking full advantage of the possibility of increasing concentration to the limits allowed by non-imaging optics or conserving (even enlarging) the trough acceptance angle for the incoming radiation. In this paper we present and propose new optical (SMS – Simultaneous Multiple Surface) solutions to obtain much larger troughs, using the same standard evacuated 70mm inner radius tube, which in fact amounts to a substantial increase of concentration [2], but without sacrificing the acceptance angle of the optic.

Another potential weakness is the fact that troughs track solidary with their respective tubular receivers. This means that there is need for flexible hosing or for rotating joints at the beginning and at the end of which row. If a fixed receiver solution can be developed this would eliminate the need for these moving joints, again with a potential positive impact on costs.

In the present paper we present fixed receiver solutions, also resulting in larger troughs with higher concentration [7] designed for the same 70mm standard evacuated tubes, simultaneously obtaining larger aperture troughs and a tracking strategy not dependent on moving joints, a solution which may well be useful for trough manufacturers seeking a total cost reduction. The new optics developed and presented will be of two different types: an infinitesimal etendue/ aplanatic type and an SMS type.

The paper will end with a performance comparison for Faro, Portugal, between a standard PT trough and the new solutions presented.

Nomenclature

θ	half-acceptance angle (deg)
φ	rim angle (deg)
η_{opt0}	optical efficiency at perpendicular direction
C_g	geometric concentration (X)
f_H	size factor
$\mathbf{G}_C$	center of gravity (m)
CAP	concentration-acceptance product
d.n.i	direct normal irradiance (kWh/m^2)

2. Large troughs

The starting point for the concept presented here is the fact that, at present, the standard evacuated tube on the market has 70mm diameter and a glass envelope with a diameter between 120 and 130mm [8].

Other tube diameters have been considered/ proposed but are not available on a commercial basis at the same cost. Thus, if larger aperture troughs are to be developed today it must be for larger concentration values. This, in turn, if done with focusing/imaging optics will result in a smaller acceptance angle [1,3].

However if non-imaging optics [3] is called upon to provide another solution it is possible to increase concentration without sacrificing the acceptance angle (something important since it would not sacrifice the intercept factor achieved by present day troughs), or even achieve higher concentration for an even larger acceptance angle.

The price to pay is the introduction of a second stage concentrator, achieving perfect coupling of the etendue captured by the primary and the etendue captured by the receiver.

A second stage concentrator must be placed outside the evacuated tube (inside it would get too warm and cause a number of intractable practical problems).

This, in turn, generates another problem, that resulting from the large gap between receiver tube and outer glass envelope.

Large gaps in etendue matched second stage concentrators are nicely handled by the so called SMS design method (with the extra letters XX to designate that two reflectors – primary and secondary – are utilized) [3,4,5]

An XX SMS solution was developed and presented in [5] for tubular receivers, without glass envelopes; therefore it suffers from Fresnel losses resulting from light going several times through a glass envelope (see Fig. 2 (a)).

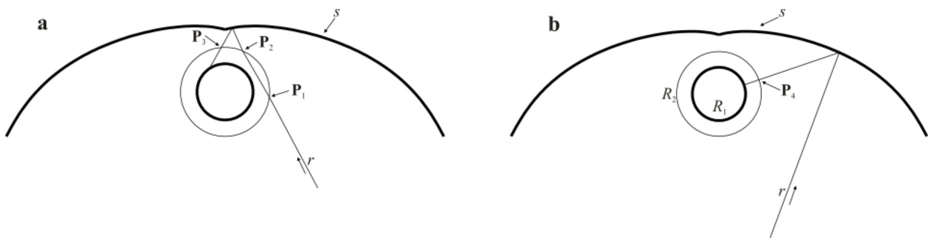

Fig. 1. (a) schematic representation of a second stage concentrator with light going several times through a glass envelope; (b) schematic representation of a second stage concentrator with light going only once through the glass envelope.

