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Combination of a light funnel concentrator with a deflector for orientated sunlight transmission

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ABSTRACT

This study presents the design of a centralized solar collection system based on combination of a light funnel concentrator with a deflector. The combined light funnel/deflector unit can guide the concentrated light onto a centralized solar receiver, which could be considered as an alternative to solar towers, but could be conveniently installed on the ground. A number of light funnel/deflector units could form an array of solar concentrators. Each unit can convert the incident sunlight into a parallel light beam with high density and guide it onto the central receiver by a deflector, so an array of such units enable the central receiver to produce solar heat at high intensity and high temperature. A ray tracing simulation is used to demonstrate the feasibility of this new design of a centralized solar collection system and to determine the optical efficiency and light intensity distribution on the centralized receiver. The working principle of the system is also verified experimentally. The light intensity distribution on the receiver at different distances from the deflector outlet is presented. The results show that, for the receiver distance of 1.0 m, the optical efficiency of a light funnel/deflector unit can reach 37.5% and 35% for a whole and a half paraboloid deflector being used, respectively. The maximum energy density of the focal speckle on the receiver reaches 2500 W/m^2.

1. Introduction

In recent times, more attention has been paid to high-temperature solar heat collection using solar concentrators. There are two mainstream methods widely adopted: heliostats reflection and paraboloid concentration.

Heliostats reflection technology has been successfully applied in solar tower power plants. The systems can acquire high temperature even above 500 °C through numerous heliostats [1], and dozens of MW-level solar power towers using this technique have been built in America, France, China and Ukraine, etc. [2,3]. However, with a deep investigation into solar tower technology, some disadvantages have been found. Firstly, an expensive tall tower, sometime over 90 m, needs to be built. In order to avoid building the tall tower, some different structures have been proposed, for example, micro-tower structure [4], multi-tower structure [5] and dual-receiver tower structure [6–8]. However the multi-tower structure or dual-receiver tower structure also has shortcoming. The main disadvantage of the multi-tower structure is its low operation temperature due to the low concentration ratio and also the low efficiency of the mirrors system. The dual-receiver tower structure still needs to establish a high reflector and may have some light loss from the reflector. Secondly, every heliostat needs to track sun individually, and this has caused a complicated tracking system and associated high cost. So, the heliostats tracking system plays a pivotal role in the system efficiency and construction cost [9]. Thirdly, when the heliostats reflect the sunlight, they cannot keep vertical towards the sun so that a big cosine effect loss will decrease the reflection efficiency of the heliostat field. Xie et al. [10] and Wei et al. [11] did some research on the cosine effect, and indicated that the heliostat field layout must be optimized for different structure towers to reduce the system cosine loss. Finally, numerous heliostats have been built around central tower, and some of them are far away from the receiver on the top of the tower. Thus the reflected solar radiation would be weakened greatly over a long distance due to optical absorption and scattering by the ambient, especially polluted air. Ballestrín and Margo gave some research on solar radiation attenuation in solar tower power plants and indicated that the solar radiation attenuation loss will reach 5% per 100 m when

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the visibility of the day is 5 km [12]. The disadvantages in solar tower power plants as described above are obvious, and it is necessary to investigate some other centralized collection structures.

Several solar funnels have been introduced by Kiatgamolchai and Chamni [13] and Hahm et al. [14]. So-called solar or light funnel is actually a three-dimensional concentrator with an entrance and an exit or receiver. It can concentrate the low density incoming solar radiation to a high intensity light onto the receiver. In fact, funnel-shape solar concentrators have many varieties, such as round CPC (compound parabolic concentrator), V-trough, square CPC and other shapes [15–17]. Three-dimensional CPC is a typical funnel shape concentrator with the characteristic of higher optical efficiency and larger acceptance angle. However, traditional three-dimensional CPC and V shape funnel concentrators are not able to focus solar radiation onto a point, and then their concentration ratios are relatively low, usually below 15. High concentration ratio can usually be achieved by lens or parabolic dishes. For example, Andreev et al. reported a photovoltaic system with Fresnel lens to concentrate sunlight [18]. The system has 1000 concentration ratio. But, the size of system is limited, because it is very difficult to make big Fresnel or convex lens.

