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An on-site test method for thermal and optical performances of parabolic-trough loop for utility-scale concentrating solar power plant

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ABSTRACT

An on-site test method for thermal and optical performances of parabolic-trough (PT) loop for utility-scale concentrating solar power (CSP) plant is proposed. This method is comprised of sequentially off-focus and in-focus tests. The off-focus test is first conducted for thermal performance as that in a complete PT loop, the front (upstream) collectors are used to heat up the heat transfer fluid (HTF) flowing through the rear (downstream) off-focus ones (the test section) while being cooled by the ambient. The front-rear order is reversible to test all the collectors. The correlation between the heat loss and the absorber (outer surface)-ambient temperature difference of the collectors is obtained by fourth-order polynomial data-fitting. Then, the in-focus test is carried out for optical performance, which is achieved based on the energy balance. The heat loss is calculated based on the correlation acquired in the off-focus test. The incident solar radiation, heat gain, cosine loss and end loss are calculated based on the meteorological data, experimental data, local time and astronomical conditions, respectively. Therefore, the optical performance, i.e. the optical efficiency, is readily achievable. The proposed test method was implemented on the 300 kWt experimental rig located in Langfang, Hebei, China. The optical efficiency is evaluated to be (70.77 ± 1.08)%, which lies within the published range. On the other hand, a thermohydraulic model for the parabolic-trough collector (PTC) loop of the 300 kWt experimental rig was developed for system-level use. This model was incorporated with the optical efficiency obtained on the experimental rig. The good agreement between the simulation results and experimental data leads to the reciprocal verifications between the proposed on-site test method and the thermohydraulic model.

1. Introduction

The parabolic-trough collector (PTC) is the earliest and the most mature concentrating solar power (CSP) technology. The annual solar-to-electric energy efficiency of a PT-CSP plant is normally 15.4–16.1%, due to low collector efficiency in the solar field (solar-to-thermal energy efficiency). Generally, the main energy losses include cosine loss, optical loss and heat loss. The cosine loss caused by incident angle is normally the largest energy loss. It takes 5–35% of annual solar radiation from antarctic to arctic circle (Sun et al., 2017). Once the orientation and configuration of a PT loop is settled, the cosine loss is fixed and calculable at a given time. The cosine loss in winter is much larger than that in summer in the high-/mid-latitude region. The optical loss is caused by multiple optical reductions throughout the concentration and absorption. It is normally the secondarily largest energy loss and takes 4–25% of annual solar radiation from antarctic to arctic circle (Sun et al., 2017). The optical loss is hard to measure directly in the process of solar-thermal energy conversion. The heat loss, which is highly sensitive to the temperature of heat transfer fluid (HTF), is due to the convective and radiative heat transfer to the ambient. The correlation of heat loss against the characteristic temperature must be acquired for accurate quantification of thermal performance.

Since the optical efficiency, the index for the optical performance, is the product of several imperfect optical processes including the mirror reflectance, overall intercept factor, the absorptivity of absorber and the transmittance of glass envelope (Valenzuela et al., 2014), it is important to accurately quantify the optical efficiency. Schiricke et al. (2007) tested the absorptivity of the absorber and intercept factor by measuring the solar flux density distribution close to the focal line of the PTC and evaluated the optical efficiency. Kutscher and Netter (2014) evaluated the optical efficiency of heat collecting element (HCE) by determining the

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Nomenclature

A_a	overall aperture area of PTC (m^2)
a_a	aperture area per unit length of PTC (m^2)
c_p	specific isobaric thermal capacity (kJ kg^{-1} K^{-1})
D	diameter (m)
DNI	direct normal irradiance (W m^{-2})
F	focal length of PTC (m)
f	friction factor (–)
h	heat transfer coefficient (W m^{-2} K^{-1})
IAM	incident angle modifier (–)
k	heat conductivity (W m^{-1} K^{-1})
L	length (m)
δl	section length (m)
$\dot{m}$	mass flow rate (kg s^{-1})
Nu	Nusselt number (–)
Q_{gain}	heat gain (kW)
Q_{inc}	incident solar radiation (kW)
$Q_{loss,cos}$	cosine loss (kW)
$Q_{loss,end}$	end loss (kW)
$Q_{loss,heat}$	heat loss (kW)
$Q_{loss,opt}$	optical loss (kW)
q	heat flow per unit length (W m^{-1})
$q_{inc,ab}$	incident solar radiation per unit length (W m^{-1})
q_{gain}	heat gain per unit length (W m^{-1})
$q_{loss,heat}$	heat loss per unit length (W m^{-1})
$q_{loss,cos}$	cosine loss per unit length (W m^{-1})
$q_{loss,end}$	end loss per unit length (W m^{-1})
$q_{loss,opt}$	optical loss per unit length (W m^{-1})
Re	Reynolds number (–)
r	mirror reflectance (–)
Pr	Prandtl number (–)
T	temperature (°C)
ΔT_{amb}	absorber (outer surface)-ambient temperature difference (K)
ΔT	total temperature rise (K)
W	aperture width (m)

