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Tailored non-imaging secondary reflectors designed for solar concentration systems

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Abstract

For the usage of solar concentration systems, non-imaging secondary (NIS) reflectors comprised of concave and convex shapes based on differential equations are proposed in this study. Ray tracing technique is adopted in the estimation of the concentrated irradiance on the receiver. The concentrated solar irradiance on the receiver of the non-imaging reflectors shows excellent performance in terms of uniformity. This study also indicates that when the primary reflector and the receiver size are fixed, the size of the non-imaging reflectors is mainly determined by the location of the start point of its mother curves.

Keywords: Solar concentration systems; Non-imaging secondary (NIS) reflectors; Ray tracing technique

1. Introduction

Secondary optical elements (SOE) are widely adopted as major components in optical systems. They can change the directions of the rays reflected from the primary reflector and provide more desired concentrated flux distributions.

Some innovative applications relative to secondary reflectors have been put forward in the recent decades. De la Mora et al. (2009) used porous silicon photonic mirrors (PSPM) as secondary reflectors in solar concentration systems. Their theoretical and experimental studies both suggested that porous silicon photonic crystals can be used as secondary mirrors in solar concentration devices as long as a temperature control is included in the solar concentration system. Ostroumov et al. (2009) analyzed the aplanats as maximum-performance light-transfer systems with radiative transfer approaching the thermodynamic limit for the first time and presented a fundamental categorization scheme, which was illustrated for far-field dual-mirror concentrators and motivated by high-irradiance solar applications. Chen et al. (2009) designed a solar concentrator combining primary parabolic and secondary hyperbolic mirrors and found that the ellipsoid mirror is slightly better than the hyperbolic mirror. Meng et al. (2013) investigated the optimal design of a symmetrical two-stage flat reflected concentrator (STFC). They summarized that when the two sides' focal spots just coincide, the concentrated flux distribution presents uniform in the extreme. Grena and Tarquini (2011) developed a secondary with two parabolic wings for the primary reflector that is the linear Fresnel lens. By using this kind of secondary, the concentrated flux can be well distributed on the upper side of the tube. Chong et al. (2011) used a parabolic reflector as the secondary after the primary reflector non-imaging focusing heliostat to obtain the maximum solar concentration (Cmax) of 1039 suns. Dai et al. (2012) developed a kind of secondary reflector with the outline compounded by a part of involute

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of circle and a part of parabolic. Their simulation results indicated that this secondary reflector can receive light and reflect it onto absorber efficiently.

On the application of the Concentrated PV systems, secondary reflectors are also quite common components. Sapia (2013) used a secondary flat optical reflector (SOE) made by a series of cold mirrors to reflect the rays from the primary parabolic dish concentrator to the heads of optical fibers. Whitfield et al. (1999) suggested that secondary reflectors increase the performance of the concentrated photovoltaics but also increase the cost. Chen and Ho (2013) pointed out that dark image on the PV receiver would greatly reduce the performance of the PV modules. They developed a kind of non-imaging secondary (NIS) to realize the elimination of the dark area and reduce the solar disk effect. Using the analytical method, NIS shapes designed with linear, quadratic and cubic curves are proposed. According to their description, the NIS includes two ray routes. One is the ray route 1, in which the reflected light from the primary surface has to be reflected onto the diameter range of the PV receiver. The other is the ray route 2, in which the reflected light from the primary reflector has to cover the radial range of the PV receiver. However, as their proposed irradiance pattern by both ray routes are distributed radially, even though their work of ray route 2 showed better performance than the ray route 1, the light was still a radial pattern. The irradiance density cannot be quite uniform. The closer to the center, the higher density is. To eliminate the dark image on the PV receiver and obtain uniform irradiance as well, the density of the irradiance should not be the radial pattern. It should be noted that, Zhou et al. (2014) proposed two versions of “disk-focus”non-imaging concentrating reflectors to obtain uniform irradiance designed for solar concentration systems and now expand into CPV systems.

In this study, we propose a kind of tailored non-imaging secondary (NIS) described by differential equations, which is different from the mother curves described by polynomial expressions. The tailored NIS includes convex design for low concentration (LCPV) usage and concave design for medium concentration PV (MCPV) and high concentration PV (HCPV) usage. Monte-Carlo ray tracing method is employed in the estimation of the concentrated solar irradiance on the PV receiver. The results of the tailored NIS are then compared with the NIS using linear, quadratic, and cubic mother curves. Finally the effects of the start points on the size of the tailored NIS are discussed.

2. Design method of the tailored NIS

In general, in the field of solar energy where the cost is usually the key issue, the research of reflective concentrator which is more cost-effective than other such as refractive one is carried out. As shown in Fig. 1, the general structure of a reflective concentrator for the usage of CPV with axis-symmetry consists of three parts: primary reflector, secondary reflector and PV receiver area. The incident solar rays reflected from the primary reflector are then reflected by the secondary, which is usually made of a smaller convex or concave parabolic surface into the receiver. As can be seen from Fig. 1, the receiver area, which cannot reflect the incident solar rays will create a dark image, which is the result of imaging characteristic of the conventional secondary reflector. A similar phenomenon will occur when the secondary is a convex reflector. The dark image mentioned above will present serious design shortages for both high concentration PV (HCPV) and low concentration PV (LCPV) and severe effect in the application of photovoltaic device as the Fill Factor (FF) of solar cell is strongly dependent upon the uniformity level of the illumination. In our study, we use another way to design the NIS to avoid the radial pattern of light for increasing the uniformity of concentrated illumination. We use the radial range ray route to design our tailored NIS. Meanwhile, as the secondary can be either a convex shape or a concave shape, we design both these two shapes.

The NIS of a convex shape is shown in Fig. 2, in which the NIS is installed below the focal point of the primary parabolic reflector. The known coordinates of the points are as follows:

$$B'\left(-R,\frac{R^2}{4L}\right),A'\left(-r,\frac{r^2}{4L}\right),A\left(r,\frac{r^2}{4L}\right),F(0,L),O'\left(0,\frac{r^2}{4L}\right).$$

where L is the focal length of the primary parabolic reflector, R the aperture radius, and r the bottom opening radius. However, unlike the geometry presented in Y.T. Chen 's work that the diameter of the PV receiver area equals the bottom opening of the parabolic reflector, the PV receiver diameter PP' can be less than bottom opening diameter AA' of the parabolic reflector for producing higher concentration ratio with the same primary parabolic reflector. The radius of the circular PV receiver $O'P$ equals a. The rays reflected from this NIS reflector has to be uniformly incident on the half radial range $O'P$. Suppose that an arbitrary ray to be incident on the primary parabolic reflector with a distance L_1 from the symmetry axis, then it is reflected onto point E on the NIS, and finally to be incident upon point M' on the PV receiver with a distance L_2 from the symmetry axis. To obtain uniform concentrated irradiance on the PV receiver area, the ratio of the area of the small disk on the receiver with radius L_2 to the PV receiver area with radius a, is supposed to equal to the ratio of the annular area of the reflector with the external radius L_1 and the internal radius r to the whole annular area of the reflector with the external radius R and the internal radius r:

$$\frac{\pi L_2^2}{\pi a^2}=\frac{\pi(L_1^2-r^2)}{\pi(R^2-r^2)} \tag{1}$$

Suppose the coordinate of point E is (x,y) and the intersection of EF and the primary parabolic reflector is M. The coordinate of M can be obtained by calculating the following equations of the line EF and the parabola AB: