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A novel free-form Cassegrain concentrator for PV/T combining utilization

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ABSTRACT

The conventional imaging solar concentrators normally obtain a Gaussian distribution on the receiving surface. The aperture size of a thermal receiver (TR) is always limited primarily to the high concentration area, discarding the edge part to be lost. The current study proposes a novel free-form Cassegrain concentrator (FFCC) for PV/T combining utilization. The remaining heat flux by the edge of focal spot is directed by the secondary mirror for electric generation. The profile of secondary reflector is constructed by the geometric construction method (GCM), aiming at achieving high concentration for the TR and uniform flux distribution for the PV receiver (PVR). The energy transmission characteristics of FFCC, including the incident vectors and heat flux distribution on the TR/PVR are both investigated. The effects of changing the receiving locations, PV/T dividing ratio, etc. are analyzed. The sun size/solar conic angular is also considered for practical use. The GCM method and simulation results in this article can provide a reference for the PV/T solar energy system and free form surface design.

1. Introduction

Concentrated solar power (CSP) systems use reflectors or lens to capture a large amount of solar rays in a small area. The form of concentrating technologies is mainly dish, trough or tower, which can be used for either thermal heat transfer (Wang et al., 2013, 2015, 2016) or generating electricity (Meng et al., 2013, 2014). Due to the better outdoor durability and lower specific costs, high temperature systems normally adopt these types as the primary concentrators (Shuai et al., 2008). A Gaussian distributions as Fig. 1 shows (Pitz-Paal, 2007) are obtained by the imaging mirror concentrators (Johnston, 1998), especially when they are formed by several individual reflector segments such as multi-dish concentrator (Meng et al., 2016; Xia et al., 2012), or the solar tower. With the increasing distance from the center of focal point, the concentrated heat flux decreases dramatically. In practical use, the aperture area of a solar thermal receiver should be truncated, in order to remain the central high concentration heat flux and discard the edge part (Pitz-Paal, 2007). A smaller aperture size have the advantages of: (i) lower radiation loss from the aperture. (ii) Higher pressure capacity. (iii) Lower incident angles are obtained so that the absorptions of the receiver can be increased.

To recycle this edge part of heat flux, non-imaging optics has become a solution. The CPC (Meng et al., 2016) or tailored edge-ray concentrator (TERC) working as the secondary reflectors can provide the widest possible acceptance angles. The optical performance of a dish concentrator assembled with 3D CPC was analyzed and was found to give higher concentration than single dish (Dai et al., 2011). TERC used as the secondary mirror was developed for the primary fresnel concentrator (Gordon and Ries, 1993) and dish concentrator (Friedman et al., 1993), which aimed at the maximization of concentration. Another solution: a two stage solar thermal receiver was demonstrated to reduce the radiation and convection loss. The low-temperature stage was implemented as a partial ring of tubular receivers (Preheaters) using pentagon concentrators surrounding the central high-temperature stage (Kribus et al., 1999). The methods above have been proved to be effective.

With the development of precision machining, the sophisticated free form surface can be created with precision. A freeform optical device helps flexibly rearrange the normal vectors on local surface elements, which is mainly used in the area of illumination engineering for road (Feng et al., 2010) and motor vehicles (Chen et al., 2010), to provide an efficient and desired target distribution (Ding et al., 2008; Miñano et al., 2009; Fournier, 2010). In recent years, it has been gradually developed in the field of concentrated photovoltaic (CPV) system for uniform distribution (Zamora et al., 2012), such as the Free Form XR Photovoltaic Concentrator (Hernández et al., 2007).

In this article, a novel free-form Cassegrain concentrator, called FFCC, is proposed for PV/T combining use. Primary dish concentrator is among the most used and reliable solution. To reduce the machining cost, FFCC is formed by the classic dish concentrator and a secondary free-form reflector. The corresponding solar

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Nomenclature

TR	thermal receiver	PVR	PV receiver
FFCC	free-form Cassegrain concentrator	GCM	geometric construction method
CSP	concentrated solar power	TERC	tailored edge-ray concentrator
C_G	concentration ratio	k	the occupation of PVR
R/r	radius	$\boldsymbol{P}_{i,j}$	points with index i, j
θ_i	reflection angle	$\boldsymbol{v}_{i,j}$	unit vectors
$\mathbf{Rot}(x, \theta_i)$	rotating matrix along x-axis with the angle of θ_i	C_i	intersection points

receiver is proposed as Fig. 2 shows. Unlike traditional solar hybrid system based on the integration of PV/thermal modules (Chow, 2010; Vorobiev et al., 2006), the current design divides PV/thermal modules through optical solution. The heat flux of high/low concentration can be adequately separated so that avoid the overheating of CPV. The central high concentration heat flux from FFCC is used for the thermal receiver (TR). The remaining heat flux by the edge of focal spot is directed by the secondary mirror for electric generation. The profile of the secondary reflector is constructed with the aid of GCM, aiming at the high concentration for TR and uniform flux distribution for the PV receiver (PVR). The current study aims to investigate the energy transmission characteristics of FFCC, including the incident vectors and heat flux distribution on the TR/PVR. Two transmission types, the forward and backward models are compared. The effects of changing receiving locations, PV/T dividing ratio, etc. are analyzed. The sun size has also been considered for practical use. The GCM method and simulation results in this article can provide a reference for the PV/T solar energy system and free form surface design.