Is there any solar collection system which can acquire advantages of solar power tower and overcome its disadvantages? In other words, can we design a system with a centralized receiver and distributed collectors, but without use of a tall tower or individual tracking strategies? This study therefore proposes a new design of solar collection system based on combination of a light funnel concentrator with a deflector to guide the concentrated sunlight onto a centralized solar receiver. This funnel has the characteristic of having a mirrored focus point near its outlet, so the receiver at the focus does not form any shade on the concentrator [19,20]. An array of light funnel concentrators can produce a high light intensity on the centralized receiver. Compared with a solar tower, these light funnels have the same tracking strategy and the centralized receiver could be installed on the ground, so the proposed design may offer an economical alternative to the solar tower technology.

2. Design of a light funnel concentrator for centralized solar collection

The light funnel concentrator proposed in this paper is shown in Fig. 1, and it is made up of two parts: a compound parabolic concentrator (CPC) and a cylindrical mirror reflector. The light funnel concentrator has a mirrored focus at the middle of its cylindrical section. The design method of the light funnel has been introduced in detail by He et al. [19]. A special design here is to attach a secondary parabolic reflector to the outlet of the light funnel, with its focus overlapping with that of the light funnel. The function of the secondary reflector is to transform the concentrated light to be a beam and direct it to a centralized solar receiver, so the secondary reflector can be called ‘deflector’. Several light funnel/deflector units can be used for a centralized solar receiver to form a new solar collection system, as shown in Fig. 1.

The light funnel concentrators follow the same tracking strategy, but the individual deflector may just need a fixed axial rotation in order to direct light to the centralized solar receiver at any time. The tracking mechanism of the light funnel is much simpler than heliostats in a solar tower system. Both the funnel and the deflector in a light funnel/deflector unit rotate around their overlapping focal point. In certain circumstances, the deflector could be just half of a paraboloid to ensure the light from the funnel could always enter the deflector during the tracking movement. Therefore, the presented design can eliminate the need for a high tower, and instead the centralized solar receiver could be simply placed on the ground if the concentration ratio of the system is not required to be very high.

3. Construction of the experimental device

To obtain enough energy and control the cost, the inlet diameter D = 1200 mm and the outlet diameter d = 260 mm of the light funnel concentrator were chosen. After a comprehensive consideration of all factors, the focus of the parabola was chosen to be f = 122 mm. These parameters define the equation of the parabola to be:

$$y = \frac{1}{4 \times 122}(x + 260)^2.$$

The dimension of the experimental system is shown in Fig. 2 in which α is the deflexion angle between the axes of symmetry of the CCD camera and the deflector, and L is the distance of the deflector outlet to Lambert target. Fig. 3 is the photo of the light funnel concentrator and deflectors. The experimental light funnel concentrator is made of Fiber Reinforced Plastics (FRP), with its inside surface being burnished and covered with aluminum sheet of 92% reflectivity.

The focus of the deflector is 20 mm, and its outlet diameter is 300 mm and height is 350 mm. The deflector is also made of Fiber Reinforced Plastics (FRP), with the same surface treatment as the light funnel. Its curve equation is $y = 0.0125x^2$.

4. The optical simulation analysis of system

4.1. The optical simulation analysis of light funnel concentrator

LightTools is a very powerful software for optical design [21]. The theory of ray tracing in LightTools is based on Monte Carlo

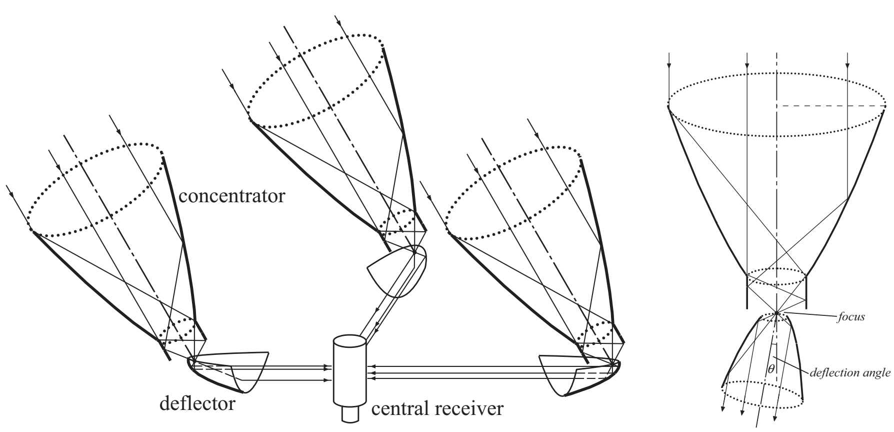

Fig. 1. Schematic of the new solar collection system.