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On-Site Parabolic-Trough Collector Characterization in Solar District Heating Plant under Quasi-Dynamic Conditions

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Abstract. The parabolic-trough collectors (PTC) are the technology most widely used worldwide in concentrating solar power (CSP) and solar thermal electrical (STE) plants. This kind of collectors have not been certified during the first decades of the CSP plant installation because of the absence of a standard for testing these large-size collectors. The existing standards for testing solar collectors were not adapted to its peculiarity. In 2018 a standard IEC 62862-3-2 has been published especially for large-size PTC testing. In the present work, this methodology has been validated in-situ in a solar heating plant in Denmark on the solar field of six PTC rows, using the monitoring data of 15 testing days selected within more than one year. Furthermore, different possible improvements are proposed.

INTRODUCTION

The testing of parabolic-trough collector (PTC) has been performed for the last decades based on different standards [1, 2]. International standards have been developed for decades to test conventional solar thermal collectors within the international committee ISO/TC 180 and the European committee CEN/TC 312. In 2012, another committee IEC/TC 117 was created especially for setting up standards for solar thermal power plants, boosted by the Spanish standardization committee AEN/CTN 206/SC 117. In this committee, a working group was created in 2015 to deal with the testing and certification of large-size PTC for concentrating solar power (CSP) plants. The publication of the new standard IEC 62862-3-2 [3] in 2018 for CSP large-size PTC testing will allow the operator of a CSP plant to certify the efficiency of the collector for the commissioning of the plant or to check its production. This standard describes the general requirements and the testing methodology for the PTC and its tracking accuracy. The efficiency testing conditions for thermal performance test under quasi-dynamic conditions are referred to the international standard ISO 9806 [4] new revision, made in 2018, which consider the large-size PTC. In some references from Fraunhoher [5,6] the in-situ methodology was presented, using dynamic method (DT). In a previous study [7], a large-size PTC array has been tested at the Plataforma Solar de Almeria (PSA) using a collector installed in East-West orientation and studying particularly the goodness of the quasi-dynamic (QDT) methodology. In-situ measurements were also performed in Malta on a solar tracking collector [8]. In the present work, six PTC rows installed in a solar thermal heating plant have been characterized using the same methodology but for in-site testing and for an orientation North-South like normally oriented in CSP plants.

Denmark is the country with most solar district heating plants worldwide, with more than 1.3 million m^2 installed area of solar collectors connected to district heating [9]. Most of the solar district heating uses flat-plate

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collector (FPC) technology, but a new plant has been installed using a 4039 m^2 PTC solar field in addition to a traditional 5960 m^2 FPC solar field. The first FPC field heats the district heating water from the return temperature level and then the PTC field heats the water to full temperature around 95 ºC with a better efficiency at higher temperature. In previous studies, more than one year data have been analyzed and compared to the production simulation of the plant with TRNSYS [10], and the accuracy of the trackers of the PTC have also been studied [11]. The purpose of the present study is to validate the standard methodology according to standard IEC 62862-3-2 [3], to check its model for optical characterization of those large PTC arrays using the QDT method, to identify the parameters influencing the collector model proposed and to see the applicability of the testing methodology to the in-situ PTC in plants.

MATERIAL

The collectors studied in this work are the six row of PTC constructed by AalborgCSP A/S in Tårs, in the northern part of Denmark [11, 12] (longitude 10.12º E, latitude 57.39 ºN). The PTCs were manufactured by Aalborg CSP A/S [12]. The receiver tubes were manufactured by Archimede Solar Energy [13]. The product name is HCEOI-12; the nominal length of the receiver tubes is 4060 mm; the absorber tube diameter is 70 mm; the glass tube thickness is 2 mm; the transmittance of the glass cover is τ= 96.5% and the absorptance of the absorber receiver surface, measured at wavelength between 0.25 and 2.5μm, is α= 96.0% [14]. The reflectors were manufactured by Rioglass, model Mirror Type LS-3, with a nominal reflectance of ρ = 94.5% [15]. Each collector is 12 m in length, each row is 124.457 m, and the collector aperture width is 5.774 m. See Fig. 1 for a general view of the plant and the PTC collectors.

FIGURE 1. Close up view of one of the PTC sections in the Tårs plant

The PTCs were tracking the sun in a direction along the tube oriented near North-South position. The orientation of the PTCs is slightly deviating from the North-South direction by 13.35º-13.37º. The exact orientation of each PTC row was estimated by a topography study with ±0.001º. The inclinometers used to measure the PTC rotation are manufactured by Gemac and are positioned on the collector structure at the drive station in the center of row. The tracking accuracy of ±0.5º had been checked in a previous study [11]. The heat transfer fluid used the plan was water

METHODOLOGY

Test collector input and output variables, were monitored by various sensors connected to a data acquisition system and recorded every minute. The final data value used for each sensor was an average of six minutes measurements. The main solar thermal collector inputs and outputs were the inlet and outlet temperatures T_{in} and T_{out} of the fluid inside the collector, the mass flow rate $\dot{m}$, the direct normal solar irradiance G_b and ambient temperature t_a close to the collector. An EKO MS-56 pyrheliometer mounted on a two axis solar tracker (Sunscanner SC1 system SC-003 A) was used for the direct normal solar irradiance G_b. A Kipp & Zonen SMP11 pyranometer is mounted on the horizontal axis to get the global irradiance G. The direct solar irradiance on the concentrator plane G_{bT} was calculated as $G_{bT} = G_b * \cos(\theta_i)$ where θ_i is the solar radiation incidence angle. The ambient temperature sensor was also a Pt100 Class A equipped with a radiation shield located close to the collectors. The mass flow rate measurement sensor was a Sitrans 149 FM MAG3100 P flow meters from SIEMENS. The incidence angles θ_i were calculated based on sun position using the algorithm proposed by Blanco-Muriel [16].

Equipment used for monitoring the collector is listed in Table 1. Most of the uncertainty sources are given by external laboratory calibration.

TABLE 1. Equipment specifications.

Physical value measured	Equipment model
Direct normal solar irradiance G_b	EKO model MS-56 pyrheliometer
Global solar irradiance G	Kipp & Zonen model SMP11 pyranometer
Inlet and outlet temperature T_{in}, T_{out}	Pt100 (Siemens-TS500 sensors)
Ambient temperature T_a	Pt100

This paper aims to validate the testing methodology proposed in the new revised ISO 9806 [4] Standard published in 2018, and which is referred to in the Standard IEC 62862-3-2 [3] for large-size PTC in-site and with orientation North-South. The performance model of a PTC, under quasi-dynamic (QDT) conditions can be written according to International standard ISO 9806 [4] and IEC 62862-3-2 [3].

The performance model of a PTC, under quasi-dynamic (QDT) conditions can be written as described in Eq. 1 or 2, according to the International standard ISO 9806 [4] and IEC 62862-3-2 [3].

$$\frac{\dot{Q}}{A_G} = \eta_{0,b} K_b(\theta_i) G_{bT} - a_1(T_m - T_a) \quad - a_2(T_m - T_a)^2 - a_5 \frac{dT_m}{dt} \tag{1}$$

$$\frac{\dot{Q}}{A_G} = \eta_{0,b} K_b(\theta_i) G_{bT} - a_1(T_m - T_a) \quad - a_8(T_m - T_a)^4 - a_5 \frac{dT_m}{dt} \tag{2}$$

The first term on the right of the expression with K_b is the optical efficiency for beam solar radiation; terms with a_1, a_2 and a_8 are thermal losses due to conduction, convection and radiation. The heat losses are referred to the temperature difference between the mean temperature in the solar field $(T_{out}+T_{in})/2$ and the ambient temperature (t_a). The optical efficiency for beam radiation $\eta_{0,b}$ can also be written as $F'(\rho\gamma\tau\alpha)_{en}$ which is the product of the heat removal factor F', reflectors reflectance ρ, intercept factor γ, transmittance of the glass cover τ, and solar absorptance of the receiver absorber surface α, respectively, at normal incidence ($_{en}$). In the case of Tårs plant, the average temperature during the year has a reduced variability, so the parameter a_1, a_2 or a_8 would have been too difficult to characterize. So, the heat losses were assumed to be linear in this range of temperature, only with a_1. And the value of a_1 was fixed to 0.04 W/(m^{2}K) based on the report [17,18] and also used in TRNSYS simulation in [10]. This value has been adapted to this temperature range and dimensions of the plant. So the model would be Eq. 3.

$$\frac{\dot{Q}}{A_G} + a_1(T_m - T_a) \quad = \eta_{0,b} K_b(\theta_i) G_{bT} - a_5 \frac{dT_m}{dt} \tag{3}$$

The parameters were identified by multiple linear regression (MLR) to analyze the collector's performance. The variable to be adjusted is the left term of the Eqs. 1-3, the output per square with no heat losses. And the parameters to identify are the optical efficiency $\eta_{0,b}$, the incidence angle modifier (IAM) $K_b(\theta_i)$ and the effective thermal capacity a_5. For the IAM, a model (Eq. 4) was used and one parameter had to be identified (b_0).

$$K_b(\theta_i) = 1 - \mathrm{b}_0\left(\frac{1}{\cos\theta_i} - 1\right) \tag{4}$$

A filter was applied to select the daily data (solar elevation $h_s > 0º$; tracking angle $\theta_T < 20º$; direct normal irradiance $G_b > 0$ W/m^2).

RESULTS

The whole test was selected (15 clear-sky days) from August 23th 2015 to August 17th 2016, with different inlet temperatures ranging from 55ºC to 80ºC. Fig. 2 shows the variability of the measured data during those testing days. The spread is within a wide range for each input representing normal collector operating conditions: direct normal irradiance G_b within [565;960] W/m^2, temperature difference tm-ta within [55;78]ºC, incidence angle within [0;60]º obtained before and after solar noon, flow rate within [62;110] m^3/h and wind speed (u) lower than 5.5 m/s.

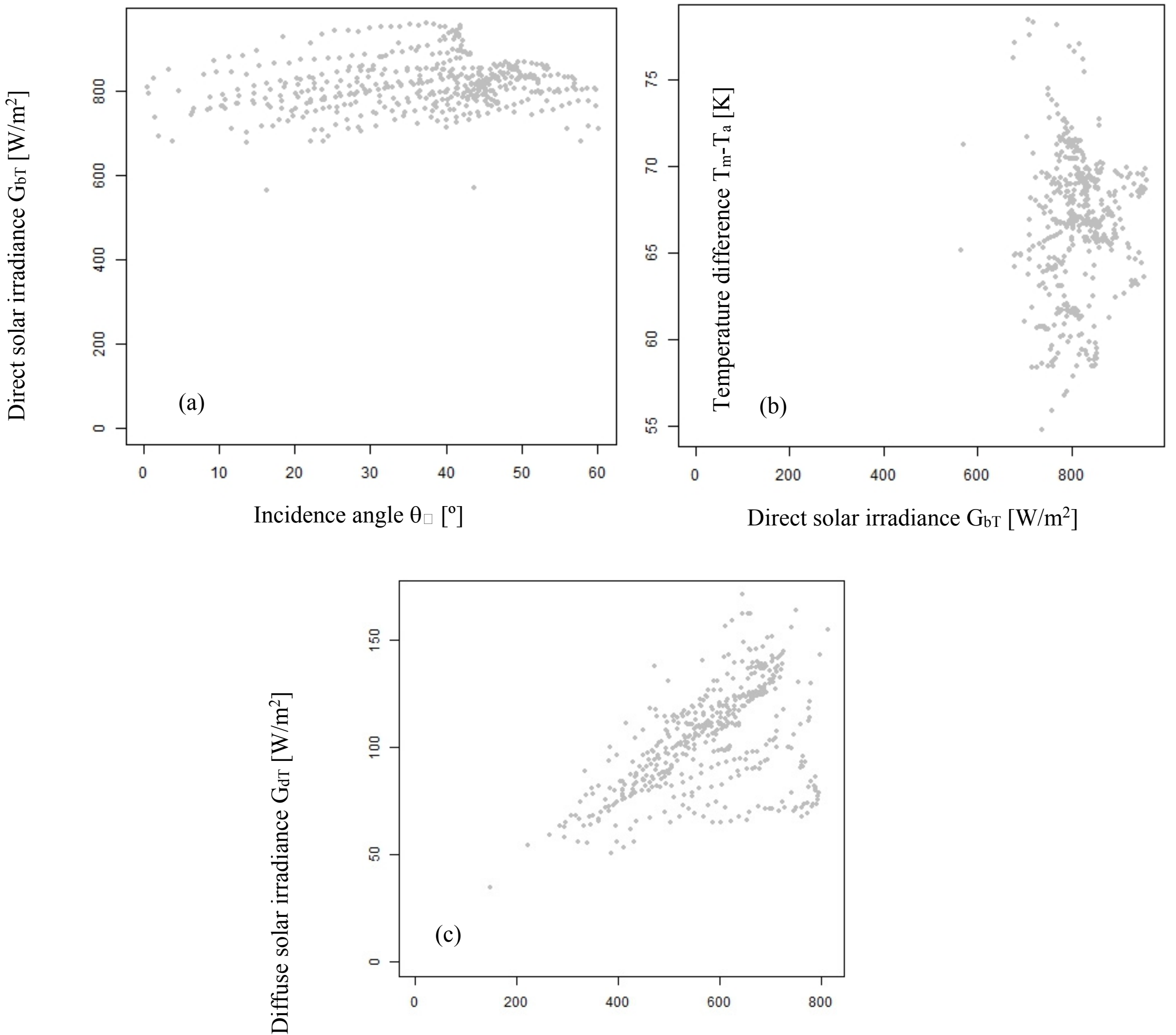

FIGURE 2. Variability of (a) Direct irradiance G_b vs. incidence angle θ_i (b) temperature difference (t_m - t_a) vs. direct irradiance G_b (c) Diffuse irradiance G_d vs. Global irradiance G

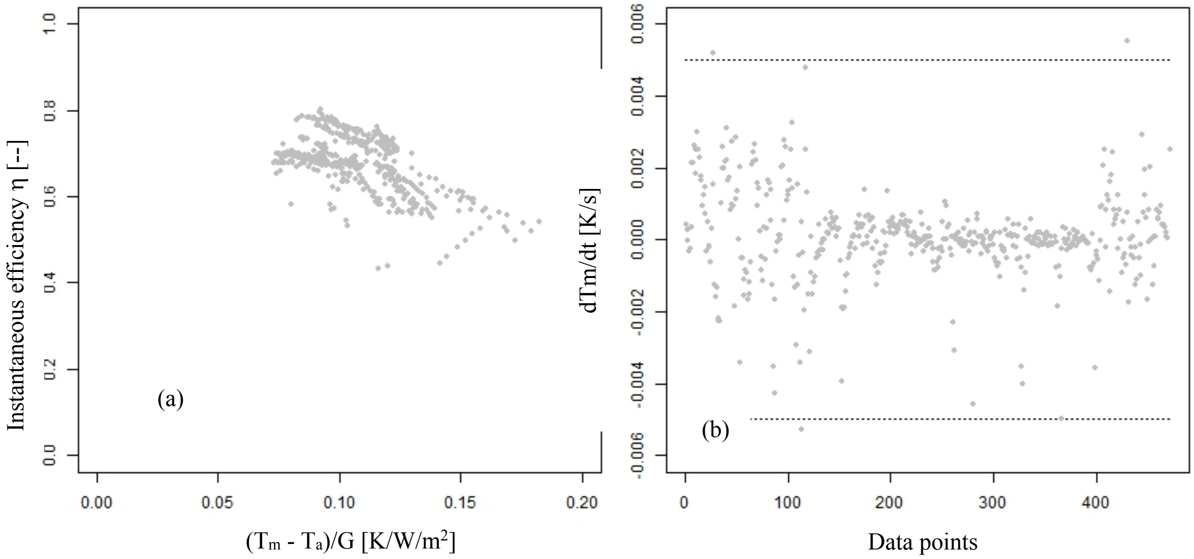

FIGURE 3. (a) Instantaneous efficiency η vs. temperature difference $(T_m - T_a)/G$ (b) collector average temperature dT_m/dt

Fig. 3 shows the instantaneous efficiency depending on the temperature difference. However, the solar district heating plant temperature range is more or less the same, so the value of the temperature difference over irradiance $(t_m - t_a)/G$ has low variability, between 0.05 and 0.15 K/W/m^2, for this reason it was decided not to fit the heat loss parameters. Most of the data selected were collected during clear sky sunny days, that is why most of the derivatives of the collector average temperature dT_m/dt were below ± 0.005 K/s (which is the ISO 9806 standard minimum requirement in order to have some unstable sky conditions), as it can be seen in Fig. 3 b. Although some points are over 0.005 K/s, as required by the standard ISO 9806

The results are shown in Table 2. Optical efficiency, effective thermal capacity and IAM were characterized, and the heat losses were fixed. The net optical efficiency was 73.6% similar to the theoretical value used in the simulation (75%). And the IAM coefficient b_0 was 0.21 also similar to the IAM used in the simulation (0.27). The effective thermal capacity was 2962 Jm^{-2}.K^{-1}.

TABLE 2. Parameter results

Parameter	Value	Uncertainty	Unity
Optical efficiency η_{0b}	0.736	± 0.004	-
IAM coefficient b_0	-0.21	± 0.02	-
Heat losses a_1 (fixed in advance to a typical value)	0.04	--	W.m^{-2}K^{-1}
Effective thermal capacity a_5	2962	± 1064	Jm^{-2}.K^{-1}

Fig. 4 shows the model fitting with measurement data. Fig. 4a shows a good agreement between measure and model points data, mostly within a 15% error.

