Evaluation of the tracking accuracy of parabolic-trough collectors in a solar plant for district heating

Sallaberry, Fabienne; Tian, Zhiyong; Jauregi, Odei Goñi; Furbo, Simon; Perers, Bengt; Zourellis, Andreas; Rothmann, Jan Holst

Published in:
A I P Conference Proceedings Series

Link to article, DOI:
10.1063/1.5067031

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Evaluation of the tracking accuracy of parabolic-trough collectors in a solar plant for district heating

Fabienne Sallaberry, Zhiyong Tian, Odei Goñi Jauregi, Simon Furbo, Bengt Perers, Andreas Zourellis, and Jan Holst Rothmann

Citation: AIP Conference Proceedings **2033**, 030015 (2018); doi: 10.1063/1.5067031
View online: https://doi.org/10.1063/1.5067031
View Table of Contents: http://aip.scitation.org/toc/apc/2033/1
Published by the American Institute of Physics

Evaluation of the Tracking Accuracy of Parabolic-Trough Collectors in a Solar Plant for District Heating

Fabienne Sallaberry[1, a)], Zhiyong Tian[2], Odei Goñi Jauregi[1, 3], Simon Furbo[2], Bengt Perers[2], Andreas Zourellis[4], Jan Holst Rothmann[4]

[1]*CENER (National Renewable Energy Centre of Spain), Solar Thermal Energy Department, Ciudad de la Innovación 7, 31621 Sarriguren, Navarra (Spain). Phone: +34 948 25 28 00*
[2]*DTU (Technical University of Denmark), Department of Civil Engineering, Technical University of Denmark, Nordvej Building 119, Kgs. Lyngby, 2800 (Denmark).*
[3]*UPNA (Public University of Navarra), C/ Arrosadia s/n; 31006 - Pamplona (Spain)*
[4]*Aalborg CSP A/S, Hjulmagervej 55, 9000 Aalborg (Denmark)*

[a)]Corresponding author: fsallaberry@cener.com

Abstract. The solar tracking system is a device which orientates solar concentrating systems in order to allow the focusing of the solar radiation on the receiver along the day. The accuracy of the solar tracker is a key parameter when compared to the acceptance angle of the concentrator in order to maximize the optical efficiency. The Taars solar heating plant was put into operation in Denmark in summer 2015 with a PTC solar field. The accuracy of the tracking system of the 6 PTC rows has been studied.

INTRODUCTION

Denmark is the country with the highest use of solar plants for district heating applications[1]. Most of the collectors used in existing large solar heating systems are flat plate collectors (FPC). Meanwhile, parabolic-trough collectors (PTC) are the most mature and prominent technologies for solar thermal power plants. A novel solar heating plant was put into operation in July 2015 in Taars, Denmark, combining 4039 m^2 of parabolic-trough collectors (PTC) with 5960 m^2 of flat plate collectors (FPC). Previous studies show the performance of the plant, both the PTC and FPC collectors [2-4].

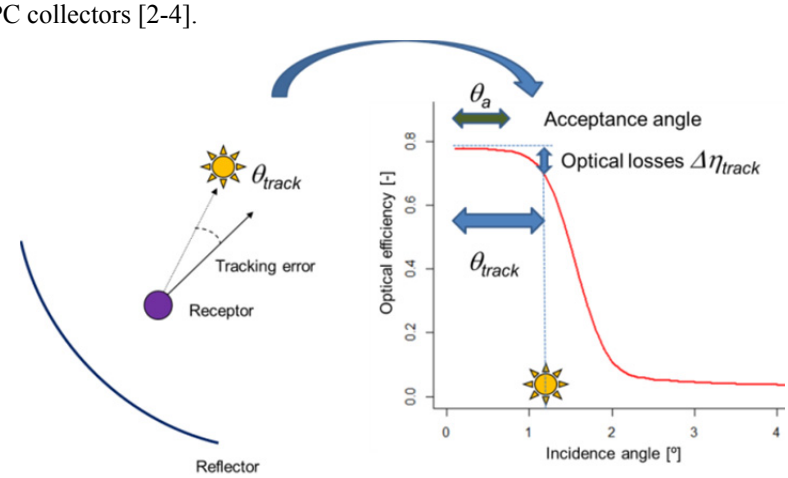


FIGURE 1. Scheme of the tracking error analysis

SolarPACES 2017
AIP Conf. Proc. 2033, 030015-1–030015-8; https://doi.org/10.1063/1.5067031
Published by AIP Publishing. 978-0-7354-1757-1/$30.00

In the present study only the PTCs were studied. Many studies done in the last decade have already characterized the PTC efficiency [5-8], but few on site efficiency studies focused on the tracking error estimation of the PTC trackers [9-11]. Fig. 1 presents a summary of the acceptance angle as described in [11] as the angle until which the tracking errors do not have a significant impact on the PTC efficiency.

Previous studies also give the state-of-the-art of the methodologies available to characterize the tracking error of concentrating-tracking collectors and its influence on the solar collector efficiency [12-13].

The acceptance angle is a key parameter of the concentrator. The suitability between the acceptance angles with the tracking angles was checked and the tracker was determined to be accurate.MATERIAL

A solar heating plant with 4039 m^2 PTC, in series with FPC collector field, has been constructed by Aalborg CSP A/S in Taars, in the northern part of Denmark [3,4] (longitude 10.12ºE, latitude 57.39ºN). This study analyses the tracking error of this PTC solar field. See Fig. 2 for a general view of the plant and the PTC collectors. The PTCs are manufactured by Aalborg CSP A/S, using receiver tubes manufactured by Archimede Solar Energy [14], and reflectors manufactured by Rioglass [15]. The receiver model is the product name HCEOI-12, with a nominal length of the receiver tube of 4060 mm (at ambient temperature); an absorber tube outer diameter of 70 mm, and a glass tube thickness of 2 mm. The reflector type is Mirror Type LS-3. Each collector length is 12 m, each row length is 124.457 m, and the collector aperture width is 5.774 m (See Fig. 2 for a view of the collectors and Table 1 for more specifications).

FIGURE 2. Schematic view of the plant; (b) View of the Taars plant (Denmark)

The PTCs track the sun in the transversal direction of the tube, and are oriented close to North-South direction. The orientation of the PTCs is slightly deviated from the North-South direction by 13.35º-13.37º. The exact orientation of each PTC row was estimated by topography study with a precision of ±0.001º. The inclinometer used to measure the PTC rotation is manufactured by Gemac. The data for the position of each of the 6 collectors were registered every 2 minutes by an inclinometer, positioned on the collector structure at the drive station in the center of the row.

TABLE 1. Geometrical parameters for the PTC collector

Parameters	Value
Absorber tube outer diameter *d* (m)	0.070
Absorber tube inner diameter (m)	0.066
Absorber tube solar absorptance (%)	96.0
Glass tube with anti-reflective solar transmittance (%)	96.5
Glass envelope outer diameter (m)	0.125
Glass envelope inner diameter (m)	0.119
Parabola width *w* (m)	5.77
Reflectors reflectance (%)	94,5
Numbers of modules per row	10
Mirror length in each module (m)	12
Geometrical concentration ratio $C_{geo} = w/(\pi\, d)$	26.24

METHODOLOGY

This study presents an analysis of the accuracy of six single-axis solar trackers of the PTC field in a solar plant for district heating.

First, the estimation is based on the measurement of inclinometers α mounted on the collector structure, as defined in Standard IEC 62862-3-2 [17]. The data analyzed are for more than one year (10/08/2015 to 17/11/2016) with a large range of incidence angles. For all data points the transversal and the longitudinal angles were calculated based on the sun position using the algorithm given by Blanco-Muriel [18]. A filter was applied to select the daily data (solar elevation h_s>0º; α>-100º; θ_T<20º; DNI > 0 W/m^2).

In order to check the accuracy of the solar tracker with a solar concentrator a definition of the acceptance angle should be defined. As for an ideal concentrating system, all the solar radiation entering with an incident angle smaller than this acceptance angle goes directed towards the receiver; whereas in a real solar collector, some optical losses exist due to optical properties, imperfections of materials, the size of the sun, the intercept factor, and the geometric imperfections. For this reason, using an accurate enough solar tracker is of high interest for the solar concentrator. The beam radiation IAM $K_b(\theta_T)$ crosses a limit threshold when exceeding the acceptance angle θ_a. The theoretical acceptance angle θ_a is defined for a PTC as described in Eq. 1, where Φ_r is the rim angle of the parabola and C_{geom} is the geometric concentration ratio [19]. The defocus angle θ_d is defined as the limit angle at which all the rays will miss the receiver, and is calculated by Eq. 2

$$\theta_a = \frac{\sin(\Phi_r)}{\pi C_{geom}} \tag{1}$$

$$\theta_d = \sin^{-1}\left(\frac{2 \cdot \tan(\frac{\Phi_r}{2})}{\pi C_{geom}}\right) \tag{2}$$

Thus, the dependency of tracking error angle on the optical efficiency has also been determined by ray-tracing simulations. A ray-tracing model was implemented in the software Tonatiuh, previously presented and validated experimentally [20]. Thus, the transversal and longitudinal incidence angle modifier IAM, $K_b(\theta_T,\theta_L)$, are estimated using a ray-tracing program. See Fig. 3 for a view of the PTC of the collector and its model in Tonatiuh.

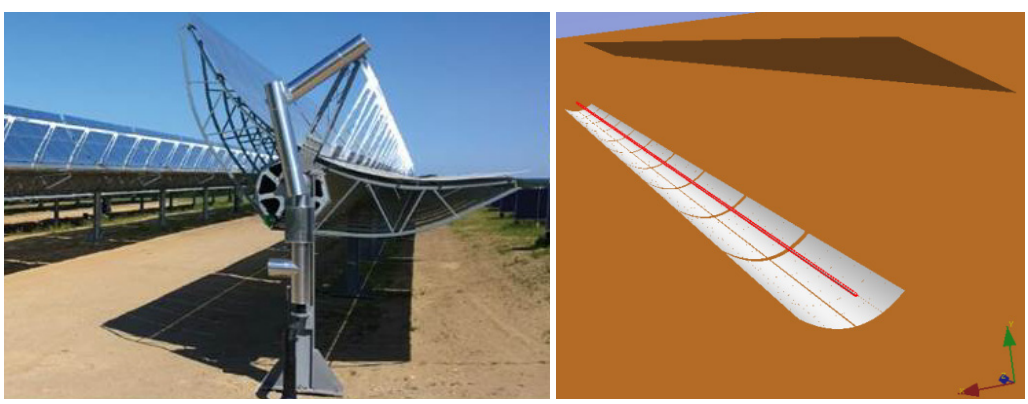


FIGURE 3. Picture and simulation of the PTC collector in Tonatiuh

In the ray-tracing program developed, the geometry of the solar concentrator is described by discrete elements with triangular surfaces. In this program four kinds of surfaces have been introduced: specular surfaces, opaque surfaces, interface surfaces (to implement glasses) and absorber surfaces (the receiver). The program calculates ray trajectories from one source (called the sun window) that emits to all the surfaces of the system, and only beam radiation is taken into account. The angular size of the sun has been modeled according to the Buie equations [21],

and Fresnel effects are handled using a Monte Carlo approach. This program can calculate the optical efficiency and the radiation flux distribution on the absorber.

For the estimation of the optical efficiency of the collector, first angle dependencies of optical properties are considered. The collector is simulated fixing the longitudinal angle and changing the transversal angle, in order to see how these dependencies affect the efficiency. The angular dependencies of the optical properties are calculated with the next expressions. The transmittance of the cover $\tau(\theta)$ dependence curve of the incidence angle is according to [22], and the normal value according to manufacturer $\tau(0º)=0.99$, as in Eq. 3.

$$\frac{\tau(\theta)}{\tau(0^{\circ})} = 1 - \tan^{5.1}\left(\frac{\theta}{2}\right) \tag{3}$$

The reflectance of the reflectors dependence curve of the incidence angle is according to [23], and the normal value according to manufacturer $\rho(0º)=0.94$. The absorptance of the receiver dependence curve of the incidence angle is according to [24], and the normal value according to manufacturer $\alpha(0º)=0.94$, as in Eq. 4.

$$\frac{\alpha(\theta)}{\alpha(0^{\circ})} = 1 - 0.017\left(\frac{1}{\cos\theta}\right)^{1.8} \tag{4}$$

The collector behaviour is simulated for angles from 0° to 90° in intervals of 10° in the longitudinal angle axis and from 0° to 2° in intervals of 0.2° in the transversal angle axis and the simulation is made with 10 million rays per iteration. The results are calculated with the information about photons that intersect with the receiver.

The optical efficiency is calculated with Eqs. 5 and 6:

$$\eta_{opt} = \frac{P_{receiver}(\theta_i)}{P_{incident}(\theta_i)} \tag{5}$$

$$P_{incident}(\theta_i) = G \cdot A_G \cdot \cos(\theta_i) \tag{6}$$

The IAM for any incidence angles, transversal and longitudinal $K_b(\theta_T,\theta_L)$, is calculated with Eq. 7:

$$K_b(\theta_T,\theta_L) = \frac{\eta_{opt}(\theta_T,\theta_L)}{\eta_{opt}(0°,0°)} \tag{7}$$

RESULTS

From the PTC dimensions, and according to the theoretical formulas Eqs. 1 and 2, the acceptance angle θ_a is 3.8 mrad (0.22º) and the defocus angle θ_d is 6.1 mrad (0.35º). The distribution of different incidence angles (tracking/transversal angle versus longitudinal angles) are presented in Fig. 4 with green dots, and the acceptance angle and defocus angle are shown with un-continuous lines. The longitudinal incidence angle change along the day from values from 0º to more +/-80º.

As seen in Fig. 4, the green dots are within the limit of the defocus angle lines, which means that for the 6 trackers, the tracking error (transversal angle) are mostly within the defocus angle θ_d (0.35º). However, some tracking errors higher than θ_d and up to 1º were observed (in the part top left of each graph inside the red ellipse). But those points were detected to be for days before 18/09/2015 when some tracking adjustment were done. It was observed that the behaviour of trackers nº 1–4 was similar, and that the trackers nº 5 and 6 had a similar behaviour too. Comparing to previous studies [16, 24], the tracking error lower than 0.5º is in line with normal PTC trackers behaviour.

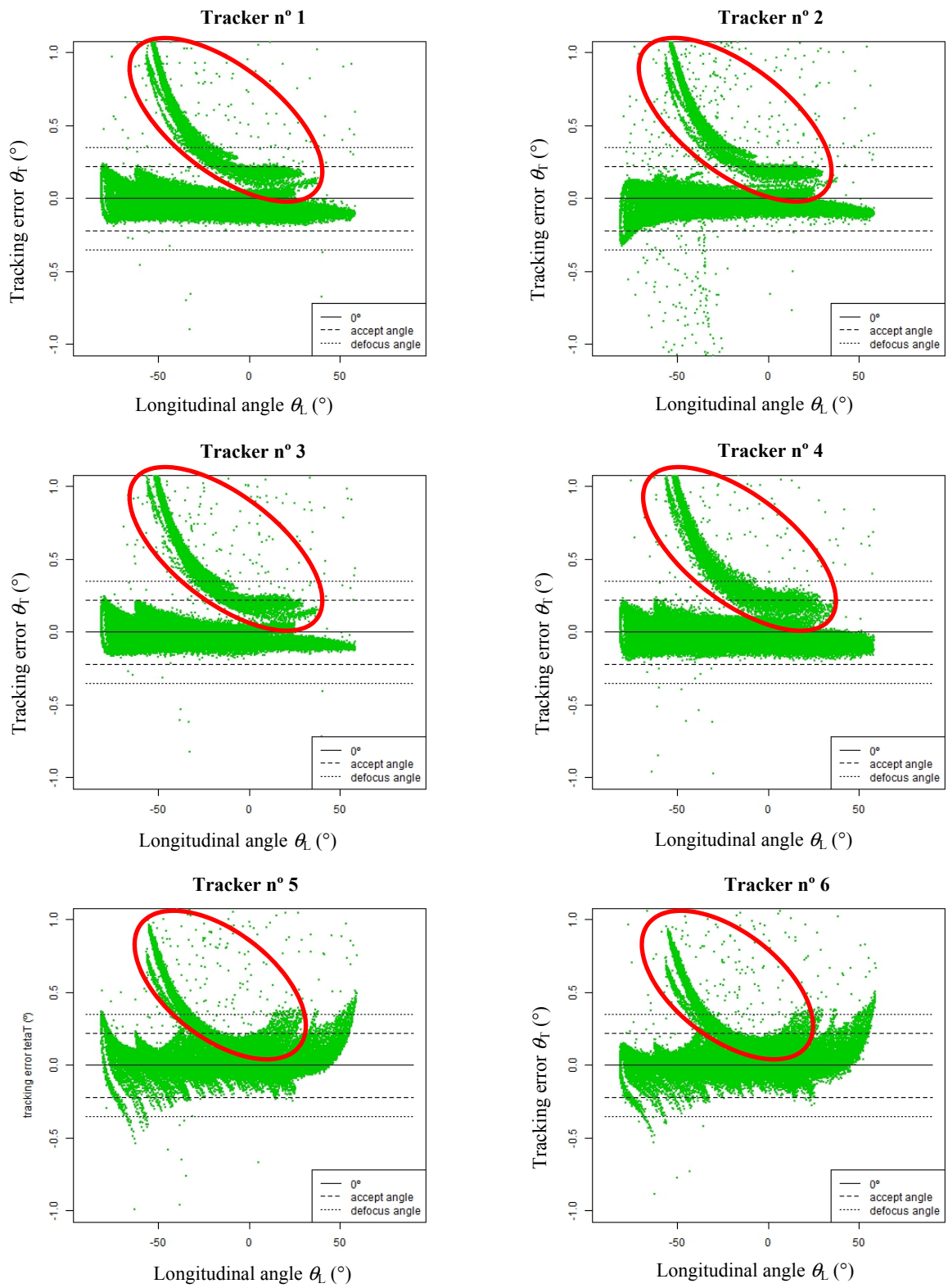


FIGURE 4. Tracking error distribution for the six solar trackers

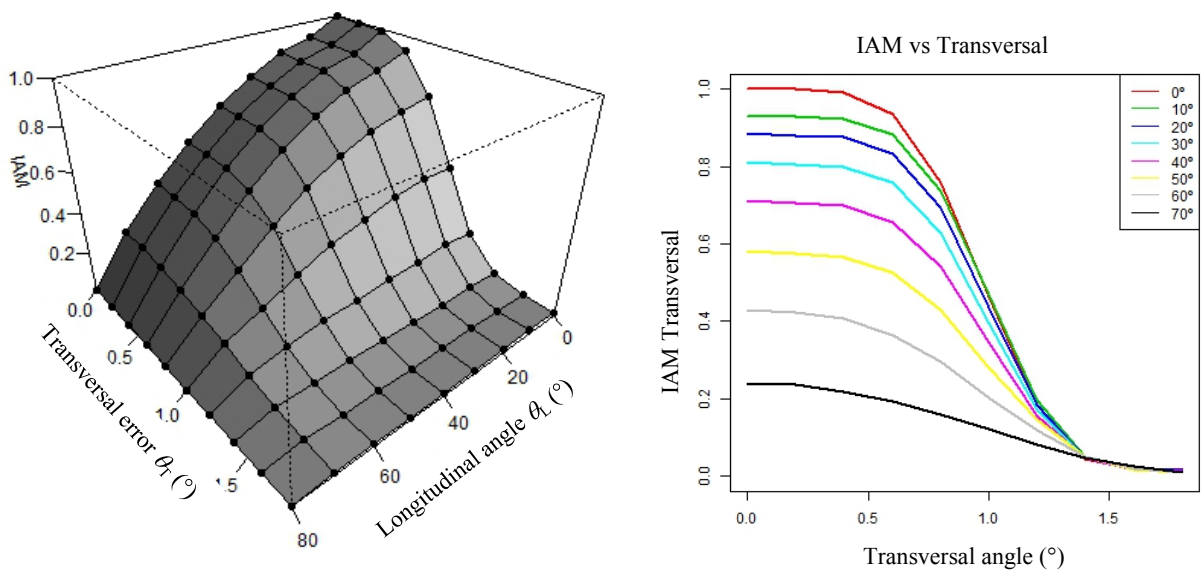
Table 2 gives an overview of the maximum, minimum, mean and standard deviation of the tracker error along the day. From the standard deviation, it is seen than the tracking error is mostly lower than ±0.5º.

TABLE 2. Summary of tracking error for the 6 PTC trackers

Tracker nº	Min θ_T [º]	Max θ_T [º]	Mean θ_T [º]	Stand. dev. θ_T [º]
1	-0.55	0.48	-0.25	0.47
2	-1.47	1.30	-0.26	0.31
3	-0.49	0.67	-0.23	0.49
4	-0.53	0.20	-0.24	0.49
5	-0.51	0.87	-0.22	0.52
6	-0.62	0.50	-0.25	0.50

From the optical simulation with Tonatiuh, the values of IAM of different longitudinal and transversal angles were calculated and shown in Fig.5.

IAM is represented as functions of the longitudinal and transversal angle independently for a clearer view of the IAM variation.



