Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 79 (2014) 258 – 262

Procedia Engineering

www.elsevier.com/locate/procedia

37th National Conference on Theoretical and Applied Mechanics (37th NCTAM 2013) & The 1st International Conference on Mechanics (1st ICM)

The design and optical analysis of compound parabolic collector

Chia-Wei Kuo[a,*], Pei-Shan Yen[a], Wen-Chey Chang[a], Keh-Chin Chang[b]

[a]*Energy Research Center, National Cheng Kung University, No.2500, Sec.1., Zhongzheng S. Rd., Guiren Dist., Tainan 71150, Taiwan*
[b]*Department of Aeronautics and Astronautics, National Cheng Kung University, No.1, University Rd., East Dist., Tainan 701, Taiwan*

Abstract

For various applications of solar thermal energy, the compound parabolic collector (CPC) is frequently used. To overcome the major limits of a traditional CPC, including a rapid increase in height for a larger aperture width and a low concentration ratio, a modified design was proposed in this paper. This research follows the recent study of Jadhav et al., which used only the region below the common focus of parabolas. Through optical analysis, a design modification was achieved by adjusting the vertical position of the receiver. From the results, setting the height of the receiver to 0.46 times the aperture width was found to permit a greater collection range of incident rays. In addition, a better method for evaluating the performance of the CPC was proposed using an intercept factor to account for the total reflection phenomenon caused by the receiver. By applying the approach to different cases of focal length, it was shown that the concentration ratio was not strongly affected by an increasing focal length owing to the low correlation between the concentration ratio and focal length.

Selection and peer-review under responsibility of the National Tsing Hua University, Department of Power Mechanical Engineering

Keywords: Compound parabolic collector; Optical analysis; Total reflection phenomenon; Concentration

1. Introduction

The compound parabolic concentrator (CPC) was designed to allow collection of large amounts of solar thermal energy. A CPC consists of two parabolas with compound rotation and is able to concentrate incident rays on a focal

* Corresponding author. Tel.: +886-6-3386501 ext. 215; fax: +886-6-3386503.
E-mail address: phxiranter@gmail.com

Selection and peer-review under responsibility of the National Tsing Hua University, Department of Power Mechanical Engineering
doi:10.1016/j.proeng.2014.06.340

region without a complex solar tracking system. However, there is a trade-off, wherein the height rapidly increases for a larger aperture width and a low energy concentration performance. Literature on this topic shows that several different designs have been proposed [1-5], each of which could successfully overcome these limits to a varying degree.

In 2013, the designs reported in the literature were further improved by Jadhav et al. [6]. Without compromising the concentration ratio (*CR*) defined in Eq. (1), the modified design used the region below the common focus of parabolas. In this case, the height of the CPC was only half the aperture width. This made fabrication and installation more achievable than previous designs.

$$CR = \frac{D}{\pi \times d} \tag{1}$$

where D is the aperture width and d is the diameter of the receiver.

In this paper, continuing upon the ideas of Jadhav et al. [6], a modified CPC is proposed through optical analysis. This design improvement is achieved by adjusting the vertical position of the receiver through optical analysis, to permit a greater collection range of incident rays. To account for the total reflection phenomenon caused by the receiver, an intercept factor is introduced for assisting in a better evaluation of performance of the CPC. From analysis, it can show whether the focal length will substantially affect the concentration ratio.

2. Modified design of CPC

The design of a modified CPC is shown in Fig. 1 (a), which is similar to that of Jadhav et al. [6]. The aperture width (D) is two times the height (H), i.e., $D = 2H$. The half-acceptance angle of the modified CPC is 1.5°. This is the rotation angle of the parabola with respect to its original axis of symmetry. For the receiver at point $\mathbf{P_3}$, a 40 mm diameter evacuated tube collector was selected. The coordinate of $\mathbf{P_3}$ will be discussed later. Optical analysis was accomplished using MATLAB®. Fig. 1 (b) shows the optical path in the CPC. The dashed lines in magenta represent the rays reflected by the wall of the CPC.

