Applied Thermal Engineering 109 (2016) 130–137

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Optical sensitivity analysis of geometrical deformation on the parabolic trough solar collector with Monte Carlo Ray-Trace method

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HIGHLIGHTS

- Effects of three kinds of geometrical deformations are studied using MRCT method.
- Concentrator profile with deformation error is mathematically described.
- Parameter study of optical efficiency of PTC system is conducted.
- The impacts of different types of deformations on the optical performance are diverse.

ARTICLE INFO

Article history:
Received 18 May 2016
Revised 21 July 2016
Accepted 9 August 2016
Available online 10 August 2016

Keywords:
Parabolic trough concentrator
Geometrical deformation
Optical performance
Monte Carlo Ray-Trace method

ABSTRACT

This paper evaluated the influences of three kinds of geometrical deformations including global deformation, local rotation deformation and local linear deformation, on the optical performance of parabolic trough solar collector (PTC). An optical analysis of PTC system with different geometrical deformations was performed with the Monte Carlo Ray-Trace method to predict the optical efficiency and the radiation flux distribution on the receiver. The results show that the elliptic profile of the concentrator mirror results in a local hot spot on the receiver, which may shorten the receiver service life, among those cases with different global deformations. The optical performance of parabolic trough concentrator is almost not affected by rotation angle in the range of −0.3 to 0.3°. And the optical efficiency could be maintained above 90% of that under non-deformation condition when the linear deformation length is less than 6.0% of half aperture width. The local deformation at the bottom of the concentrator induces a more apparent deficit of the performance compared with the case of top local deformation. Additionally, the optical efficiency is inversely proportional to the length of part which is removed from the concentrator.

1. Introduction

Owing to the increasing energy demand and severer environmental issues, the developments of renewable energy sources are attaching much worldwide research attention [1,2]. The solar energy seems to be one of the most promising solutions due to its environmental friendliness, sustainability and inexhaustibility [3,4]. Many technologies have been invented and adopted in industrial applications for solar energy utilization [5,6], such as the concentrating solar power (CSP) technologies [7]. The parabolic trough solar collector (PTC) technology accounts for many of existing commercial CSP plants and is the most commonly used large-scale solar power technology for medium-high temperature applications [8,9]. It has the lowest cost among solar power systems [10,11]. Parabolic trough concentrator and receiver are recognized to be core components in the PTC system [12]. The optical performance of the parabolic trough concentrator and receiver is crucial to PTC system. Therefore, the effects of the influential parameters, such as receiver configuration, tracking error, geometric parameters, operating conditions, and geometrical deformation, on the optical performance have been investigated in the last few years.

Liang et al. [13] found that the offsetting of the absorber in width direction of aperture impacted the optical performance more significantly compared to that in the normal direction. With an increase in rim angle, the impact of tracking error on the optical efficiency of a given PTC system was became weaker. However, the sensitivity of the tracing error depends on the width of the PTC system: it was more sensitive in a wider PTC. Grena [14] carried out an optical simulation regarding a parabolic solar collector with a three-dimensional ray-tracing technique. The impacts of tracking error, sun inclination, defocalisation, dust and aging on the total

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http://dx.doi.org/10.1016/j.applthermaleng.2016.08.058
1359-4311/

Nomenclature

a	aperture width (m)
c_1	the ratio of rotation deformation length to half aperture width
c_2	the ratio of linear deformation length to half aperture width
c_3	the ratio of removed part length to half aperture width
d_a	outer diameter of absorber tube (m)
d_g	outer diameter of glass cover (m)
$d_{\min}$	width of the focal shape (m)
e	conic constant
f	focal length (m)
g	gap length (m)
I	solar radiation intensity (W/m^2)
L_{ar}	active receiver length (m)
L_l	the length of local linear deformation (m)
L_r	the length of removed part (m)
p	the path of conic curve in mathematics
L_θ	the length of local rotation deformation (m)
q_a	solar radiation absorbed by receiver (W/m^2)
q_c	solar radiation incident on concentrator (W/m^2)

