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A novel sun-tracking and target-aiming method to improve the concentration efficiency of solar central receiver systems

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ABSTRACT

The solar central receiver (SCR) system is an important candidate for solar thermal utilization. The cosine loss and astigmatism of heliostats are two major factors which lead to the low concentration efficiency of SCR systems. Most public discussions of concentration efficiency improvement of SCR systems focused on astigmatism correction; however, not so many studies were given to reducing cosine loss of heliostats. In this paper, we proposed a new sun-tracking and target-aiming method for SCR systems in order to eliminate the cosine loss and enhance the concentration efficiency. We calculated the tracking formulae of the sun-tracking strategy and target-aiming strategy by using coordinate rotation transformation method, designed an aspheric lens in target-aiming device by using non-imaging optics principles, and finally constructed the optical model of the proposed system in TracePro software to simulate its concentration performance. The computational results demonstrated the kinematic feasibility of the sun-tracking strategy and target-aiming strategy. The simulation results showed that the proposed method can improve the concentration efficiency of SCR systems obviously in some cases. This novel sun-tracking and target-aiming method sheds light on the field efficiency improvement of SCR systems.

1. Introduction

Solar energy is an essential resource of sustainable energy because of its ubiquity, abundance, and sustainability. As an important candidate for solar thermal utilization, the solar central receiver (SCR) system employs a large field of heliostats which are oriented to redirect the solar energy onto a fixed target (central receiver) located on top of a tower [1]. To date, SCR systems have been established worldwide and showed their great potential in solar thermal utilization [2]. However, the high capital cost of SCR systems is still limiting their large-scale deployment. One effective way to ameliorate the situation is to increase the optical efficiency of the central receiver, which decreases the size and thus the cost of heliostat field. The optical concentration efficiency of SCR systems, which is defined as the ratio between the reflected power arriving on the receiver aperture (or other types of solar receiver) and the product of the incident solar power by the total area of heliostats [3], still remains relatively low. For example, the annual mean optical concentration efficiency (insolation unweighted) of PS10 [4] SCR system is only about 64.01% [5] (the main influencing factors of this efficiency are summarized in Table 1). Therefore, finding new solutions to improving the optical concentration efficiency of SCR systems has been one of the most important research focuses.

Previous studies have shown that the optical concentration efficiency of SCR systems is determined by various loss mechanisms, such as cosine, shading and blocking, spillage, reflection, and atmospheric attenuation [6–8]. Take PS 10 plant for example, the main influencing factors of the field optical efficiency of PS 10 plant are summarized in Table 1. Among these factors, the astigmatism effects and cosine loss of the conventional altitude-azimuth mounting heliostats are two major causes that lead to low concentration of SCR systems. Astigmatism refers to the aberrant spread of sun rays on the receiver caused by oblique reflection at the heliostat surface [11]. For usual altitude-azimuth mounting heliostats in SCR systems, the focal distance for parallel rays in the tangential plane is reduced by the square of a factor $1/\cos i$ (i is the incidence angle) due to oblique reflection at the heliostat surface, while in a sagittal plane the focal distance is not affected. Thus the heliostat appears shorter in the tangential direction and this causes an astigmatism. This astigmatism is detrimental for SCR systems because it would introduce spillage losses and thus reduce the

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Nomenclature

f	focal length of the paraboloidal mirror
H	height of the solar receiver
h	vertical distance between the target and the vertex of paraboloidal mirror in ground coordinate system
l	distance between the vertex of the paraboloidal mirror and the center of the plane mirror
m	coordinate component of the target in south-north direction in the ground coordinate system
n	coordinate component of the target in east-west direction in the ground coordinate system
n'	refractive index of the SMS lens
R_c	aperture radius of the paraboloidal mirror
S	horizontal distance between the solar receiver and the solar tracker
S'	actual distance between the solar receiver and the solar tracker
S_c	incident solar irradiance
α_s	solar altitude angle
γ	deviation angle of the target-aiming device from the due south direction
γ_s	solar azimuth angle
θ_1	rotation angle of the first axis of the solar tracker
θ_2	rotation angle of the second axis of the sun tracker
θ_3	rotation angle of the first axis of the target-aiming device
θ_4	rotation angle of the second axis of the target-aiming device
θ_s	half of the divergence angle of the incident sun rays

concentration efficiency of SCR systems. The cosine loss is the energy loss caused by oblique incidence of the solar radiation onto the heliostat surface [13]. Due to the oblique incidence, the effective area of the heliostat surface decreases as compared to the actual area of the heliostat. Some incident solar energy is thereby lost. The larger the solar incident angle is, the larger the fraction of the cosine losses. The cosine loss also exists in many other solar energy collection systems (such as flat photovoltaic systems, concentrated photovoltaic systems, and compound parabolic collectors) besides SCR systems. In order to reduce the cosine loss and boost the collected energy, various types of sun tracking systems have been developed [14,15]. For example, an ideal sun tracker would keep the PV panels, photo-thermal panels, solar concentrators, telescopes or other solar systems in an optimum position perpendicular to the solar radiation during daylight hours, thereby eliminating the cosine loss and increasing the collected energy. But in SCR systems, the cosine loss always exists due to the oblique incidence of solar radiation onto the heliostat surface.

So far, most of studies aiming to enhance the concentration efficiency of SCR systems have centered on the correction of astigmatism. For example, R. Zaibel et al. [16] proposed an Astigmatism Corrected Target Aligned (ACTA) heliostat, which is a non-symmetric heliostat with two different main radii of curvature and with different tracking axes. The ACTA heliostat makes it feasible to correct part of the astigmatism. Results showed that with this corrected heliostat the yearly average concentration improvements of up to around 50% for northern heliostats were achieved, and for southern heliostats, large improvements of factors 3 to 4 in were achieved. In order to further improve the concentration performance of the heliostats, K.K. Chong et al. [17] proposed a Non-Imaging Focusing Heliostat (NIFH). In the NIFH heliostat, a good approximation to the full astigmatism correction can be done with the application of target aligned mount. In addition, a prototype of solar furnace system using fixed geometry NIFH heliostat was constructed. The simulated results showed that the maximum solar concentration of 1039 suns was achieved, and the prototype of solar furnace had been verified to achieve the temperature of at least 1737 K. Y.T. Chen et al. [18–21] carried out many researches on the spinning-elevation tracking method. They proposed a non-imaging focusing heliostat to achieve high concentration while keeping the fabrication cost relatively low [22]. Their modification from the conventional heliostat comprises two steps: firstly, some grouped slave mirrors are designed such that they are able to be controlled to realize a variable focusing; secondly, the usual azimuth elevation tracking mode is replaced by an rotation-elevation mode. These modifications can further mitigate the effect of astigmatism of the conventional heliostat. They also designed the first prototype of this heliostat [23]. Experiment results showed that the highest furnace temperature of 3400 °C had been recorded through the melting of pure tungsten wires, which witnessed a quite satisfactory high concentration. C.S. Lim and L. Li [24] analyzed the flux distribution of a solar furnace which consists of the aforementioned non-imaging focusing heliostat and a spherical concentrator through a digital simulation approach, and

Table 1
Influencing factors of the field optical efficiency of PS 10 plant [9–12].

	Value	Annual mean/ instant value	Explanation
Different influencing factors			
Cosine efficiency	>81%	Annual mean value	The cosine efficiency corresponds to the cosine loss of heliostats, which is the energy loss caused by oblique incidence of the solar radiation on heliostat.
Heliostat reflectivity	88%	Annual mean value	The heliostat reflectivity is the reflectivity of the heliostat surface.
Atmospheric attenuation	95%	Annual mean value	The atmospheric attenuation corresponds to the energy loss caused by long-distance transport of the reflected sun rays. It can be simplified as a function of the distance between the heliostat and receiver.
Interception efficiency	Unpublished	Annual mean value	The interception efficiency is calculated as the ratio between the number of the sun rays intercepted by the receiver aperture and the number of total reflected rays.
Shadowing and blocking efficiency	>95.5%	Annual mean value	The shadowing and blocking efficiency refers to the efficiency considering the shadowing of incident sun rays by other heliostats and the blocking of reflected sun rays by other heliostats.
Annual mean optical efficiencies			
Annual mean field efficiency	Unpublished	Annual mean value	The annual mean field optical efficiency is the ratio between the total collected solar energy on the solar receiver and the total incident solar energy in a year.
Insolation unweighted annual mean field efficiency	64.01%	Annual mean value	The insolation unweighted annual mean field optical efficiency is the annual mean field optical efficiency calculated under the assumption that the value of the incident solar insolation is constant.