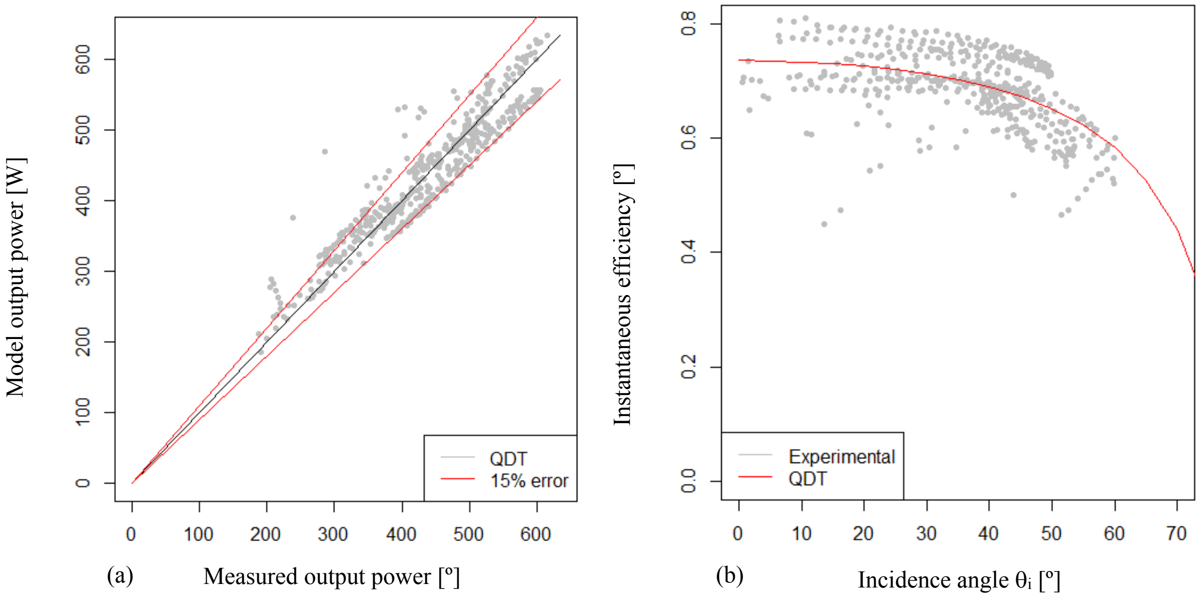

FIGURE 4. (a) Model output data vs measured data, and (b) instantaneous efficiency data vs incidence angles

Some points to be taken into account are for example the dirt of the DNI sensor that could increase unfairly the efficiency, as the DNI sensors are much more sensitive to dirt than a normal pyranometer with glass dome. In Tårs plant, the sensor has only been cleaned once a year in spring before the main summer season. In another plant in Brönderslev (North of Denmark), an automatic cleaning with pressurized air has been tried and seems to have good results. But for a standardized test this sensor should be cleaned regularly to insure the direct solar irradiance value. The diffuse radiation was not used in this analysis as the shadow ring was on the flat-plate collector plane and not on the PTC plane. But this variable could have an influence and could be taken into account in future works. Also the cleaning of the collectors should be considered in testing. In Tårs plant, the collectors have been cleaned in the start after the construction works and then only naturally cleaning by rain storms. This effect might also give some scatter during one year analysis, but could not be taken into account precisely in this paper. In a collector array like Tårs there are pipes between the collector rows that may need some correction, to have the highest accuracy in the analysis. In future works, the pipe loss could be included in the Eqs. 1-2. from plant data.

CONCLUSIONS

In Spanish standardization committee AEN/CTN 206/SC 117/WG2 a testing methodology was proposed to the international committee IEC TC 117. One working group has been specially created in order to define the testing standards for PTC (Standard project IEC 62862-3-2). This standard was published in 2018 and can be bought in IEC web page [17]

Six PTCs rows used for solar district heating in Denmark design by Aalborg CSP were analyzed using the standard IEC 62862-3-2 with the QDT method. The optical efficiency, the IAM and the effective thermal capacity were characterized during 15 testing days.

The methodology proposed in standard IEC 62862-3-2 has been experimented under real testing conditions on six large-size parabolic trough collectors. The results showed that the proposed methodology is possible to implement for an on-site parabolic trough collector testing. However the heat losses cannot really be determined as the temperature range in the collectors are similar along the testing days as seen in [8]. However, other effects such as the cleanliness of the sensors and of the collector should be considered in future works.

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