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# Non-imaging concentrating reflectors designed for solar concentration systems

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**Abstract**

In this study, two versions of non-imaging dish reflectors designed for providing uniform flux profiles on the receiver are proposed. These two reflectors, namely Type I and Type II, are designed according to two different ray routes and described by differential equations. Both the reflectors are determined by three dimensionless parameters: bottom opening diameter, receiver diameter, and the distance from the bottom to the receiver. By using ray tracing technique, radiation flux distributions on the receivers of these non-imaging reflectors are investigated. The results suggest that for concentrating collimated incidence, both the two non-imaging concentrating reflectors have good performance in terms of concentrated flux uniformity on the receiver. However, the Type I reflectors present more uniform flux maps than Type II reflectors for concentrating solar rays. It is also concluded that the value of the distance from the bottom to the receiver has an effect on the angle between the incident ray and the reflected ray, which is relative to the performance of concentrating solar rays. Bottom opening diameter and receiver diameter function to codetermine the geometrical concentration ratio (CR) of the reflectors.


*Keywords:* Non-imaging reflector; Solar concentration; Flux map uniformity; Ray tracing technique

## 1. Introduction

Parabolic dish collectors (PDC) are ‘point-focus’ collectors and are widely used optical components in solar concentration systems. They can achieve very high concentration ratios, sometimes even above 1000 suns. Parabolic dish collectors are usually high-cost as they are usually manufactured by using very large and precise mirrors. Compared with refractive Fresnel lenses that usually made by polymethyl-methacrylate (PMMA), they are also very heavy.

Due to the ‘point-focus’ characteristic, parabolic dish cannot provide uniform flux distributions on the receiver which is locating at its focal plane. However, in several special applications uniformity of concentrated flux is required. As far as we know, there are two ways to realize the improvement of flux uniformity on the receiver by using a parabolic dish. One is the application of a secondary optical element (SOE). Currently usage of kaleidoscope homogenizers as secondary is a typical way to realize a uniform flux map on the receiver (Meller and Kribus, 2013; Kreske, 2002; Ries et al., 1997; Helmers et al., 2013). In addition to kaleidoscope homogenizers, Chen and Ho (2013) designed a kind of non-imaging secondary (NIS) to realize the improvement of flux uniformity and the

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elimination of solar disk effect. Moreover, 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. However, although usage of a SOE is a good way to increase the flux uniformity, it increases the complexity of the system. The total cost might increase as well (Whitfield et al., 1999). The other way to increase uniformity is to put the receiver slightly away from the focal plane of the parabolic dish, Just as Li et al. (2011) indicated in their ray tracing simulations. In practice, we observed that Nepveu et al. (2009) obtained more uniform flux by putting the receiver plane slightly away from the focal plane in their dish/Stirling system. However, this way still cannot provide sufficiently uniform concentrated flux.

In this study, two versions of non-imaging dish reflectors (namely Type I and Type II) utilizing two different ray routes are proposed, tailored to provide desired uniform flux profiles without any secondary optical elements. Ray tracing technique is employed to estimate the performance for the two designs. The effect of the parameters on performance is also investigated.

## 2. Methodology

As mentioned above, for increasing the uniformity of flux map on the receiver, two solutions are sometimes adopted in the solar concentration systems with primary parabolic reflectors. The first way is to put the receiver forward or backward from the focal point of the primary parabolic dish. Fig. 1 shows the receiver put backward from the receiver. The other way is the usage of secondary concentrators. Also as illustrated in Fig. 1, a homogenizer is added after the primary as the secondary concentrator to obtain uniform flux map. Each way has its advantages and disadvantages. Putting receiver slightly away from the parabolic dish focal plane is a simple method but the uniformity of flux map is still not sufficiently enough. As for the usage of SOE, although uniformity increases, the complexity of the concentrating system increases due to the addition of secondary concentrators as well. Thus an idea to design a simple concentrator without any secondary to realize uniform concentrated flux came out, as presented in Fig. 1.

The detailed schematic diagrams of the two versions of 'disk-focus' non-imaging concentrating reflectors are illustrated in Figs. 2 and 3, respectively. Instead of concentrating rays to a point like the traditional parabolic dish collector, these proposed non-imaging reflectors concentrate rays onto a small circular disk. The non-imaging reflectors are designed by two ray routes. The first ray route is depicted in Fig. 2, in which the collimated rays reflected from the reflector generatrix $AB$ will cover the upper half radial range of the receiver area $CO'$. Meanwhile, there should be the ray route that cover the lower half radial range of the receiver area $C'O'$. The corresponding ray route is presented in Fig. 3. Obviously both the two ray routes meet the edge ray principle. For convenience, the design by the first ray route is named Type I reflector and the other by the second ray route the Type II reflector. Both of these concentrating reflectors are formed by rotating the generatrix around the symmetry $z$-axis, which is toward the sun. Figs. 2 and 3 also display the geometrical parameters of the Type I and Type II reflector, respectively, where $D$ is the aperture diameter of the non-imaging reflector; $d$ is the diameter of the bottom opening of the reflector; $a$ is the diameter of the circular receiver area; $L$ is the distance from the receiver to the bottom of the reflector; and $z$-axis is the principal axis. In this paper, the receiver diameter $a$ is designed less than or equal to the bottom diameter $d$.

In Fig. 2, point $A$ with the coordinate $(0, d/2)$ is the start point of the generatrix $AB$ and also the only known coordinate of the generatrix $AB$. As for point $B$, although its $y$-coordinate is known as $D/2$, its $z$-coordinate remains unknown. Thus there is an only one known initial condition that is the point $A$ to describe curve $AB$. Consider an arbitrary ray with a displacement $H_1$ from the symmetric axis to be incident on the reflector at a point $M$ with the coordinate $(z, y)$, as shown in Fig. 2. The reflected ray from $M$ is then supposed to reach a point $M'$ with a displacement $H_2$ from the symmetric axis on the receiver. Angle $\theta$ is the angle between the incident ray and the reflected ray at point $M$. The two dashed lines going through point $M$ are the tangent line of this point and the angular bisector of angle $\theta$, respectively. Obviously the slope of tangent line at the point $M$ is equal to the derivative $y'$ of point $M$. As for Type I reflector, in order to concentrate all of the parallel rays reflected by the reflector uniformly onto the receiver area, the ratio of the area of the small disk on the receiver with diameter $2H_2$ to the circular receiver area with diameter $a$, is supposed to be equal to the ratio of the annular area of the reflector with the external diameter $2H_1$ and the internal diameter $d$ to the whole annular area of the reflector with the external diameter $D$ and the internal diameter $d$:

$$\frac{\pi H_2^2}{\pi \frac{1}{4} a^2} = \frac{\pi\left(H_1^2 - \frac{1}{4} d^2\right)}{\frac{1}{4}\pi(D^2 - d^2)} \left(\frac{d}{2} \leqslant H_1 \leqslant \frac{D}{2}, 0 \leqslant H_2 \leqslant \frac{a}{2}\right) \tag{1}$$

And also for Type II reflector, to obtain uniform intensity on the receiver, the ratio of the area of the small disk on the receiver with diameter $2H_2$ to the receiver area with diameter $a$, is supposed to be equal to the ratio of the annular area of the reflector with the external diameter $D$ and the internal diameter $2H_1$ to the whole annular area of the reflector with the external diameter $D$ and the internal diameter $d$:

$$\frac{\pi H_2^2}{\pi \frac{1}{4} a^2} = \frac{\pi\left(\frac{1}{4} D^2 - H_1^2\right)}{\frac{1}{4}\pi(D^2 - d^2)} \left(\frac{d}{2} \leqslant H_1 \leqslant \frac{D}{2}, 0 \leqslant H_2 \leqslant \frac{a}{2}\right) \tag{2}$$

To evaluate the reflectors more conveniently, we introduce the dimensionless numbers, namely: