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State of the Art of Performance Evaluation Methods for Concentrating Solar Collectors

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Abstract. For the development and establishment of concentrating solar thermal collectors a reliable and comparable performance testing and evaluation is of great importance. To ensure a consistent performance testing in the area of low-temperature collectors a widely accepted and commonly used international testing standard (ISO 9806:2013) is already available. In contrast to this, the standard ISO 9806:2013 has not completely penetrated the testing sector of concentrating collectors yet. On that account a detailed literature review has been performed on published testing procedures and evaluation methodologies as well as existing testing standards. The review summarizes characteristics of the different steady-state, quasi-dynamic and fully dynamic testing methods and presents current advancements, assets and drawbacks as well as limitations of the evaluation procedures. Little research is published in the area of (quasi-) dynamic testing of large solar collectors and fields. As a complementary a survey has been conducted focusing on currently implemented evaluation procedures in this particular field. Among the ten participants of the survey were project partners of relevant industry and research institutions within the European project STAGE-STE (Work package 11 - Linear focusing STE technologies). The survey addressed general aspects of the systems under test, as well as required process conditions and detailed characteristics of the evaluation procedures. In congruence with the literature review, the survey shows a similar tendency: the quasi-dynamic testing method according ISO 9806:2013 presents the most common and advanced evaluation procedure mainly used in the context of tracking concentrating collectors for the performance assessment of parabolic trough collectors operating with thermal oil or pressurized water. These common solar systems can be evaluated with minor adaptions to the testing standard. Evaluation procedures focused on in-situ measurements in solar fields or collectors are scarce and complex as well as an evaluation of linear Fresnel collectors or other systems operating with non-common heat transfer media like molten salt and direct steam. As those are still

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presenting niche products and testing wise challenging systems under real test conditions a more sophisticated evaluation procedure such as the dynamic testing method is expected to be better suited.

INTRODUCTION

For the development and establishment of concentrating solar thermal collectors a reliable and comparable performance testing and evaluation is of great importance. To ensure a consistent performance testing in the area of low-temperature collectors a widely accepted and commonly used international testing standard (ISO 9806:2013) is already available[1]. In contrast to this, the standard ISO 9806:2013 has not completely penetrated the testing sector of concentrating collectors yet. The reasons for this are diverse. Among them are technical limitations in the established methods which increase the effort of applying the methods to an inappropriate extent. Furthermore some specific characteristics of concentrating collectors are not represented by the given theoretical models (e.g. two-dimensional incidence angle modifier including the effect of row end losses, cleanliness of mirrors during testing, use of different heat transfer media and in-situ measurements).

On that account a detailed literature review has been performed on published testing procedures and evaluation methodologies as well as existing testing standards, which will be presented in the first section of this article. As a complement a survey has been conducted among ten participants of relevant industry and research institutions within the European project STAGE-STE (Work package 11 - Linear focusing STE technologies), giving indications on the up-to-date state of the art of currently implemented testing procedures. The survey addresses general aspects of the system under test, as well as required process conditions and detailed characteristics of the evaluation procedure.

LITERATURE OVERVIEW

Literature screening showed a multiplicity of different publications in the field of solar thermal collector testing procedures. Therefore, the publications with their respective testing procedures were differentiated into two aspects: their testing methodology on the one hand side and their application on the other hand side, allowing a more structured and traceable comparison of the different testing methods. In Figure 1 the detailed literature review is summed up according to the introduced categories. The methodologies are grouped into steady-state (SST), quasi-dynamic (QDT) and dynamic (DT) testing, whereas the application of the published testing procedures are classified into non-tracking (stationary) collectors, tracking concentrating collectors and large solar fields of tracking concentrating collectors.

The upper part of Figure 1, highlighted in light blue, shows that the majority of publications in the field of collector testing is dealing with non-tracking collectors. In this area a multiplicity of diverse testing and evaluation procedures has been published. For clarity reasons, publications of steady-state testing for non-tracking collectors have not been listed, as they are plenty and of less interest concerning testing procedures for concentrating collectors. Especially the quasi-dynamic testing procedure was investigated, adapted and applied in several publications for different technologies, mainly based on the work done by the research group of Perers (e.g. see Perers (1997)[2]). Moreover the QDT-method presents part of the basis of the current testing standard ISO 9806:2013[1] and other standards (see Kramer et al. (2011)[3]). As a counterpart to the QDT-procedure the dynamic testing method has firstly been introduced by Muschaweck and Spirkl (1993), containing a more sophisticated collector simulation tool, but less restriction in measurement data[4]. The QDT-method is based on a linear collector equation and quite strict boundary conditions, which allow the use of multiple linear regression (MLR). In contrast the DT-method is based on different kinds of specific (dynamic) collector simulation models allowing a more flexible combination with an optimization algorithm consisting for example of a non-linear least-squares (NLS) minimization approach. A comparison of both mathematical approaches by Fischer et al. (2003) showed that they are equivalent in their results, NLS minimization only being more flexible[5].