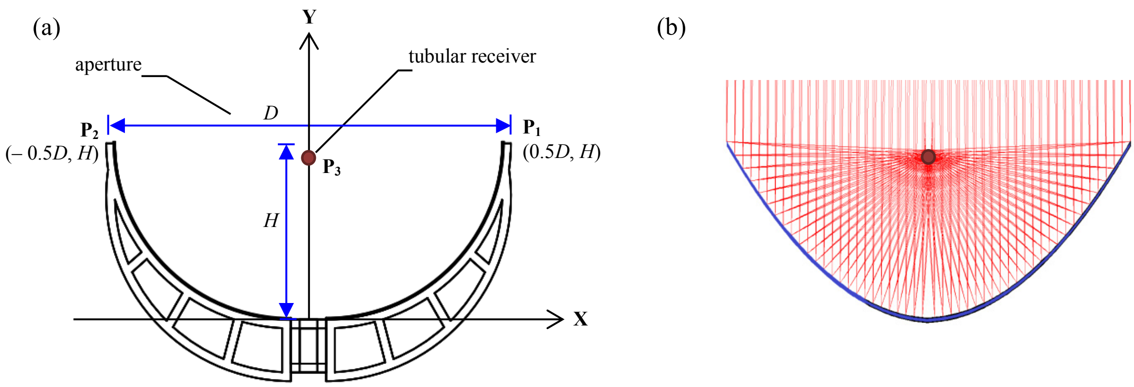

Fig. 1. Modified design of CPC in (a) sectional view and (b) optical analysis.

2.1. Vertical position of tubular receiver

In the original design of Jadhav et al. [6], the vertical position of the tubular receiver was equal to H (or $0.5D$). However, it is a question as to whether there is a design improvement. Thus, an optical analysis was performed based on a focal length of 0.5 m and a variable *H/D* ratio, as shown in Fig. 2. The analysis involved the comparison of the sum of the allowable incident angles with respect to the y-axis that could strike the receiver with or without reflection. As shown in Table 1, if the vertical position of receiver was 0.46*D* (i.e., 0.46 times the aperture width) a greater collection range of incident rays could be permitted. In other words, the optimal coordinate of point $\mathbf{P_3}$ was (0, 0.46*D*). Note that owing to the symmetry of the CPC, the analysis was also applicable to the –*x* situation.

Table 1. Sum of allowable incident angles that could strike the receiver with respect to y-axis.

H/D	The +*x* position of the CPC, between 0 and 0.5*D*				Sum of allowable incident angles
	0.01*D*	0.17*D*	0.33*D*	0.49*D*	
0.45	0°–1.5°	0°–1.5°	0°–1.5°	0°–1.1°	5.6°
0.46	0°–1.5°	0°–1.5°	0°–1.5°	0°–1.5°	6.0°
0.47	0°–1.5°	0.3°–1.5°	0°–1.5°	0.3°–1.5°	5.4°
0.48	0°–1.5°	1.1°–1.5°	0.3°–1.5°	0.3°–1.5°	4.3°
0.49	0°–1.5°	1.1°–1.5°	1.1°–1.5°	1.1°–1.5°	2.7°
0.50	0°–1.5°	0	0	0	1.5°
0.51	0°–1.5°	0	0	0	1.5°
0.52	0°–1.5°	0	0	0	1.5°

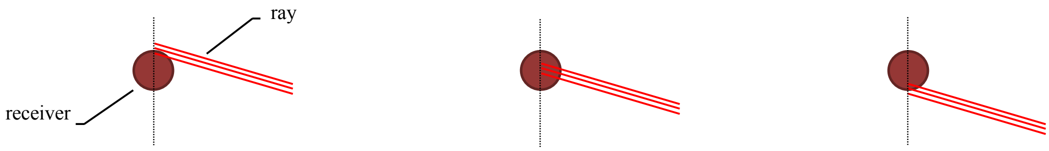

Fig. 2. Optical analysis of vertical position of receiver, for different +*x* positions of the CPC.

2.2. Total reflection phenomenon

If a ray strikes the tubular receiver at an incident angle larger than the critical angle (41.5°) with respect to the normal, the ray will be entirely reflected by the receiver and it will not penetrate. This is the phenomenon of total reflection. Because this behavior would decrease the concentration ratio, Eq. (1) should be corrected by introducing an intercept factor (*IF*). As defined in Eq. (2), the intercept factor is the mean of the ratio of θ_r to θ_c, where θ_r is the sum of allowable positive incident angles with respect to the normal of the receiver; θ_c is the half-acceptance angle of the CPC, i.e., $0 \le \theta_r \le \theta_c$ and θ_c is 1.5°. This is because the CPC is symmetrical about the y-axis.

$$IF = \overline{\sum(\theta_r/\theta_c)} \tag{2}$$

As noted, the optimal vertical position of the receiver is 0.46*D*. Using these design parameters, including the half-acceptance angle of 1.5° and a receiver of 40 mm in diameter, the correlation between *IF* and focal length can be investigated. This is shown in Fig. 3 (a). The relationship in terms of +*x* position of the CPC is shown in Fig. 3 (b). From the analysis, the *IF* had a maximum value at the minimum focal length. As the focal length increased, the *IF* was found to decrease following a gradually flattening curve. An inverse first-order polynomial equation, as formulated in Eq. (3), describes this correlation. The coefficient of determinant (R^2) is 0.9907, which indicates a good fit to the *IF* in Eq. (2).

$$IF_r = 0.052 + \frac{0.244}{f} \tag{3}$$

where IF_r is the intercept factor through regression analysis and f is the focal length.

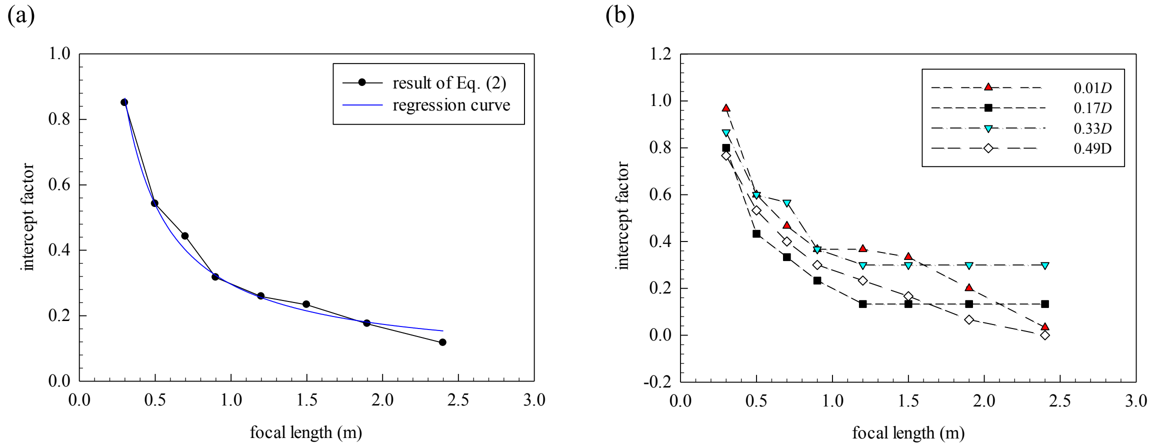

Fig. 3. Variations in (a) intercept factor and (b) that in terms of +*x* position, for different focal lengths.

Applying the values of *IF* to Eq. (1), a corrected concentration ratio (CR_{cr}) was determined; the corrected concentration ratio is given by Eq. (4). Based on this approach, the variations in concentration performance for different focal lengths can be sufficiently investigated. As shown in Table 2 and Fig. 4, a low correlation between CR_{cr} and focal length is suggested. The CR_{cr} varies slightly from 8.0 to 9.0 as the focal length increases from 0.3 m to 2.4 m. This change is less drastic than in the case of the uncorrected concentration ratio, neglecting the total reflection phenomenon. Thus, the inclusion of *IF* for assisting in a better evaluation of performance of the CPC is justified. It is shown that an increasing focal length has a limited effect on the concentration ratio.

$$CR_{cr} = CR \times IF \tag{4}$$

Table 2. Analysis of intercept factor and concentration ratio.

f (m)	0.30	0.50	0.70	0.90	1.20	1.50	1.90	2.40
D (m)	1.18	1.97	2.76	3.55	4.74	5.92	7.50	9.47
H (m)	0.32	0.53	0.74	0.95	1.26	1.58	2.00	2.52
IF	0.85	0.54	0.44	0.32	0.26	0.23	0.18	0.12
CR	9.4	15.7	22.0	28.3	37.7	47.1	59.7	75.4
CR_{cr}	8.0	8.5	9.7	9.0	9.8	10.8	10.7	9.0

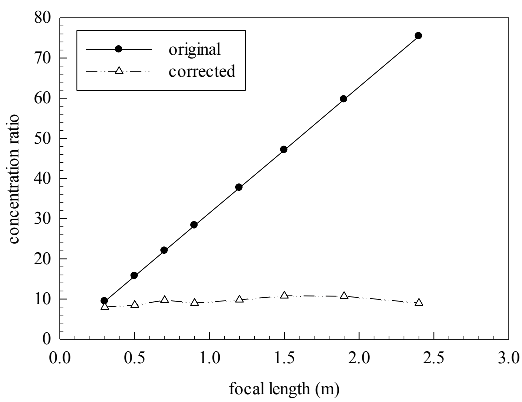

Fig. 4. Comparison of corrected concentration ratio against original concentration ratio.

3. Conclusion

Continuing the research of Jadhav et al. [6], a modified design of CPC was presented in this paper. Using the region below the common focus of parabolas, the height of the CPC could be effectively reduced without compromising the concentration ratio. This modification was achieved by adjusting the vertical position of the receiver through optical analysis. It was shown that in the case where the height of the tubular receiver was 0.46 times the aperture width, a greater range of incident rays could be collected. In addition, to account for the total reflection phenomenon caused by the receiver, an intercept factor was introduced. This permitted a better evaluation of the correlation between the performance of the CPC and the focal length. From the analysis, it was suggested that an increasing value of focal length would not substantially affect the concentration ratio.

Acknowledgements

This work was financially supported by the Bureau of Energy, the Ministry of Economic Affairs, Taiwan, Republic of China, under Grant No. 102 – D0304.

References

[1] A. Rabl, Optical and thermal properties of compound parabolic concentrators, Sol. Energy 18 (1976) 497-511.
[2] R. Oommen, S. Jayaraman, Development and performance analysis of compound parabolic solar concentrators with reduced gap losses – oversized reflector, Energ. Convers. Manage. 42 (2001) 1379-1399.
[3] R. Tchinda, Thermal behaviour of solar air heater with compound parabolic concentrator, Energ. Convers. Manage. 49 (2008) 529-540.
[4] D. Jing, H. Liu, X. Zhang, L. Zhao, L. Guo, Photocatalytic hydrogen production under direct solar light in a CPC based solar reactor: reactor design and preliminary results, Energ. Convers. Manage. 50 (2009) 2919–2926.
[5] H. Zheng, T. Tao, J. Dai, H. Kang, Light tracing analysis of a new kind of trough solar concentrator, Energ. Convers. Manage. 52 (2011) 2373-2377.
[6] A.S. Jadhav, A.S. Gudekar, R.G. Patil, D.M. Kale, S.V. Panse, J.B. Joshi, Performance analysis of a novel and cost effective CPC system, Energ. Convers. Manage. 66 (2013) 56-65.