(a) (b)

FIGURE 5. (a) 3D view of the longitudinal and transversal IAM obtained by ray-tracing (b) View of the IAM as function of transversal incidence angle for different longitudinal angles

The simulated transversal IAM $K_b(\theta_T)$ is presented in Fig. 5b and it can be seen that it decreases for transversal angles θ_T between 0.5º and 1º, which is a much larger range than the theoretical defocus angle calculated from Eq. 2. From this curves and the value from Fig. 4 it is estimated that the optical losses due to tracking error would be neglected.

Fig. 6 shows the power flux diagram on the perimeter of the receiver tube. It is seen in Fig. 6b how the distribution of the flux is moving around the tube perimeter while the transversal incidence angle is increasing.

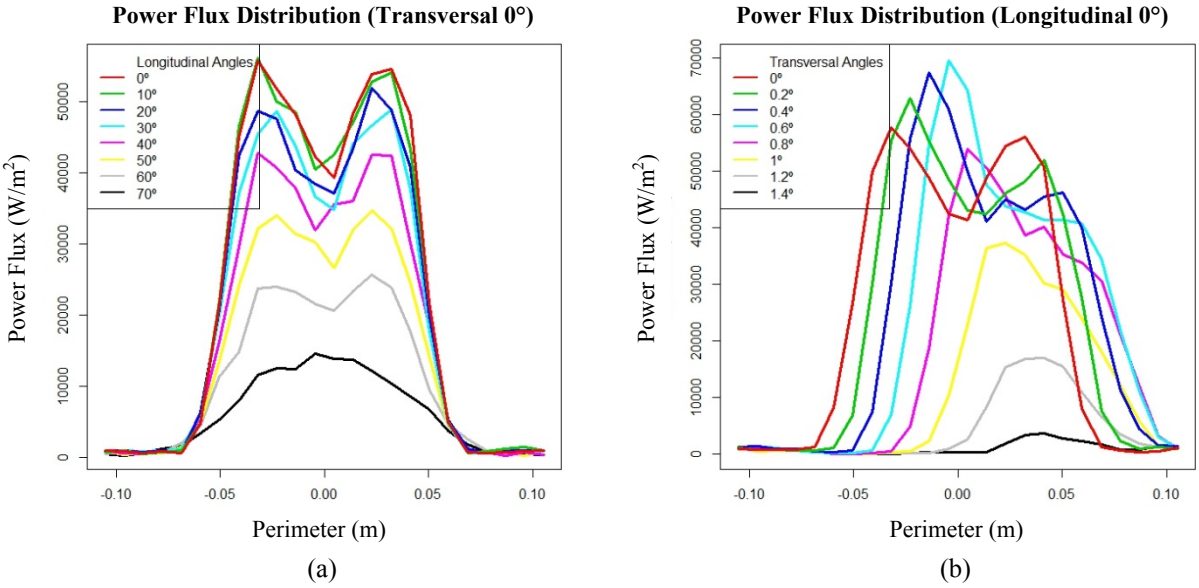


FIGURE 6. (a) View of the perimeter flux distribution for different longitudinal angles, (b) View of the perimeter flux distribution for different transversal angles

CONCLUSIONS

Six PTCs rows with solar tracker used for district heating in Denmark were analyzed. The IAM was determined by optical simulation, in particular for transversal incidence angles in order to estimate the impact of the missfocusing of the tracker on the collector efficiency. The results show that the tracking error was most of the time lower than ±0.2º which is lower than the theoretical defocus angle of the concentrator. But, in some cases, the tracking error reaches more than 1º, which could cause some optical losses reducing the PTC performance.

ACKNOWLEDGEMENTS

The research leading to these results is thanks to collaboration between CENER and DTU during the year 2016-2017 and to the Danish Energy Agency due to the support through the EUDP program. Great thanks to Aalborg CSP making all measured data avaiable and giving all detailed facts about the collectors.