In the area of tracking concentrating collectors there does exist an American testing standard ASTM E 905-87 based on steady-state testing[6]. Even a guideline for the acceptance testing of parabolic trough solar fields is based on stationary measurements[7]. An approach of steady-state testing has been applied for measuring the performance of large parabolic-trough collectors[8]. It is currently considered as a first reference approach for the proposal of a national standard in the Spanish National Committee AENOR (see Sallaberry et al. (2015)[9]) and will be an input for discussion in the International Committee IEC TC 117 (Solar thermal electric plants). Nevertheless these testing procedures are either very time consuming or (if not the latter) mostly not comprehensively characterizing the

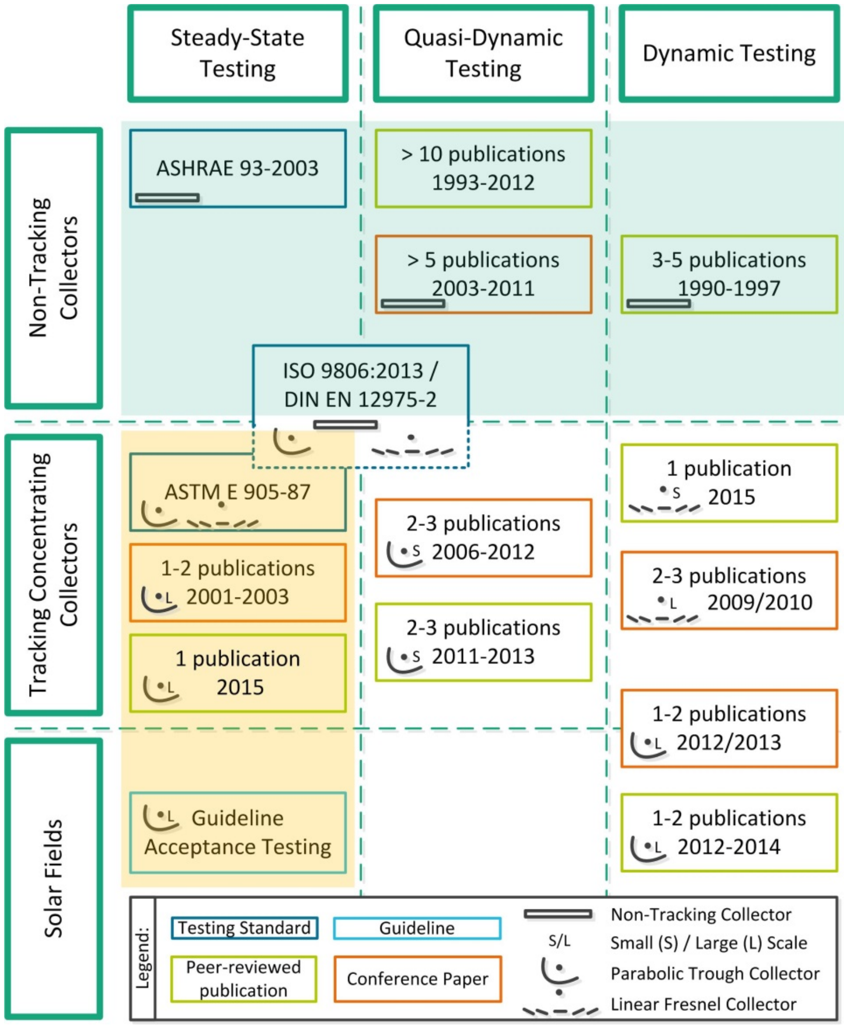

FIGURE 1. Summary of published testing and evaluation procedures with focus on concentrating solar collectors (overview compiled by Fraunhofer ISE).

collector or field performance, as they are limited to particular conditions (high DNI, normal incidence at solar noon etc.).

In Figure 1 the testing standard ISO 9806:2013 is marked with dotted lines in the area of tracking concentrating collectors, as it is not fully applicable to all concentrating collectors without modifications. Publications in this field show, that the QDT-method is successfully applied particularly for small-scale parabolic trough collectors (marked with an S), as restrictions to measurement conditions can still be met (see Fischer et al. (2006)[10] and Janotte et al. (2009)[11]). For a global characterization of large-scale collectors (marked with an L), either parabolic trough or linear Fresnel, mainly the dynamic testing method is applied, as with higher working temperatures, energy loads to be cooled to meet stationary inlet conditions cannot easily be fulfilled. In particular for the characterization of linear Fresnel collectors due to their special optical characteristics in terms of a two-dimensional IAM, new approaches by dynamic parameter identification[12,13], or modifications to the QDT-methods are inevitable (compare with Hofer et al. (2015)[13]).

Apart from the steady-state guideline for the acceptance testing of solar fields, there are few publications presenting a more sophisticated characterization and acceptance testing of parabolic trough solar fields based on dynamic testing procedures (see Janotte (2012)[14]). Quasi-dynamic testing is rarely applied to large collectors or solar fields, which might be an indication, that the QDT-method with its restriction in measurement data is not entirely suited for the performance evaluation of larger systems. A guideline focusing on characteristics, assets and drawbacks as well as practical indications for the use of dynamic solar collector and solar field performance testing is currently being compiled (see Hofer and Janotte (2015/16)[15]).

With the existence of testing standards for non-tracking collectors (in Figure 1 highlighted area in light blue) and for steady-state testing procedures (in Figure 1 highlighted area in light orange), standardization in the area of dynamic testing procedures for tracking concentrating solar collector and fields is still lacking, while research and its publication is existing, but scarce. To get a more comprehensive overview on current testing approaches, a survey on (not necessarily published) currently implemented dynamic testing and evaluation procedures was conducted, which will be presented in the following section.

SURVEY ON DYNAMIC EVALUATION PROCEDURES FOR SOLAR COLLECTORS AND FIELDS

As an addition to the literature review, a survey has been set up focused on the characteristics of currently used evaluation methods for the performance evaluation of solar collectors and fields. The participants of the survey are linked to the working group of WP 11 (Linear focusing STE technologies) of the European project STAGE-STE and consist of: Fraunhofer ISE (subtask leader), CIEMAT, DLR, SENER, Acciona, ENEA, CENER, University of Évora, LNEG and FBK. According to the list of participants, the survey is not designed to address the complete solar thermal sector. It is particularly concentrated on research institutions and relevant industries focused on tracking/concentrating solar thermal collectors and fields, as the literature review showed a gap of publications in this area (see right bottom part of Figure 1).

Within the ten participants, the characteristics of 12 different testing/evaluation procedures were analyzed. Table 1 summarizes the general aspects of the different evaluation procedures concerning system characteristics, such as the type of collector to be evaluated or the heat transfer fluid being used. It shows that the majority (83 %) of the evaluation procedures are used for the characterization of parabolic trough collectors, whereas only 25 % are used for linear Fresnel collectors and 33 % for CPC collectors and other non-tracking medium temperature collectors. The percentages do not add up to 100 % as there are several methods that can be used for several collector types. 83 % of the evaluation methods are designed for solar collector evaluation, only 25 % can be applied to solar fields. Concerning the used heat transfer fluid for the characterization of the systems, mainly thermal oil (67 %) and pressurized water (50 %) are used, whereas only 8 % of the evaluation methods are performed with molten salt. A performance evaluation with direct steam based on a dynamic measurement approach does currently not exist within the partners of the survey. 16 % indicate, that performance evaluation based on steady-state measurements can be performed. The figures show that the most commonly used evaluation method is designed for parabolic trough collector operating with thermal oil or pressurized water. A reason why the evaluation methods can rarely be applied to other collector types and heat transfer fluids may have to do with the dispersion of the solar system on the one side and with the complexity and peculiarities linked to these systems under test on the other side.

Details of the evaluation methodology for the testing procedures under review can be found in Table 2. The results show that around 67 % of the evaluation procedures are based on a quasi-dynamic testing approach. 25 % are based on dynamic testing procedures and 8 % are only able to evaluate in steady-state measurement conditions. Concerning the mathematical approach of the reviewed evaluation procedures, 50 % are identifying performance parameters with multiple linear regression (MLR) while the other 50 % are using a parameter identification method based on a non-linear least-squares minimization (NLS) approach. This indicates that the testing method itself is

TABLE 1. Survey results concerning general aspects of testing system characteristics for the different evaluation procedures.

