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Research paper

Performance analysis of a novel sun-tracking CPC heat pipe evacuated tubular collector

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HIGHLIGHTS

- A TCPC collector combines crank rod mechanism and CPC collector is proposed.
- The solar incident angles and optical performances are numerically investigated.
- The thermal performances at different tracking modes are experimentally studied.
- The average optical efficiency at ITM is 3.6% higher than that at the CTM.
- The output energy at a tracking mode is 1.9~2.3 times higher than that at the FM.

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ABSTRACT

A tracking compound parabolic concentrating (TCPC) solar collector with concentration ratio of 2.3, which combine the CPC, heat pipe evacuated tubular receiver and crank rod transmission mechanism together, was developed and studied in this paper. A theoretical model was created to simulate the solar incident angles and the optical performance of the TCPC collector. In addition, thermal performances of the TCPC collector at different operation modes were investigated experimentally. The simulation results show that, the transversal projection angle (θ_t) is the vital factor that affects the optical performance. When θ_t is within the range of -23.5° and 23.5°, the incident angle modifier (IAM) of the TCPC collector reaches 0.95~1.14. By means of tracking, the average optical efficiency is over 60%, while it is decreased to 30% under the fixed mode (FM). The output energy of the TCPC collectors during the test period can be highly increased, which is 1.9~2.3 times higher than that at the FM. Furthermore, the intermittent tracking mode (ITM) is more power frugal and efficient as the average optical efficiency is 3.6% higher than that at the Continuous tracking mode (CTM). These verify that the ITM is the optimal operation mode for the TCPC collectors.

1. Introduction

Solar thermal energy technology includes hot water preparation, cooling, industrial process and space heating is one of the most important renewable energy technologies. In commercial solar thermal energy utilization, the parabolic trough collectors (PTC) are used frequently. However, some other designs, for example Compound Parabolic Concentrating (CPC) solar collectors are also considered, as they do partly collect diffuse radiation and cost effective [1].

Concept of CPC was introduced by Winston [2], which is a non-imaging type of concentrator and receives most attention in solar thermal energy utilization. Heretofore, many papers concerned on the optical and thermal performances of the CPC solar collectors have been presented. Rabl [3] developed a simple analytic technique for the calculation of the average number of reflections for radiation passing through a CPC, which is useful for computing optical loses. Then, a more complete analysis of the optical properties of the CPC was discussed by Jones [4]. Thermal performances of the CPC collector with an evacuated double pipe receiver in steady-state condition [5] and in dynamic-state condition [6] were

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Nomenclature

A	Area, m^2
c	specific heat of the water, J/(kg·K)
C	geometric concentration ratio
G	solar irradiance, W/m^2
$\overline{G}$	daily average solar irradiance, W/m^2
h	solar altitude angle, °
$K(\theta)$	incident angle modifier at a given solar incident angle
$K(\theta_t,0)$	incident angle modifier at a transversal projection angle
$K(0,\theta_l)$	incident angle modifier at a longitudinal projection angle
$\dot{m}$	mass flow rate, kg/s
Q	heating capacity of the water, W
s	rotation angle, °
t	Time, s
T	temperature, °C
$\overline{T}$	daily average temperature, °C
U	heat loss coefficient for daily linear regression, W/(m^2·°C)

Subscripts

a	ambient
f	water in the tank
in	inlet
l	Longitudinal projection
out	outlet
t	transversal projection

Greek symbols

$\eta_o(0,0)$	optical efficiency at the normal incident angle, %
$\eta_o(\theta)$	optical efficiency at any incident angle, %
$\eta_o(\theta_t,0)$	optical efficiency at a transversal projection angle, %
$\eta_o(0,\theta_l)$	optical efficiency at a longitudinal projection angle, %
η	instantaneous thermal efficiency, %
$\overline{\eta}$	daily thermal efficiency, %
$\overline{\eta}_o$	daily average optical efficiency, %
θ	solar incident angle, °
θ_t	transversal projection angle, °
θ_l	longitudinal projection angle,°
β	tilt angle of the TCPC collector, °
γ	the azimuth angle of the TCPC collector°
κ	the included angle between sunlight and V-axis, °
τ	the included angle between sunlight and E-axis, °
σ	the included angle between sunlight and S-axis, °
α	the solar azimuth angle, °
δ	the solar declination, °
λ	the geographic latitude, °
ω	the hour angle, °

