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Design and ray tracing of a compound parabolic collector with tubular receiver

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ABSTRACT

Ray tracing for solar collectors shows the behavior of light rays which falls on collector surface and reflected to the receiver. Accordingly the solar collectors are designed or modified to enhance thermal performance. Compound parabolic collectors (CPC) are capable of collecting and reflecting a large amount of solar radiation towards the receiver with less tracking effort. With the help of ray tracing technique its performance can be increased by minimizing the optical losses. In this paper, the limiting diameter (LD) of the tubular receiver at the focus of CPC is determined by the geometrical method of ray tracing. The CPC is designed and ray tracing analyses were performed without receiver to differentiate the region of maximum collection and no collection of reflected rays. The region where not a single reflected ray enters from a CPC half follows an elliptical shape which is tangent internally to the LD of the receiver at the focus and its geometrical relation with the acceptance angle is presented. The geometrical relationship between LD and maximum diameter is also determined. The receiver height is obtained on the basis of receiver surface covered and collector surface utilized.

1. Introduction

Compound parabolic collector (CPC) is a non-imaging type of solar collector made by combining two parabolas either in symmetric or asymmetric manner (Rabl, 1976; Jenkins and Winston, 1996; Mallick et al., 2006; Tripanagnostopoulos, 2014). Several attempts (Cairo and Clark, 1987; Antonini et al., 2013; Mussard and Nydal, 2014; Kuo et al., 2014) were made for increasing the concentration ratio and thermal performance by optical analysis. In parabolic trough collector (PTC), the incident solar rays reflected towards the single point called the focus of parabola. So it achieves the greater collection of the reflected rays but it needs continues tracking along the movement of the sun (Antonelli et al., 2014; Pandolfini and Krothapalli, 2014). This drawback is overcome by the CPC with the help of acceptance angle phenomenon which requires less tracking. Also CPC has greater flexibility in design to accommodate desire shape, size and simplicity in operation. Acceptance angle, absorber height and absorber tube diameter are one of the major considerations in designing the CPC. Here, the type of absorber plays the significant role in enhancing the thermal performance by collecting the maximum reflected rays from concentrator surface. Flat faced absorbers are placed at the bottom of CPC (Tchinda, 2008; Guiqiang et al., 2012; Sánchez et al., 2014; Yu et al., 2015) whereas the tubular (pipe) absorbers are placed at or near the combined focus of CPC (Cairo and Clark, 1987; Ubomba-Jaswa et al., 2010; Gudekar et al., 2013). Acceptance angle of CPC is an angle within which all direct and reflected solar rays will arrive on the absorber. Hence, a proper size of receiver and its location needs to study while designing the CPC. The receiver has to be placed where maximum concentration of reflected rays occurs to achieve maximum amount of radiation. According to Kuo et al. (2014) the receiver is placed in the region below the common focus of parabola which results greater collection of reflected rays as well as reduction of CPC height without affecting the concentration ratio.

The objective of this paper is to perform geometrical or graphical (Riveros and Oliva, 1986) ray tracing analysis on CPC with low acceptance angle. With the help of this analysis the diameter and location of tubular receiver are determined and its geometric relationships are presented. From the observations of ray tracing analysis it was found that the concentration of reflected rays near focus follows a certain pattern. The region where the maximum concentration of reflected rays occurs was below the focus and the region where not a single reflected ray found was around the common focus of CPC. In this region, if a receiver is placed it will receive only direct radiation from the sun and no heating due to reflected rays.