Category	**Type**	**Share**
Evaluated collector type	Parabolic trough	83 %
	Linear Fresnel	25 %
	Non-tracking collectors	33 %
System under test	Solar collector	83 %
	Solar field	33 %
Heat transfer fluid used	Thermal oil	67 %
	Pressurized water	50 %
	Molten salt	8 %
	Direct Steam	0 % (DT) / 16 % (SST)

independent of the mathematical approach. While QDT-data can be evaluated with MLR or NLS, the DT-method requires a NLS approach, as it provides higher flexibility due to the simulation model being more complex than a linear one-node collector equation of the QDT-method. Concerning the required process conditions during testing, 75 % of the procedures are based on constant inlet temperature and mass flow, which is in accordance with the summed share of QDT- and SST-procedures. Likewise 25 % are able to tolerate variations in irradiance, inlet temperature and inlet mass flow in agreement to the percentage of the DT-method.

One aspect of the survey also implies the analysis of parameters included in the evaluation procedure corresponding results can be found in Table 3. As all of the testing procedures assess the collector output power of the system under test, inlet/outlet temperatures and mass flow rates are always taken into account, as well as direct normal irradiance. Ambient temperature is considered in the evaluation procedure similar evident in 92 % of the cases. With respect to collector parameters, optical efficiency at normal incidence $\eta_{opt,0}$ and heat loss parameters are always taken into account. Additionally direct IAM values are included in the majority (92 %) of the reviewed methods.

For wind velocity (50 %), global irradiance (42 %) and pressure (17 %) measurements no clear statement can be drawn from the survey. Diffuse IAM-values as well as cleanliness of the mirrors are taken into account in 33 % of the methods. This indicates that the different evaluation procedures are adapted to the particular situation and needs of the system under test. No strict conclusions on the relevance or irrelevance of these parameters can be given within the context of the survey. The particular adaptions of the procedures show that a testing and evaluation procedure for concentrating solar collectors needs to be flexible enough for a large spectrum of diverse collector systems to be tested.

Having an overall look onto the shares of the survey, it becomes evident, that 80 % of the evaluation methods for solar collectors use the QDT-procedure of the current testing standard ISO 9806:2013 with smaller adaptions. Similarly 67 % of the methods for solar field performance evaluation use a dynamic testing approach. This indicates, that for the majority of collectors tested among the survey partners (mainly parabolic trough collectors operating with thermal oil or pressurized water), the QDT-procedures are suited for the determination of the collector performance, whereas for the majority of solar fields a more flexible, dynamic testing approach is required. With respect to the application of the DT-procedure the survey showed, that dynamic testing is required either for testing

TABLE 2. Survey results concerning evaluation methodology for the different evaluation procedures.

Category	Type	Share
Testing method	QDT	65 %
	DT	25 %
	SST	8 %
Mathematical approach	Multiple linear regression	50 %
	Non-linear least-squares minimization	50 %

TABLE 3. Survey results concerning considered parameters for the different evaluation procedures.

Category	Type	Share
Process conditions	Mass flow	100 %
	Inlet and outlet temperature	100 %
	Pressure	17 %
Ambient conditions	Direct normal irradiance	100 %
	Global irradiance	42 %
	Ambient temperature	92 %
	Wind velocity	50 %
Collector conditions	Optical efficiency at normal incidence	100 %
	Heat loss parameters	100 %
	IAM direct irradiance	92 %
	IAM diffuse irradiance	33 %
	Cleanliness	33 %

of solar fields or for in-situ testing of solar collectors, as these systems do not allow an extensive intrusion into the process conditions and therefore require a more flexible evaluation routine.

CONCLUSION

A detailed literature review focused on dynamic testing procedures for concentrating solar collectors was performed. In addition, a survey among ten project partners of the European project STAGE-STE WP 11 was conducted. Both analyses showed the same tendency: the quasi-dynamic evaluation procedure according to the testing standard ISO 9806:2013 is mainly used in the context of tracking concentrating collectors for the performance assessment of parabolic trough collectors operating with thermal oil or pressurized water. These common solar systems can be evaluated with minor adaptions to the testing standard.

Nevertheless similar to published literature, the survey showed that evaluation procedures focused on in-situ measurements in solar fields or collectors are scarce and complex as well as an evaluation of linear Fresnel collectors or other systems operating with non-common heat transfer media like molten salt and direct steam. As those are still presenting niche products and testing wise challenging systems under real test conditions a more sophisticated evaluation procedure such as the dynamic testing method is likely to be better suited.

In terms of testing standardization, the DT-method may present a considerable alternative to overcome the limitations of QDT-procedures and assure a reliable and comparable performance assessment of large concentrating solar systems. Still advanced research is necessary in the development of improved or alternative testing procedures, especially with respect to linear Fresnel systems, large solar fields and systems operating with direct steam.

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