Greek symbols

α_a	absorptivity of absorber tube
δ	finite size of the sun ($\delta = 16'$)
η	optical efficiency
η_d	optical efficiency with deformation
η_i	optical efficiency without deformation
η^*	relative optical efficiency
θ	angle of local rotation deformation (°)
ρ_r	reflectivity of concentrator mirror
τ_g	transmissivity of glass cover
φ_m	rim angle (°)

optical efficiency and the radiation distribution on the receiver were investigated. Zhao et al. [15] analyzed the effects of installation and tracking errors on the flux distribution at different incident angles and geometric concentration ratios. The errors were elevated with an increase in the incident angle, or a decrease in concentration ratio. Stynes and Ihas [16] developed a technique to measure the absorber alignment of PTC system with a calibrated digital camera and four photogrammetric targets. Then the sagging of absorber could be quantified with this technique, through measurement of absorber alignment along full length. This measurement of absorber alignment was meaningful to determine the intercept factor of a collector accurately. Guo et al. [17] summarized the influences of wind velocity, working fluid flow rate, ambient temperature, solar incident angle, glass cover diameter and absorber diameter, on the performance of the solar receiver. They found that the optical heat loss took the major part of the energy loss compared with the heat losses of solar receiver. Yang et al. [18] conducted simulations using the Monte Carlo Ray-Trace (MCRT) method to study the optical concentration ratio of PTC concentrators in different conditions. At the same time, the effects of the defocusing phenomenon and tracking error on the PTC concentrators were discussed. Besides, this research provided a reference for the design and assemblage of the high-performance PTC concentrators. Cheng et al. [19,20] adopted the unified MCRT model in the simulations for the sensitive analysis of PTC system. Different geometric parameters were tested, including aperture width, focal length, rim angle, the absorber diameter, the glass cover diameter and the active receiver length.

The processing and installation errors may induce geometrical deformation of the parabolic trough concentrators, which in turn affects the optical performance of PTC system. The results of the study [21] demonstrated that the PTC system was typically affected by geometrical deformations of the parabolic trough concentrator. Sansoni et al. [22] conducted ray tracing simulations to test the optical performance and concentration properties. The interactions among mirror deformations, sun tracking, angles, and collected light were reported. Although mirror deformation was described with an innovative mathematical method, the influence of mirror deformation was not further investigated. Binotti et al. [23] extended the analytical approach of First-principle Optical Intercept Calculation (FirstOPTIC) and investigated the impact of three-dimensional effects on the optical performance. It gave a correction of the general approach to specularity mirror errors for non-zero incidence angles. However, the investigation majorly focused on the analytical approach rather than the parametrical study.

Although a large number of investigations about optical performance of the PTC system are reported, there are still few studies concerning a systematic and general analysis of geometrical deformation. Therefore, an optical analysis of the PTC system with geometrical deformation was carried out based on the MCRT method to investigate the influence of geometrical deformation on the parabolic trough concentrator. This paper presents the most significant results of this investigation, illustrating different types of geometrical deformations. In addition, model validation is performed to validate the simulation tool. Then the impacts of global deformation, local rotation deformation and local linear deformation on the optical performance are discussed.

2. Model and method description

2.1. Physical model

The PTC system mainly contains of two core components, the parabolic trough concentrator and a tubular solar receiver, as shown in Fig. 1(a). The parabolic trough concentrator directs the solar radiation with mirrors, whereas the tubular solar receiver absorbs the reflected energy, which is positioned along the focal line of the concentrator. After the collection, the heat transfer fluid circulates through the absorber tube and takes the thermal energy away for further usage. The tubular solar receiver is enveloped by a glass cover which decreases the convective heat loss to the surrounding [24].

Fig. 1(b) shows a detailed schematic of a cross-section of the PTC model and some significant parameters [25]. The focal length (f) gives rise to the magnitude of solar image, while the aperture width (a) is usually correlated to the input energy of the concentrator. Given that the solar beam is non-parallel (with a light cone δ), the divergence phenomenon should be concerned. In the real application, there is a small gap between two halves of the concentrator in which to install the flange or to support the bracket due to the structural constrains. It helps to reduce the manufacturing cost of the concentrator without losing efficiency, because the area is always shadowed by the receiver.

The model of PTC system is made up of Large Aperture Trough 73(LAT 73) [26] and Siemens UVAC 2010 receiver [27]. The LAT 73