In the present paper we present an XX SMS optic with light going through the glass envelope just once as schematically shown in Fig. 2 (b). [2]

The solution proposed is shown in Fig. 3.

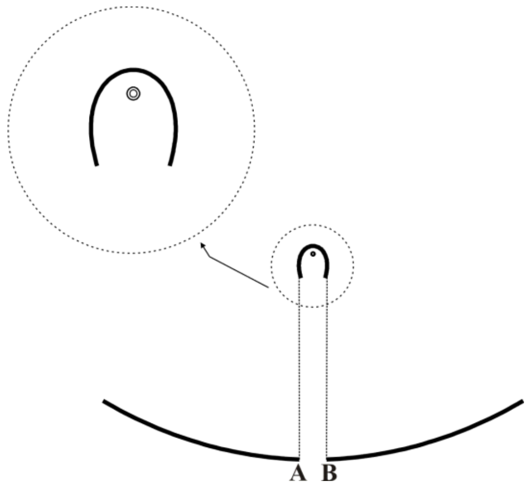

Fig. 3. XX SMS optic for an evacuated tubular receiver, designed for a large gap and with light going only once through the glass envelope. The gap [**A**,**B**] between the two sections of the primary is optimized in order to avoid shading losses from the secondary concentrator.

In Table 1 the characteristics of one possible XX SMS solution for the 70 mm evacuated tube are presented . A conventional, standard trough of 5.77 m aperture area is also presented for comparison. Both are designed for the same half acceptance angle θ=0.694 (i.e. a little below 3 sun-widths – 0.27deg).

Table 1. Comparison results between PT and XX SMS.

	η_{opt0}	C_g	CAP	ϕ (deg)	Aspect Ratio (Height/Width)	Aperture width (m)	Mirror length (m)
PT	0.81	26.24	0.32	80.3	0.30	5.77	6.40
XX SMS	0.72	50.38	0.61	55	0.51	11.08	11.71

Table 2 summarizes the material properties assumed for the calculation above.

Table 2. Material properties.

	Reflectivity	Absorptivity	Transmissivity
Mirrors	92% [9]	-	-
Receiver Tube	-	95% [8]	-
Glass Cover	-	-	96% AR-coated glass tube [8]

As can be seen it was possible to achieve an entrance aperture nearly twice as large as the standard PT and an overall optical performance CAP [4], much closer to the limit of 1. The optical efficiency at normal incidence is larger in the case of the standard PT, mainly because there is on average one less reflection (no secondary).

In terms of energy delivered (optical performance only) a calculation was done with hourly d.n.i. data for Faro, Portugal [2]. In Table 3 the results are summarized.

Table 3. Performance comparison.

	d.n.i (kWh/m^2)	Collected Energy same vacuum tube (kWh)[2]
PT	2234	7526.56
XX SMS		12739.23

As can be seen the XX SMS solution is able to deliver 1.71X more energy per row as the standard solution, reducing by about a factor of 2 the number of receivers, pipes, pumps, heat transfer fluid volume and all the losses associated with them.

3. Fixed receiver troughs

One of the problems facing parabolic troughs of today is the fact that each trough and its associated receiver track together the apparent motion of the sun, creating the need for flexible hosing or rotating joints to connect them to the fixed piping transporting the Heat Transfer Fluid (HTF). This results in mechanical and thermal stresses increase O&M costs and in the vulnerability of the full collector field.

What if only the mirror tracks and the receiver is left fixed?

Standard troughs, are designed for maximum concentration and that means a rim angle close to 90 deg.[4,7] . This results in a center of gravity for the trough + receiver, ending far from the receiver center, the place where it should be if a simple/balanced/light mechanical tracking system was to be implemented for a fixed receiver.

