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Test of a solar parabolic trough collector with rotatable axis tracking

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HIGHLIGHTS

- The prototype of 300-kW_{th} solar parabolic trough collector is tested.
- The rotatable axis tracking except for the north-south axis is adopted.
- Adopting rotatable axis tracking reduces the daily average cosine loss by 10.3%
- The experimentally efficiency of the solar collector is reached by 40% in winter.
- Adopting rotatable axis tracking enhances average collector efficiency by 5.0%

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ABSTRACT

The concentrating solar power is a promising technology for scalable solar electricity. The conversion of concentrated sunlight into heat is of paramount importance in the concentrating solar power. The current commercial parabolic trough collector has an annual average efficiency of approximately 50%, and the poor efficiency mainly results from the cosine loss. In this paper, a 300-kW_{th} solar parabolic trough collector with north-south and rotatable axis tracking is originally presented. The rotatable steel-support frame and the slide rail can achieve the horizontal rotation of the parabolic trough collector. The rotation of the collector can change the surface azimuth angle of the collector, further reducing the solar incidence angle and thus reducing the cosine loss. Two patterns of tracking are adopted in this prototype. In summer, the solar incidence angle is small, and the north-south axis tracking is adopted. In winter, the solar incidence angle is large, and the cosine loss is serious, so using the rotatable axis tracking enables more solar irradiation to be harvested. The experimental results show that, by using the rotatable axis tracking, the daily average efficiency can be enhanced from 43% to 48% in winter. This study provides a promising approach for effectively reducing the cosine loss for the scalable parabolic trough collector, providing the possibility of improving the annual average collector efficiency and realizing cost-effective solar energy use.

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1. Introduction

The concentrating solar power is regarded as a significant candidate for large-scale renewable electricity. The concentration of solar energy mainly harvests direct sunlight from sunshine (called direct normal irradiance, i.e., DNI). On clear days, the DNI represents 80–90% of the solar energy reaching the Earth's surface [1]. Thus far, two main tracking methods, line focus and point focus, have been employed to concentrate the direct sunlight entering into the earth. The solar parabolic trough collector, as one of popular solar technologies, has been widely applied in the industrial processing of heat and solar thermal electricity, in which north-south or east-west axis line tracking is adopted. This type of solar parabolic trough collector has the potential for low cost, simpler tracking control and large-scale commercial application [2]. Up to 2013, most existing solar power stations (71.0%) used a parabolic trough collector to harvest solar energy, as it is a relatively mature technology compared to other technologies [3,4].

The solar collector efficiency is a key and important indicator for evaluating the performance of solar energy utilization. For the solar parabolic trough collector with line focus, the peak efficiency of the collector has been reported in the range between 70% and 77% [5–7]. Meanwhile, the annual average efficiency is relatively low and is still limited to approximately 50% [8–10]. Thus, half of the concentrated solar energy is not yet utilized over an entire year when larger solar fields are employed. The energy loss of the solar

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Nomenclature

A	aperture area of the collector (m^2)
c_p	specific heat at constant pressure ($kJ\,kg^{-1}\,k^{-1}$)
D	aperture width of the collector (m)
d	outer diameter of the tube (m)
DNI	direct normal irradiance ($kW\,m^{-2}$)
m	flow rate ($kg\,s^{-1}$)
P	pressure (kPa)
Q_{Solar}	input solar energy (kW)
Q_{abs}	absorbed solar heat (kW)
Q_{loss}	energy loss (kW)
$Q_{release}$	released heat (kW)
T	temperature (K)
t	time (s)

Greek symbols

η	solar collector efficiency
δ	uncertainty
∂	partial differential

Subscripts

collector	collector
in	inlet of the collector
out	outlet of the collector
oil	conduction oil
th	thermal
tube	receiver tube
water	water

parabolic trough collector mainly exists as optical loss, thermal loss and cosine loss. The optical loss is mainly caused by the materials of the mirror and glass envelope. The thermal loss occurs via radiation and convection due to the difference in temperature between the absorber tube and the ambient environment. The cosine loss occurs due to the non-zero solar incidence angle and can be even higher, up to 50%, in winter [11,12].

Most parabolic trough collectors adopt north-south axis tracking and only track the solar azimuth angle rather than the solar elevation angle. Both the solar azimuth angle and the solar elevation angle determine the solar incidence angle, i.e., the angle between the sun's rays and the normal vector to the aperture of the collector surface. For the northern hemisphere, the parabolic trough collector has a smaller solar elevation angle in winter, resulting in a larger solar incidence angle and serious cosine loss, and thus part of the solar incidence sunlight is not concentrated and not further utilized [13–15].

To reduce the cosine loss of the parabolic trough collector using the north-south tracking mode, Donald [16] proposed that, if the tilt angle of the solar collector could be adjusted monthly, the collector would maintain a higher solar elevation angle all throughout the year and thus obtain a higher annual performance. El-Kassaby [17] further gave two empirical equations to calculate the optimum tilt angle for each month and all year at any latitude, respectively. The calculated results indicated that, using the monthly optimum tilt angle, the collector can concentrate 99.2% of the annual solar incidence energy to the receiver. Yi et al. [18], using a numerical stochastic algorithm method, calculated the annual optimum tilt angle for five typical cities in China and gave an expression between the tilt angle and the annual direct solar radiation for each city. Lubitz [19] studied the optimum tilt angle for single-axis tracking surfaces at each site versus latitude in the contiguous United States of America. The calculation indicated that the optimum tilt angle for a single-axis tracking panel was, on average, 18.6°. Additionally, the decision of whether to manually tilt panels required balancing the added cost in labor and panel support versus the extra energy generation and the cost value of that energy. Eck et al. [20] designed and constructed a tilted parabolic trough collector with a length of 25 m and tilt angle of 4°. In fact, this tracking method proposed a challenge for the state-of-the art parabolic trough collector having a large mirror field (a single row is 300 m [21]).

In addition, two-axis tracking was taken as one of the most efficient and primary tracking methods for the parabolic trough collector technology. This type of tracking maintained a zero incidence angle and then removed the effect of cosine loss on collector performance. Khalifa et al. [22] investigated the performance improvement of a two-axis tracking concentrating solar energy collector. It was concluded that a two-axis tracking system may increase the energy gain of the collector by up to 75%. Yao et al. [23] proposed that low-accuracy trackers cannot be used in concentrating solar power system because their accuracy can lead to a great loss of the solar energy intercepted by the receiver. Additionally, if a two-axis tracker, designed for high-accuracy tracking purposes, is used in a concentrating solar power system, there will be extra operational costs imposed by the control process.

The well-known Helioman 3/32 parabolic trough plant using two-axis tracking was installed in Europe [24]. This operation plant showed higher efficiency, which benefited from a zero incidence angle by adopting the two-axis tracking. This plant experience illustrated the problem that this type of two-axis tracking must provide stricter rigidity and tracking accuracy when suffering from high wind loads, as well as greater mechanical complexity. National Renewable Energy Laboratory (NREL) [25] designed and manufactured a large-payload parabolic trough collector with two-axis tracking that was capable of carrying a maximum vertical load of 9000 pounds with a tracking accuracy of 1 milliradian. Bakos and Al-Soud [26,27] proposed a small-scale parabolic trough collector with two-axis tracking that has resolved the problem of frequent tracking and standing in the sun. It was noticed that two-axis tracking was mainly adapted to the small-scale parabolic trough collector field.

As indicated in previous works, single-axis tracking is suitable for large-scaled concentrating solar power system. However, the solar incidence angle varying with the diurnal and seasonal movement of Earth is not zero, and the cosine loss seriously impairs the collector efficiency. Adjusting the tilt angle of the collector can reduce the solar incidence angle and thus reduce the cosine loss. It is a fact that this type of method also adds panel support and poses a challenge for the large-scale field. Although the parabolic trough collector with two-axis tracking can remove the effect of cosine loss on collector performance, increased tracking accuracy and greater mechanical complexity limit its large-scale application. In our previous studies [28–30], solar energy loss was theoretically analyzed and compared between rotatable axis tracking and north-south axis tracking in a solar-coal hybrid system. The results showed that the rotatable axis tracking method has the potential to reduce cosine loss and thus enhance the annual solar-field efficiency by approximately 4 percent points.

In this paper, the prototype of a 300-kW_{th} solar parabolic trough collector, which has rotatable axis tracking and north-south axis tracking, is presented to carry out the test on the solar thermal performance in typical days. Compared with normal single-axis tracking, the tracking accuracy of rotatable axis tracking can be

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