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Improving the performance of a 2-stage large aperture parabolic trough solar concentrator using a secondary reflector designed by adaptive method

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Abstract

In this study, the efficiency of a large aperture 2-stage parabolic trough concentrator (PTC) is improved using an innovative design method for the secondary reflector (SR). The design method is based on an adaptive approach in which the SR is step-wise optimized to maximally reflect back to the absorber tube (AT) the part of solar radiation reflected by the primary reflector (PR) but not captured by the AT. The adaptive design method results in a SR design which consists of several parabolas with different focal lengths, each having a focus which lies in the focus of the PR. This ensures that the originally unabsorbed solar radiation will now hit the surface of AT. The optical efficiency of the PTC could be increased by 5.2% and thermal efficiency by 4.9%, respectively, compared to a case without optimized SR. In addition, the uniformity of the solar radiation flux on the AT's outer wall could be doubled, its temperature was more even, but also the pressure on the back of the PR could be reduced. The new adaptive design approach of the SR could help to better optimize PTC systems.

Keywords: parabolic trough concentrator; secondary reflector; adaptive method; optical efficiency;

thermal efficiency; pressure

Nomenclature

Symbols		θ	absorber tube circumferential angle, °
C_1, C_2, C_u	constants for the realizable k- ϵ turbulence model	ρ_r	reflecting of the collector mirror
C_p	specific heat capacity, Jkg ⁻¹ K ⁻¹	ρ	density of HTF, kg m ⁻³
DNI	direct normal irradiance, Wm ⁻²	σ_{spec}	mirror specularity error, mrad
D	inner diameter of the absorber tube, m	σ	Stefan Boltzmann constant, Wm ⁻² K ⁻⁴
D_{abs}	outer of the absorber tube, m	$\sigma_k, \sigma_\epsilon$	Prandtl number for the transport of turbulent dissipation rate, ϵ/k
D_{gla}	diameter of the glass cover, m	σ_T	Prandtl number for energy
E	heat flux, Wm ⁻²	τ_{gla}	transmissivity of the glass cover
f_i	focal length of each parabola, mm	ω_i	angle of the distance (h_i), °
f	focal length of PR, m	ζ_{abs}	absorptivity of the selective coating
G_k	generation of turbulent kinetic energy due to mean velocity gradients, kgm ⁻¹ s ⁻³	Subscripts	
h_i	distance from the intersection point to the origin point, mm	aft	after
h_{a-g}	convective heat transfer coefficient, Wm ⁻² K ⁻¹	abs	absorber tube
L	length, m	a	ambient temperature
M	primary reflector aperture width, m	ave	average
N	uniformity, %	gla	glass cover
P_r	Plante number	in	inlet conditions
Q_u, Q_{loss}	heat absorbed and lost, W	max	maximum
T	temperature, K	min	minimum
u, v, w	x, y, z velocity components, ms ⁻¹	opt	optical
x, y, z	Cartesian coordinates	out	outlet conditions
Greek letters		s	sky conditions
α	half acceptance angle, °	th	thermal
β	rim reflection ray angle, °	Abbreviations	
ϵ_{abs}	emissivity	AR	Absorber tube
γ	angle interval, °	CSP	concentrating solar power

$\eta_{\text{opt}}, \eta_{\text{th}}$	optical and thermal efficiency, %	HTF	heat transfer fluid
φ	the half rim angle, °	PTC	parabolic trough concentrator
λ	thermal conductivity, $\text{Wm}^{-1}\text{K}^{-1}$	PR	Primary reflector
μ	dynamic viscosity, N s m^{-2}	SR	Secondary reflector

1. Introduction

Solar energy is a promising clean energy technology, which can help in reducing fossil-fuel consumption and carbon emissions [1-2]. Though photovoltaics is at present the most popular solar technology, concentrating solar power (CSP) technologies have also received attention as these can be accompanied with heat storage and could better ensure dispatchable operation. There are several types of solar concentrators [3] available, but the parabolic trough concentrator (PTC) is the most popular standing for almost 90% of all CSP systems [4]. The cost of energy produced with PTCs is still much higher than that of fossil-fuel based power plants [3]. Strategies to improve the cost-effectiveness include using large aperture or high-concentration ratio systems. These have several advantages such as shorter solar concentrator assemblies, which reduce the amount of drives and controls. Moreover, the higher the concentration ratio, the more useful energy the system can produce [3]. Typical concentration ratios of PTCs are presently above 100 [5, 6]. In order to ensure that light is maximally captured by the absorber tube (AT) of the concentrator, a secondary reflector (SR) is essential in large aperture PTCs forming then a so-called 2-stage concentrator. Adding a SR could also increase the concentration ratio and rim angle [7-11]. A state-of-the-art 2-stage large PTC with a Compound Parabolic Concentrator (CPC) SR has reached a 63% optical efficiency and a 40% thermal efficiency at 650 °C [8, 9]. Also, flat plate mirrors have been used as SR with the center line of the SR located in the focus of the PR [12-15], but yielding a much lower maximum solar concentration ratio (55 suns) than a traditional system without SR (151 suns) [13]. A SR constructed of multi-piece mirrors forming a hyperbolic-shaped reflector, but now with the AT in the focus of the SR far away from the PR, could yield an optical efficiency of 76% and a thermal efficiency of 23% [16]. A somewhat similar design demonstrated a high concentration ratio, but also multiple reflections which could increase the optical losses [17-18], though the heat flux density on the absorber may be more even [19-20].

The state-of-the-art design of the SR in a 2-stage large aperture PTC as described above often has

the AT in the focus of the SR far away from the focus of the PR, which leads to multiple reflections of the sun-rays before hitting the absorber [21] and reduces the optical performance [17-20]. In addition, the absorptance of the tube is angle-dependent and in above designs the light could hit the tube at larger angles leading to additional losses, compared to zero incidence angle which gives the best absorptivity [22]. The present study strives to reduce these loss components by using a novel adaptive method to design the SR. In this design, the AT is located in the focus of the PR contrary to traditional designs. The unabsorbed solar radiation from the PR is reflected back by the SR vertically (0°) on the AT. Such a design could therefore lead to reduced optical losses and hence to improved optical and thermal performance of the PTC. Both the SR design for the PTC and the method proposed for designing the SR in this paper show novelty compared to the state-of-the-art.

The paper is structured as follows. In Section 2, the new design approach for the SR is presented, followed by an optical analysis in Section 3 and a thermal analysis in Section 4 of the new design. Section 5 shows how the new design affects the pressure distribution on the reflector caused by the wind speed. The paper ends with Conclusions in Section 6.

2. Physical model

The principle of a 2-stage large aperture PTC system is shown in Fig.1. It is made up of a primary mirror (PR), secondary mirror (SR), and an absorber tube (AT). The foci of the primary and secondary mirrors coincide and the AT is located in that focal point. The light reflected by the PR is absorbed by the AT, and the part of light not captured by the AT is reflected back by the SR vertically on the AT.

Figure 1. Schematic diagram of a 2-stage large aperture PTC system.

The curve equation of the PR can be expressed as follows:

$$x^2 = 4fy \quad (1)$$

where f =focal length of the PR. The relationship of the aperture width (M), the focal length (f), and the half rim angle (φ) of the PR is the following [3, 23]:

$$f = \frac{M}{4 \tan(\frac{\varphi}{2})} \quad (2)$$

The relation between the half acceptance angle (α), the half rim angle (φ), and the rim reflection ray angle (β) is:

$$\beta = \pi/2 + \varphi - \alpha \quad (3)$$

To reflect back the light vertically to the absorber, which is not directly captured by the AT, a new adaptive approach to design the SR is proposed in this paper. In this approach, several parabolas

with different focal lengths are used, the foci of all parabolas being in the focus of the PR. The new approach is illustrated in Fig. 2.

Figure 2. Schematic diagram of the SR.

The focal length of each parabola of the SR is f_i and the direction of the focal length is $\beta-1/2\gamma-i\gamma$. The parabolic equation is the following based on Eq.(1):

$$x_i^2 = 4f_i y_i \quad (4)$$

The focal length (f_i) can be obtained from the following formula using Eq.(2):

$$f_i = h_i \frac{\sin(\beta - 0.5\gamma - i\gamma - \omega_i)}{2 \tan(\frac{\beta - 0.5\gamma - i\gamma - \omega_i}{2})} \quad (5)$$

The distance between the left end of the i^{th} parabola and the focal length is X_{i-L} :

$$X_{i-L} = h_i \sin(\beta - 0.5\gamma - i\gamma - \omega_i) \quad (6)$$

The distance between the right end of the i^{th} parabola and the focal length is X_{i-R} :

$$X_{i-R} = h_{i+1} \sin(\beta - 0.5\gamma - i\gamma - \omega_{i+1}) \quad (7)$$

where i stands for the running number of the parabola and starts at 0, L means left and R means right. As shown in Fig. 2, the intersection point is formed by intersecting of the light with an angle $\beta - \gamma$ and the parabola with a focal length of f_{i-1} . The distance from the intersection point to the origin point is h_i and ω_i is the angle of the distance (h_i).