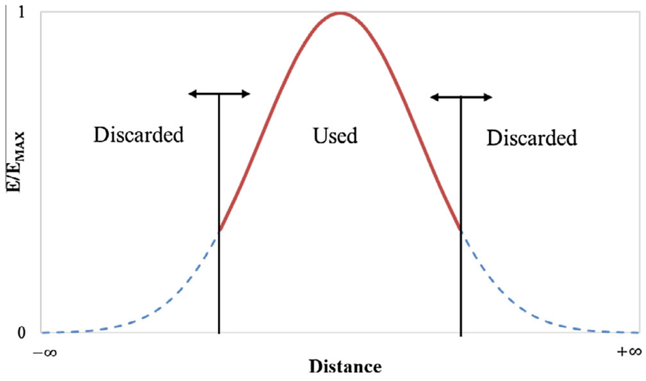

Fig. 1. Gaussian distribution (normalized to the maximum heat flux) obtained by the imaging mirror concentrators (Pitz-Paal, 2007).

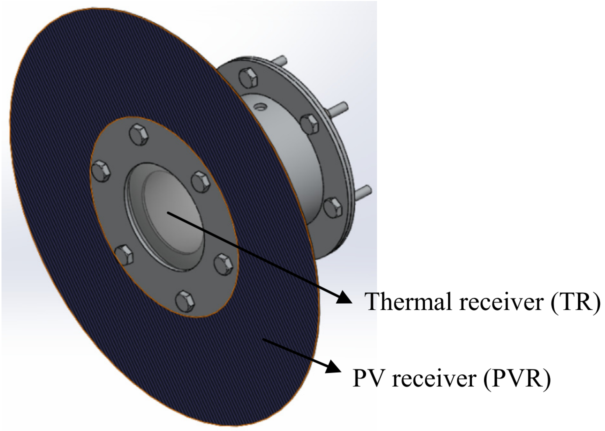

Fig. 2. The sketch of TR/PVR based on FFCC technology.

2. Geometric construction method for FFCC

During recent years, the design methods for free form optics have been widely developed. Owing to the variety of practical applications, there is no universal method for the free form surface creation. Available methods include multi-parameter optimization (Benítez and Miñano, 2007), Wassermann-Wolf differential equation method (Cheng et al., 2010), tailoring method (Ries and Muschaweck, 2002), point-to-point mapping (Fournier et al., 2010), simultaneous multiple surface method (SMS) Dross et al., 2004 and geometric construction method (GCM) Tsai, 2015. GCM is a direct calculation method that constructs the interior reflecting/refracting mirror of optical system, using every single ray as a bridge. It is especially suitable when the specific light source and target distribution are required. Cheng jointed continuous small planar surface to construct the free form mirrors, which is applied in the non-imaging illumination system (Cheng et al., 2012). Tsai developed a free form concentrator for the uniformity improvement of flux distribution on solar cell (Tsai, 2015). The adopted GCM is to connect several circular arc segments in the needed profile. Referring to the GCM proposed by Tsai (Tsai, 2015), a similar model is extended for both of TR/PVR use in the current study. Particularly, several constraint conditions must be added in GCM for the point focusing requirement.

This section introduces the surface creation method of FFCC based on particular imaging points on TR/PVR. Since the model is axisymmetric, the FF surface can be generated by a curve. Two conditions should be satisfied by the curve: (1) optical condition, here is the law of specular reflection, (2) smooth and continuous requirements. So the quantity of the sampling points needs to be added. And the normal vector on each point should be perpendicular to the slope of the generated curve.

Fig. 3 presents the mathematical model of FFCC. Suppose that the energy receiver locates at the original point O_1 of primary parabolic reflector. According to the law of conservation of flux, the size of primary concentrator and PVR satisfy the followed equation:

$$k(R_{\max}^2 - R_{\min}^2)/C_G = (r_{\max}^2 - r_{\min}^2) \tag{1}$$

where R and r are the radius of primary concentrator and PVR, respectively. C_G represents the concentration ratio of PVR component. k is the CPV occupation and defined as:

$$k = W_{pv}/W_{total} \tag{2}$$

Note that W_{pv} is the target electrical output power, and W_{total} means the total input solar power.

The incident solar rays hit the primary reflector at the discrete points of $\boldsymbol{P}_{1,j-1}, \boldsymbol{P}_{2,j-1}, \ldots, \boldsymbol{P}_{k,j-1}, \ldots, \boldsymbol{P}_{n,j-1}$, where $\boldsymbol{P}_{k,j-1}$ represents the critical point that dividing TR and PVR. These points need to satisfy the relationship of $z^2 = y^2/4f$, where f represents the focal