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Nomenclature

a	vertical distance between horizontal reflected ray and focus observed from ray tracing analysis (mm)
a^*	vertical distance between horizontal reflected ray and focus obtained from geometrical relationship (mm)
b	major axis of ellipse (mm)
D	absorber/receiver tube diameter (mm)
D_m	max absorber/receiver tube diameter (mm)
h	height of CPC (mm)
H	height of focus (mm)
H'	receiver height (mm)
Hp	height of parabola (mm)
W	aperture width (mm)
2θ	acceptance angle (°)
Φ	incident angle (°)
δ	collector coverage angle (°)
ω	reflector coverage angle (°)

Subscripts

I	incident ray
n	normal
R	reflected ray
t	tangent

Abbreviations

CPC	compound parabolic collector
LD	limiting diameter
PTC	parabolic trough collector

All the reflected rays will tangent to receiver and it is considered as a limiting diameter (LD) of the receiver at the focus. The geometrical construction and optical analysis of this relation is presented in this paper. The maximum receiver diameter is also determined by ray tracing analysis and its location and relation with LD is presented. The region where no reflected rays from CPC half follows an elliptical shape which is tangent internally to the LD of the receiver at the focus. Most of the reflected rays are in tangency with this ellipse. The relation of the major and minor axis of the ellipse depends on the acceptance angle and CPC height. A 68 number of iterations were performed on designed CPC to select suitable height of the receiver and plotted against the collector and receiver coverage angle.

2. Construction of CPC

CPC consists of two parabolic segments assembled at a certain angle called the acceptance angle. The receiver is located near the focus of these parabolas where solar rays reflected and concentrated. Many researchers used the traditional CPC design (Tchinda, 2008; Pei et al., 2012; Sellami and Mallick, 2013) where the receiver is placed at the bottom of the CPC. The modified design of the CPC with tubular receiver is shown in Fig. 1. The CPC is designed for mounting in East-West direction and tracking in South-North direction. This method of installation reduces the number of tracking according to the sun position (Jadhav et al., 2013). In Fig. 1, Hp and H is the height of the parabola and height of the focus respectively. W is the aperture width of CPC, 2θ is the acceptance angle and D is the diameter of the receiver which is placed at the common focus of parabolas.

The design is much similar to the design of (Jadhav et al., 2013; Kuo et al., 2014). In these design the authors used the relation that aperture width is two times the height of CPC. But it is corrected as the aperture width W is four times the height H i.e. $W = 4H$. This relation follows the general equation of parabola (1). If the acceptance angle is considered then the relation becomes,

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

$$H = Hp \cos\theta \quad (2)$$

$$W = 4Hp \cos\theta \quad (3)$$

whereas f is a focus length and equal to H.

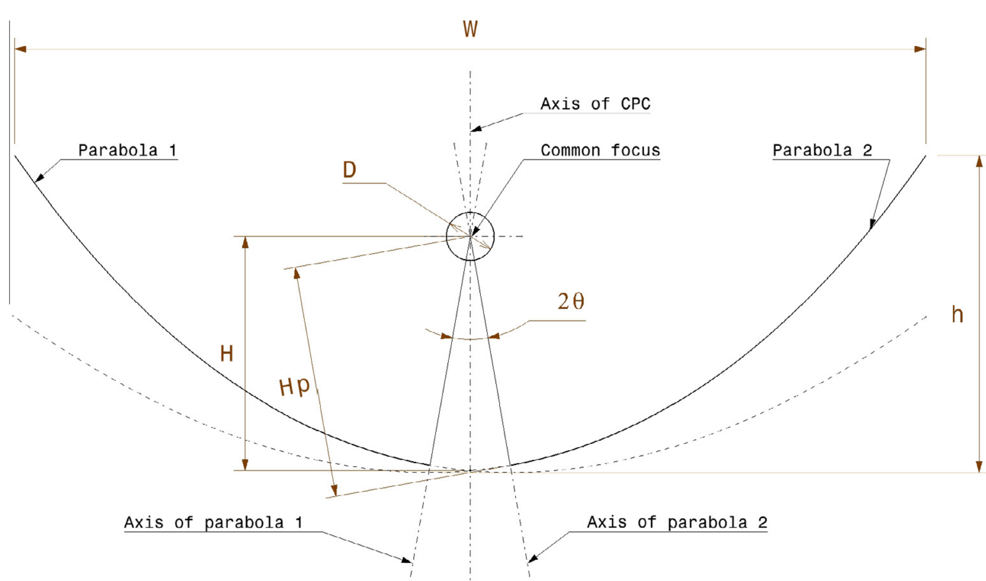

Fig. 1. Construction of CPC with tubular receiver.