Greek letters

α	thermal diffusivity (m^2 s^{-1})
γ_T	overall intercept factor (–)
ε	absorbance (–)
η_{col}	overall efficiency (%)
η_{opt}	optical efficiency (%)
θ	incident angle (°)
τ	transmittance (–)

Superscripts

if	in-focus test
of	off-focus test

Subscripts

1	related to working fluid
2	related to inner surface of absorber
3	related to outer surface of absorber
4	related to inner surface of glass envelope
5	related to outer surface of glass envelope
6	related to ambient
7	related to sky
amb	ambient
ave	average
cond	conductive heat transfer
conv	convective heat transfer
HTF	heat transfer fluid
in	inlet
i, j	index
out	outlet
rad	radiative heat transfer
tube	absorber tube

slopes of temperature-to-time curve for the thermal mass and the absorber. It is noteworthy that the overall optical efficiency of PTC is not simply the product of the optical efficiencies of HCE and reflecting mirror. Random factors such as deformation and tracking error would significantly influence the optical performance of PTC (Guven and Bannerot, 1986; Zhu, 2013). In other words, only the optical efficiency measured with an on-site test method makes sense for the practical performance evaluation.

Kutscher et al. (2012) separately evaluated the thermal loss in an indoor test and the optical efficiency in an outdoor test when the PTC was operating at ambient temperature. The collector efficiency was then achieved by post-processing the data obtained from the two tests (there was no cosine loss due to double-axis tracking mode). Lüpfert et al. (2003) introduced the ET150 PTC with lighter framework and tested the optical efficiency when the operating temperature was close to the ambient. Janotte et al. (2009) introduced a quasi-dynamic test method with wider toleration of data fluctuation. Heat loss terms and optical efficiency were tested in this method. Good agreement with traditional steady-state method validated the proposed method. In addition, the influences of uncertainties of measurement equipment on the thermal and optical performances test of collectors were also analysed in Janotte et al. (2010). In the above-mentioned literatures, optical efficiency were tested when the operating temperature was much lower than the normally operating temperature of solar field. However, the length of practical PT loops is beyond 100 m and the operating temperature is much higher than the ambient temperature (Janotte, 2016). The optical performance changed with the operating temperature due to the deformation of HCE supports. Therefore, above-mentioned methods is not suitable for the optical performance evaluation of practical PTCs.

Valenzuela et al. (2014) proposed a test method for optical efficiency of large-size PTCs. They first obtained the correlation of heat loss with HTF-ambient temperature difference by linear data-fitting of cooling test data. Then, they conducted heating test when the incident angle equals 0. To guarantee the zero-incident-angle condition, they used a PT loop working in east-west single-axis tracking mode. They calculated the heat loss according to the linear correlation and obtained the optical loss based on energy balance of PTC. However, in this method, the HTF temperature, instead of the outer surface temperature of absorber are used to calculate the temperature difference regarding ambient temperature. Note that the HTF temperature is higher than the outer surface temperature of absorber in the cooling test while lower than that in the heating test. For example, the deviation in the temperature could reach above 8 K in normal working (heating) conditions. Therefore, errors could be introduced when the correlation obtained by cooling test data is used for the heating test data to calculate the optical efficiency. More importantly, it is well known that almost all the utility-scale PT-CSP plants implement the north-south single-axis tracking mode due to the good balance between performance and cost, which means that the zero-incident-angle condition in