The specific steps of designing the SR can then be summarized as follows:

Step 1: As shown in Figs. 1-2, the equation of the reflected light from the edge of the PR can be expressed as follows:

$$y = x \tan \beta + (f \tan^2(\frac{\varphi}{2}) + 2f \tan(\frac{\varphi}{2}) \tan \beta - f) \quad (8)$$

The intersection of the reflected light with angle β and the y-axis serves as the start point of the SR. The distance (h_0) between the intersection point and the origin (focus of the primary reflector) is:

$$h_0 = f \tan^2(\frac{\varphi}{2}) + 2f \tan(\frac{\varphi}{2}) \tan \beta - f \quad (9)$$

It is required that the absorber absorbs light in the angle interval γ , so the light from the center of the angle interval should be illuminated at the center of the AT. The angle of the first parabolic focal length is $\beta - \gamma/2$ and the focal length f_0 can be written based on Eq.(5) as follows:

$$f_0 = h_0 \frac{\sin(\beta - 0.5\gamma - \omega_0)}{2 \tan(\frac{\beta - 0.5\gamma - \omega_0}{2})} \quad (10)$$

where $\omega_0 = 90^\circ$. The first parabola can then be determined from Eq.(4) as

$$x_0^2 = 4f_0 y_0 \quad (11)$$

The distance (X_{0-L}) between the left end of the first parabola and the focal length can be determined from Eq.(6) as:

$$X_{0-L} = h_0 \sin(\beta - 0.5\gamma - \omega_0) \quad (12)$$

Step 2: For the second parabola with an angle interval of γ and reflected light from angle $\beta - \gamma$, the ray equation is as follows:

$$y = x \tan(\beta - \gamma) + [f \tan^2(\frac{\varphi - \gamma}{2}) + 2f \tan(\frac{\varphi - \gamma}{2}) \tan(\beta - \gamma) - f] \quad (13)$$

The ray with an angle $\beta - \gamma$ intersects with the first parabola, the distance between the intersection

point and the origin point being h_1 and the angle of the distance (h_1) is ω_1 . The angle of the second parabolic focal length is $\beta-3\gamma/2$ and the second parabolic focal length f_1 is then:

$$f_1 = h_1 \frac{\sin(\beta - 1.5\gamma - \omega_1)}{2 \tan(\frac{\beta - 1.5\gamma - \omega_1}{2})} \quad (14)$$

The second parabola is designed with the following equation:

$$x_1^2 = 4f_1y_1 \quad (15)$$

The distance (X_{0-R}) between the right end of the first parabola and the focal length can be determined from Eq.(7) as:

$$X_{0-R} = h_1 \sin(\beta - 0.5\gamma - \omega_1) \quad (16)$$

The distance (X_{1-L}) between the left end of the second parabola and the focal length can be determined from Eq.(6) as:

$$X_{1-L} = h_1 \sin(\beta - 1.5\gamma - \omega_1) \quad (17)$$

In an analogous way, the next parabola can be determined, and so on. The last parabola closes the loop. The resulting SR is shown in Fig. 2. The outer diameter of the AT can be obtained from the condition

$$D_{abs} \geq \max 2[f_0, \dots, f_i] \sin(\frac{\gamma}{2}) \quad (18)$$

3. Optical analysis

In the next, a case design of a SR is presented followed by an optical analysis. The PR used for the case has an aperture width (M) of 8m [3, 24] and a half rim angle (ϕ) of 50° . The half acceptance angle (α) is 0.5° [25], focal length (f) is 4.3m, and the angle interval (γ) is 5° . When the length of the parabolic trough is 10 m. The total area of the primary mirror is 80 m². The concentration ratio is 114.3. The angle of the focal length of the parabola constituting of the SR is:

$$\beta - 1/2\gamma - i\gamma = 137.5^\circ \quad (19)$$

Applying the adaptive design method, the SR is symmetrical and the half of it will constitute of 19

separate paraboloids whose parameters are shown in Table 1.

Table 1. Design parameters of the SR.

Running order, i	0	1	2	3	4	5	6	7	8	9
focal length	137	132	127	122	117	112	107	102	97	92
f_i (mm)	50	52	54	56	58	59	61	63	64	66
x_{i-L} (mm)	47	45	44	43	43	41	41	41	41	41
x_{i-R} (mm)	45	43	41	40	38	38	37	36	36	35
i	10	11	12	13	14	15	16	17	18	19
focal length	87	82	77	72	67	62	57	52	47	42
f_i (mm)	68	69	71	73	74	76	78	80	81	83
x_{i-L} (mm)	41	41	41	42	43	44	45	48	48	65
x_{i-R} (mm)	35	35	35	35	36	36	37	38	39	41

According to the design method provided in Section 2 and the data provided in Table 1, the first parabola is designed from the y-axis and the parabola behind is determined in turn. SR consists of 38 separate paraboloids, and the path of rays reaching the AT after the SR and without the SR in SolTrace ray-trace software is shown in Fig. 3.

Figure 3. An illustration of the SR design based on parameters in Table 1.

As shown in Fig. 3, the symmetrical distribution of SR consists of 38 separate paraboloids with different focal lengths. The focus of each parabola is located at the center of the AT, i.e. in the focus of PR.

The optical efficiency of the design is calculated using the SolTrace ray-trace tool [3], which is well suited to analyze complex solar optical systems [26, 27]. The geometric and optical parameters for

the design are given Table 2 [3]. Tracking parameters similar to the LS-3 PTC system are used [28]. A PTC with and without SR will be considered.

Table 2. Geometrical and optical parameters used for the optical efficiency analysis [3].

Parameter	Value
Inner diameter of the AT, D (m)	0.066
Outer diameter of the AT, D_{abs} (m)	0.07
Diameter of the glass cover, D_{gla} (m)	0.120
Collector aperture width, M (m)	8
Geometrical concentration ratio	114.3
Length, L (m)	4
Half rim angles with and without SR, ϕ ($^{\circ}$)	50, 80
Focal lengths of PR with and without SR, f (m)	4.3, 2.4
Absorptivity of the selective coating, ζ_{abs}	0.96
Reflectance of the collector mirror, ρ_r	0.97
Transmissivity of the glass cover, τ_{gla}	0.96
Mirror specular error, σ_{spec} (mrad)	0.5
Direct normal irradiance (DNI), (W/m^2)	1000

As the first case of the optical analysis, we compare the solar radiation flux on the surface of AT for a design without a SR and with an optimized SR. Fig. 4 shows the analysis results. The solar radiation distribution on the surface of AT is symmetrical, but shows several local maxima with the SR. At the center ($x=0$), the flux with SR is lower than without, but will be higher when moving closer to the edges of the absorber. This is well demonstrated by Fig. 5 which shows the solar radiation density as a function of the circumferential angle (for the model, see Supplementary Information S2).

(a)

(b)

Fig. 4. Solar radiation flux distribution on the outer wall of the AT. (a) Without SR, (b) with SR.

Figure 5. Distribution of solar radiation flux in the circumference of the AT.

Based on Figs. 4-5, the average solar radiation flux (E_{ave}) on the absorber of the PTC with SR is 271.6 kW/m^2 and the design without the SR comes slightly lower, or, 252.6 kW/m^2 . The optical efficiency (η_{opt}) of the PTC is calculated using the following:

$$\eta_{opt} = \frac{E_{ave} \times \pi \times D_{abs}}{DNI \times M} \quad (20)$$

which gives $\eta_{opt} = 69.4\%$ for the PTC without the SR and $\eta_{opt} = 74.7\%$ for the PTC with the SR, respectively.

The uniformity of the solar radiation flux on the AT can be calculated from the following equation [29-30].

$$N = 1 - \frac{\int_0^{\pi \times 0.035} |E_{\theta} - E_{ave}|}{\frac{\pi \times 0.035 \times \theta}{180} \times E_{ave}} \times 100\% \quad (21)$$

where θ is the circumferential angle of the AT, E_{θ} is the solar radiation flux at θ on the surface of AT. Using the circumferential distributions from the Supplementary in Eq. (21), the uniformity with the SR is 67.1%, while without the SR it is more than halved to 30.3%.

4. Heat transfer analysis

Next the impact of the SR design on the thermal performance using a heat transfer model described in Supplementary Information (SI).

First, the thermal efficiency (η_{th}) of the PTC was assessed. η_{th} is defined as follows:

$$\eta_{th} = \frac{Q_u}{DNI \times M \times L} \quad (22)$$

where Q_u is the heat absorbed by HTF, L is the length of absorber tube, M is the aperture width, and DNI is the direct normal radiation. The resulting thermal efficiency is shown in Fig. 7 for a HTF flow rate range of 0.1-4 m/s.