Abbreviations

CPC	Compound parabolic concentrator
CTM	Continuous tracking mode
FM	Fixed mode
IAM	Incident angle modifier
ITM	Intermittent tracking mode
PTC	Parabolic trough collector
TCPC	Sun-tracking CPC

preferentially revealed and were brought to a level of thoroughness, respectively. In particular, the axial heat transfer in the CPC collector was taken into account in the dynamic-state condition [6]. Eames and Norton [7] performed a detailed parametric analysis of heat transfer in CPC collectors using a unified model for their optical and thermo-physical behavior.

For an ideal CPC collector, the acceptance angle, as the maximum angle at which all rays incident on the concentrator are transmitted to the receiver, is a key parameter. Thus, the CPC collectors with a low concentration ratio, i.e. with a large incidence angle, could run very well at the stationary mode. The economic optimization [8], geometric and optical properties [9] and the thermal optimization [10] of the stationary CPC collectors were investigated. Besides, Pinazo [11] derived the correlation of the solar incidence angle and the acceptance angle of the CPC collector with arbitrary orientation, which would be useful to estimate the energy absorbed by the CPC receiver and provide guidance for the operation of the CPC collectors. Whereas, in a particular situation, some optical losses exit due to the imperfect focusing and the optical properties of the materials [12]. A majority of publications on reforming the CPC constructions and improving the optical and thermal performance of the CPC collectors have been carried out. For example, A novel lens-walled CPC was described and the optical performance was determined by Su et al. [13]. The simulation results indicated that the lens-walled CPC had a larger acceptance angle and an apparently better performance compared with the mirror CPC. Aghbalou et al. [14] combined the CPC and heat pipe absorber together, developed a novel solar collector and used as the generator in a solar adsorption system. Tripanagnostopoulos et al. [15] and Souliotis et al. [16] designed a novel asymmetric CPC collector, which showed a good thermal performance when used in water heating system. Gudekar [17] presented a cost effectively designed working model of CPC collector for solar medium temperature applications, which showed potential of improving thermal efficiency up to 71% by single tilt adjustment per day for a daily 6 h operation. Li et al. [18] investigated the optical and thermal performance of the CPC solar collectors with the U-shape evacuated tubular absorber. The CPC collector with a concentrating ratio of 6 did need to be adjusted five times per day due to its small half-acceptance angle. Moreover, Khalifa and Mutawalli [19] made an experiment on the effect of two-axis tracking CPC solar collector deducing that the tracking solar collector showed a better performance with an increase in the collected energy of up to 75% compared with identical fixed solar collector. Kim et al. [20] built a single axis tracking CPC solar collector system, with the reflector inside a double-layer glass evacuated-tube to minimize the convective heat loss, was reported more stable and about 14.9% higher than that of the fixed system. Tang et al. [21] developed a polar axis tracking CPC photovoltaic system to follow the tracks of the sun all day long, of which the solar energy obtained per year was 2.1–2.3 times higher than that of the stationary system. Conclusively, the designs that take advantage of CPC collectors (even with low concentration ratios) with solar tracking are promising ways to improve both the optical and the thermal performances of the CPC collectors. However, the conventional solar tracking CPC systems arrange the CPCs together on a tracking panel, which has limited the number of the CPCs greatly and hindered their integrated in roofs of the buildings, causing them to be comparatively expensive and unsuitable for large-scaled applications in the middle-low temperature areas.

Motivated by above situations, the cost-effective tracking CPC solar collectors, which combine the crank rod transmission mechanism and CPC collectors together are designed and constructed. The crank rod transmission mechanism, which is relatively cheap and easy to assembly is taken to adjust the orientation of the TCPC collectors to track the sun. Each TCPC collector includes a CPC