Concentration for a standard PT is given by eq.(1) (see also Fig. 4) where θ is the half design angle for the radiation incident on the aperture and φ is the rim angle of the parabola); the highest concentration happens, for any given half-acceptance angle θ, when φ is close to 90º.

$$C_{Par} = \frac{\sin\varphi}{\pi \sin\theta} \tag{1}$$

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[1] For a receiver of 70 mm of diameter.

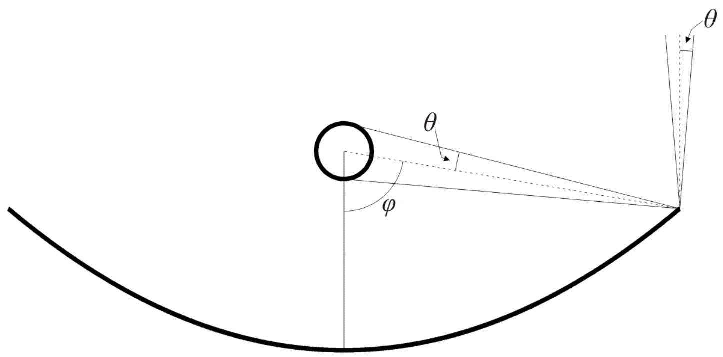

Fig. 4. A standard PT designed for a tubular receiver.

To bring the center of the receiver to the center of the tube (focal point in the case of a PT) one needs to extend the parabola well beyond 90°, and have rim angles above 110° or even 120°, resulting in a larger aperture trough.

Again the standard tubular receiver has 70mm diameter and therefore, to keep the same concentration, second stage concentration optics must be used. Also, and as in (II) before, there is a glass envelope and a large gap, and the solution should take that into consideration just as was done and explained there.

In this paper we present two possible solutions, where again the concern was with obtaining higher concentration, conserving the same accpetance angle and doing so as close to the limits as possible:

- The first is based on the theory of aplanatic optics, apllied to tubular receivers which is designated by infinitesimal etendue limit optics.
- The second based on SMS theory as before.

The first option leads to a simpler design and, for acceptance angles below 20 mrad it has been shown [10] to yield a result very close to what would be the ideal SMS approach. It can be already apreciated that a good portion of the dificulty of these designs is that now, the second stage concentrator tends to stand in the way (blocks) the radiation refelcted off the primary; therefore “gaps“ must be created on the secondary mirror for the radiation to go through.

The second option is a true SMS , which used the first solution as the basis for its full devellopment, simplifying the search for a final solution.

Both can be seen in detail in [7]. They have in common the fact that they extend to a much larger rim angle, as a way to bring the centre of gravity, and center of tracking axis to the center of the receiver tube.

It is not the ojbect of this paper to present a solution which would exactly do that, since this would depend on practical manufacturing constraints which we do not posess.

Fig. 5 shows the XX SMS optic with a center of gravity at point $\mathbf{G}_C$ obtained through the infinitesimal etendue limit.

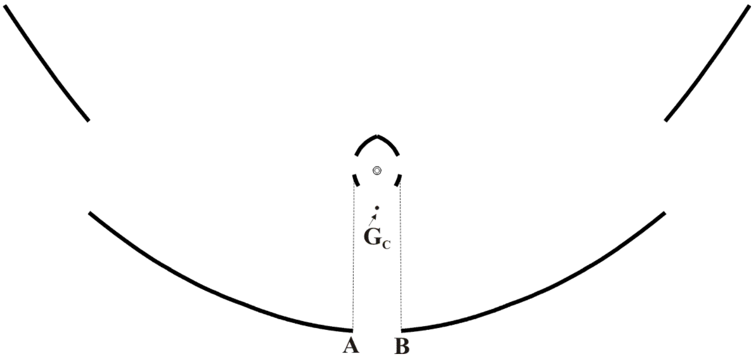

Fig. 5: The XX SMS with a center of gravity at point $\mathbf{G}_C$. Once again the gap [**A**,**B**] is optimized to avoid shading losses produced by the secondary concentrator.