Figure 7. Variation of thermal efficiency and heat with flow rate.

As shown in Fig. 7, the thermal efficiency of the PTC and the heat absorbed by the HTF with the SR is higher than without SR, thus indicating an improvement in thermal efficiency when using a SR. The difference in the thermal efficiency is 4.9%.

The slight fluctuation of the thermal efficiency in Fig. 7 is due to the better heat transfer as the fluid velocity increases, i.e. the Reynolds number increases with the flow rate. Also, a higher flow rate would decrease the differences in the heat transfer temperature which also contributes to the fluctuation. Figure 8 shows the calculated maximum and minimum temperatures on the absorber tube verifying the above statement. It also shows that the temperature on the AT is lower at the outer wall when using a SR, which contributes to the better efficiency as well.

There is an increase of thermal efficiency at 2.5 m/s in Fig. 7. The main reason is that the heat

absorbed by the HTF is proportional to the convective heat transfer coefficient and inversely proportional to the temperature difference of the convective heat transfer. As the flow rate increases, the convective heat transfer coefficient increases and the temperature difference decreases resulting in an increase at 2.5m/s.

Figure 8. Maximum and minimum temperature on the outer wall of the absorber tube with flow rates from 0.1 to 4 m/s.

The circumferential temperature distribution on the absorber tubes is demonstrated in Fig. 9 for a 0.5m/s inlet flow rate, which indicates that the case with SR has a more uniform distribution. This is verified in Fig. 10 which shows that the maximum temperature difference with the SR is 13.4K and without the SR it is 18.4K, i.e. the maximum temperature difference is reduced by 5K. This difference, however, depends on the flow rate (see Fig. 11), i.e. at low flow rate it increases, but at higher rates the difference disappears.

Figure 9. Surface temperature of the absorber tube for a flow rate of 0.5m/s. (a) Without SR, (b) with SR.

Figure 10. Circumferential temperature distribution on the outer wall of the absorber tube. Flow rate is 0.5 m/s.

Figure 11. The variation of the maximum temperature difference with inlet velocity of the HTF.

5. Pressure distribution from wind on the concentrator

Next, the effect on the pressure distribution on the concentrator due to wind when using the SR was investigated using the numerical flow model (see Supplementary Information).

The geometries used for the load calculations were the following: PTC without SR had half rim angles of 80° and a depth of 1.678m; with SR 50° and 0.933m, respectively. The roughness on the back concentrator was 1.5mm. At high wind speeds, the concentrator is automatically turned so that the wind is perpendicular to the central axis of the concentrator and blows to the back [39].

The k- ϵ model was used to calculate the turbulence [39]; the element size in the fluid field is 5mm and thickness of first layer is 0.2mm in the inflation. Wang et al has shown that the larger the number of grids, the higher is the calculation accuracy [38]. Therefore, the mesh size in this paper is much smaller than reported in literature [39-40].

The maximum and average pressure on the parabolic concentrator from 6 to 22 m/s is shown in Fig. 12. At low wind speeds, the difference between a design with SR or without SR is negligible, but grows with increasing wind speed. For example at 14 m/s, the average and maximum (in brackets) pressure on the back of the PTC without the SR is 25061Pa (32675Pa at the edge on the concentrator), whereas with a SR it reduces to 20120Pa (25893Pa), which indicates improved load conditions with SR. The pressure distribution along the PTC in this case is illustrated in Fig. 13.

Figure 12. Average pressure on the PTC with wind speed.

Figure 13. Pressure distribution on the parabolic trough concentrator for 14 m/s. (a) Without SR, (b) with SR.

6. Conclusion

In this study, a novel adaptive method to design a secondary mirror (SR) for a large-aperture parabolic trough concentrator (PTC) was described. Using this new approach, both the optical and thermal efficiency of the PTC could be improved. The resulting SR consists of many parabolas with different focal lengths, the foci of all parabolas being in the focus of the primary reflector (PR) to guarantee that unabsorbed light hits the absorber tube.

The performance improvements and benefits through the SR design can be summarized as follows:

- SR improved the optical efficiency by 5.3% over a design without SR and the uniformity of the solar radiation flux on the absorber tube (AT) was improved by a factor of 2;
- SR improved the thermal efficiency by 4.9 % over a design without SR, but also improved the uniformity of the circumferential temperature on the AT;
- SR reduced the pressure on the back of the PTC caused by wind.

Though the design principle of the SR is seemingly more complex than traditional designs, the above performance improvements indicate that the new design approach could also lead to cost improvements of PTC.

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