REFERENCES

1. W. Weiss, M. Spörk-Dür, F. Mauthner, 2017. Solar Heat Worldwide. Global Market Development and Trends 2016. Detailed Market Figures 2015. SHC Solar Heating & Cooling Programme, International Energy Agency, Edition 2017.
2. B.Perers, S.Furbo, J.Dragsted. Thermal performance of concentrating tracking solar collectors. DTU R-292. Technical University of Denmark, DTU Byg. August 2013
3. B. Perers, S. Furbo, Z. Tian, J. Egelwisse, F. Bava, and J. Fan, "Tårs 10000 m2 CSP + Flat Plate Solar Collector Plant - Cost-Performance Optimization of the Design," Energy Procedia, vol. 91, pp. 312–316, 2016.
4. Z. Tian, B. Perers, S. Furbo and J. Fan., Annual measured and simulated thermal performance analysis of a hybrid solar district heating plant with flat plate collectors and parabolic trough collectors in series, Manuscript, July, 2017.
5. N. Janotte, E. Lüpfert, R. Pitz-Paal, 2012. Acceptance Testing and advanced Evaluation Strategies for Commercial Parabolic Trough Solar Fields. 18th SolarPACES Conference, 11 - 14 September 2012, Marrakech, Morocco.
6. D. Kearney, 2011. Utility-scale parabolic trough solar systems: performance acceptance test guidelines

7. L. Valenzuela, R. López-Martín, E. Zarza, 2014. Optical and thermal performance of large-size parabolic-trough solar collectors from outdoor experiments: A test method and a case study. Energy 70, 456–464. doi:http://dx.doi.org/10.1016/j.energy.2014.04.016
8. MC Bhatnagar, JC Joshi, AK Mukerjee. Determination of tracking error in an automatic sun tracking system. Sol Wind Technol 1987;4(3):399–403.
9. M. Minor, P.García High-precision solar tracking system. London, U.K.: World Congress on Engineering; 2010.
10. M. Oliveira Análise do desempenho de um gerador fotovoltaico com seguidor solar azimutal. Porto Alegre; 2008. http://hdl.handle.net/10183/14737
11. F. Sallaberry, F. Alberti, J.-L. Torres, L. Crema, M. Roccabruna and R. Pujol Nadal. Characterization of a medium temperature concentrator for heat process – tracking error estimation. EuroSun Conference, 16 – 19 September 2014, Aix-les-Bains, France.
12. F. Sallaberry, A. García de Jalón, J.-L. Torres, R. Pujol-Nadal, Optical losses due to tracking error estimation for a low concentrating solar collector. Energy Conversion and Management 92 (2015) 194–206
13. F. Sallaberry, Ramón Pujol-Nadal, Bengt Peres. Optical losses due to tracking on solar thermal collectors. EuroSun Conference, 11 - 14 October 2016, Palma de Mallorca (Spain),
14. Archimede Solar Energy receiver tube datssheet, http://www.archimedesolarenergy.it/en_specifiche-prodotto-hceoi-12.htm
15. Rioglass Mirror Type LS-3 datssheet, http://rioglass.com/parabolic-trough-mirrors/
16. F. Sallaberry, R. Pujol-Nadal, M. Larcher, M. H. Rittmann-Frank, Direct tracking error characterization on a single-axis solar tracker, Energy Conversion and Management 105 (2015) 1281–1290
17. Standard draft IEC 62862-3-2 "Solar thermal electric plants - Part 3-2: Systems and components - General requirements and test methods for parabolic-trough collectors" (publication planned in 2017).
18. M. Blanco-Muriel, D.C. Alarcón-Padilla, T. López-Moratalla, M. Lara-Coira. Computing the solar vector. Solar Energy. 70 (2001) 431-41.
19. Bendt, P., Rabl, A., Gaul, H., and Reed, K. Optical analysis and optimization of line focus solar collectors. Tech. rep., Solar Energy Research Inst., Golden, CO (USA), 1979
20. Blanco, M., Mutuberria, A., Monreal, A., Albert, R., 2011. Results of the empirical validation of Tonatiuh at Mini-Pegase CNRS-PROMES facility. 17th SolarPACES Conference, 20 - 23 September 2011, Granada, Spain.
21. Buie D., Monger A. G., Dey C. J., 2003, "Sunshape distributions for terrestrial solar simulations"
22. S. Furbo, Z. Chen, J. Fan and J. M. Schultz, "Solar transmittances for glass covers with and without anti reflection treatment under real climatic conditions".
23. Marco Montecchi, 2013, "Approximated method for modelling hemispherical reflectance and evaluating near-specular reflectance of CSP mirrors".
24. Tesfamichael T. Wäckelgard E., 2000, "Absorptance and incident angle modifier of selective absorbers for solar thermal collectors"F. Sallaberry, L. Valenzuela, A. García de Jalón, J. Leon, Ig. D. Bernad, 2015. Towards Standardization of in-Site Parabolic Trough Collector Testing in Solar Thermal Power Plants. 21st SolarPACES Conference, 13 - 16 October 2015, Capetown, South-Africa.