Again a performance comparison can be made of both solutions against a standard PT, using the same characteristics as in Tables 2 for all cases.

Table 4 and 5 summarizes the results obtained.

Table 4. Comparison between the PT, XX SMS and XX infinitesimal etendue concentrators.

	Aperture width (m)	Mirror length (m)	Receiver radius (m)	$\mathbf{G}_C$ (G_x, G_y) (m)	f_H	φ (º)	C_g(X)	θ (º)	CAP	η_{opt0}
PT	5.77	6.40		(0,-1.27)	1.06	80.3	26.24	0.694	0.32	0.81
XX SMS #1	8.63	10.87		(0,-0.41)	0.10	112.92	39.24	0.784	0.54	0.65
XX SMS #2	10.84	13.63	0.035	(0,-0.58)	0.11	113.15	49.29	0.604	0.52	0.67
XX Infinitesimal etendue #1	8.62	10.86		(0,-0.41)	0.10	112.91	39.20	0.722	0.49	0.69
XX Infinitesimal etendue #2	10.84	13.60		(0,-0.58)	0.11	113.15	49.29	0.542	0.47	0.69

Table 5. Comparison of collected energy in Faro, Portugal.

	d.n.i (kWh/m^2)	Collected Energy same vacuum tube (kWh)[3]
PT		7526.56
XX SMS #1		8953.79
XX SMS #2	2234	11649.87
XX Infinitesimal etendue #1		9353.48
XX Infinitesimal etendue #1		11927.05

As can be seen it is possible to design troughs for a fixed receiver that will deliver more energy per trough than the standard PT, operate with a fixed receiver and again reduce the number of rows (and pipe length, etc.) for a given nominal capacity field.

h_R is an adimensional factor (see Fig. 6) and it relates the position of the center of gravity of each optic with its geometric dimensions. It is given by:

[3] For a receiver of 70 mm of diameter.

$$f_{\mathrm{H}} = \frac{a}{b} \quad (2)$$

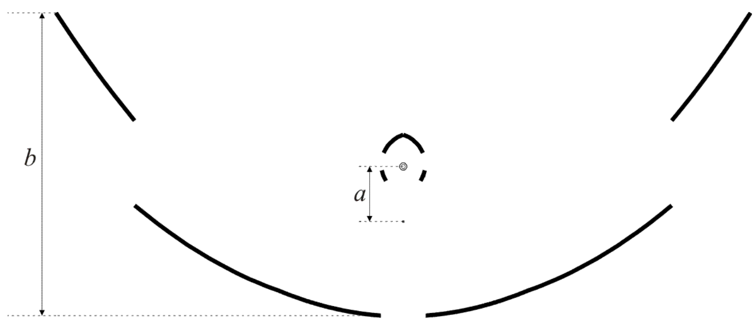

Fig. 6: Definition of f_{H}

4. Conclusions

In this paper several solutions were presented with the potential of cost reduction in the field of PT technology. The word potential is used explicitly because the paper does not attempt at calculating to the end (i.e. for manufacture) the solutions presented.

A potential seems to exist associated with substantial reduction in the number of rows in a given solar collector field, for the same energy delivery, if larger aperture troughs are used.

Lower investment costs are possible as well as lower O&M costs, as explained.

The price to pay for these new solutions is the existence of a second stage concentrator, but its cost might be well diluted on a per sqm cost basis.

Two solutions for a fixed receiver, an option which eliminates one of the potential problems of PT fields associated with rotating joints or flexible hoses, were also presented.

The paper presented a comparison of the performance (before heat losses) of all the solutions presented against the performance of a standard parabolic trough, in the same sunny location, Faro, Portugal. All troughs were designed for the same acceptance angle and for the same evacuated tubular receiver.

These results allow for a first round of calculations around potential cost reductions in any given situation, since the different troughs, with their different costs , associated receivers, pipe length and other components in a given field, can be compared in terms of energy delivery.

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