In Situ Characterization of Thermal Collectors in Field Installations

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Abstract

Reliable and significant determination of the collector performance in field installations is necessary for a number of reasons, such as commissioning tests or product certification. The standard measurement methods from ISO 9806 are subject to numerous restrictions and only partially applicable to solar field installations. In a current project, different solar thermal plants are being monitored in order to examine the adaptability of standard procedures and measurement equipment to the requirements of in situ testing in comparison with a non-standard dynamic testing approach. Within the scope of the examinations is the comparability of field and laboratory results with respect to different evaluation methods, measurement equipment, system boundaries and process conditions. A new software tool to handle and visualize large data volumes was implemented as well as an advanced analysis procedure of parameter quality via alternative confidence interval computation. This is crucial to evaluate the uncertainties associated with larger field testing.

Keywords: field measurement, collector performance, quasi-dynamic method, parameter quality, bootstrapping method

1. Introduction

From design optimization to commissioning tests, from process monitoring to yield assessments and product certification of special collector technologies, which are not suitable for laboratory testing: the number of technical issues is large that require reliable methodologies to evaluate the energy output of thermal collectors in field installations. While the choice of proper measurement instrumentation and data acquisition as well as the choice of a suitable evaluation methodology depend on the very target of the examination, other challenges have to be met in any case:

- Reliable data transfer and data integrity have to be ensured
- Large data volumes have to be managed and processed
- Data shall be visualized and accessible quickly and easily
- Significant results shall be achieved without compromising regular plant operation
- Results should be of general validity and transferable to other plants of similar design

The project "ZeKon in-situ" deals with both technical issues related to the metrological recording of ambient conditions and collector performance, and issues related to secure data transmission and automated data processing and visualization. The measurement data is transferred via LTE using cryptographic procedures. Using a new tool for time series management and data visualization designed to handle big data volumes, the collectors are characterized with different evaluation methods. The focus of the project is on the applicability of the quasi-dynamic test method (QDT) known from EN ISO 9806 to measurement data recorded in the solar field under normal operating conditions and the derivation of necessary adjustments. In comparison, the data is evaluated using an alternative dynamic test method (DT), which has already been successfully validated and extensively used in the past to measure and evaluate concentrating collectors (Hofer et al. 2015; Zirkel-Hofer, 2018). The project objective is to enable collector parametrization during regular plant operation, applicable for the broadest possible range of technologies and designed to customer request in terms of cost and accuracy.

In this paper, the first results of a collector measurement in the field, including necessary adjustments of the methodology, are compared with the results of the characterization of an identically constructed collector in

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the laboratory according to the normative specifications.

2. Methodological approach

2.1 Experimental setup

When measuring the collector in the laboratory as a reference, all normative regulations regarding measurement technology, collector design and permissible operating conditions according to EN ISO 9806:2017 were satisfied (EN ISO 9806:2017). The evaluation with the QDT method was also carried out in accordance with the normative specifications regarding the determination of the collector parameters as well as the required measurement sequences and data basis.

In the field measurement, the identically constructed collector was measured as part of a collector field. The first and the last collector of a row were equipped with measuring technology in order to be able to balance both, the individual collectors and the row as a whole. For the measurement of global and diffuse irradiation, an SPN1 irradiation sensor from Delta-T Devices was used instead of the class 1 pyranometer according to ISO 9060 (Figure 1). This sensor allows the determination of global and diffuse irradiance without tracking or the adjustment of a shading device and is therefore suitable for field measurements without regular access to the system. However, compared to standard measurement technology, the sensor has a higher measurement uncertainty, the influence of which will be investigated in the further project, but has not yet been taken into account in this comparison. All other sensors used in the field meet the normative requirements.

Figure 1: SPN1 sensor for the determination of diffuse and global irradiance

2.2 Measurement methods

It is the objective of "ZeKon in-situ" to investigate prerequisites and methods for reliable and meaningful characterization of collectors in the field. The quasi-dynamic test method of EN ISO 9806 presents the focus of interest in this examination. Because the normative restrictions of QDT to the permissible process conditions are too strict for meaningful application in the field, the possibilities to expand these restrictions are explored in the project.

As an alternative, the DT method, which has successfully been applied in evaluations of concentrating collectors, is being adapted to an application for flat plate and vacuum tube collectors. It is based on a dynamic plug-flow simulation model and using an optimization algorithm to identify performance parameters based on thermal measurement data of the collector output (Hofer et al., 2015). Its major advantage compared with the QDT from ISO 9806:2017 is the absence of any limit to the variations in mass flow and inlet temperature. It uses the very same collector equation in a dynamic simulation and produces the identical set of parameters.

2.3 Evaluation of parameter quality

In order to assess the quality of performance measurements, a solid knowledge of the uncertainty and interdependence of different parameters is required. This applies to laboratory measurements, but above all to measurements in the field, which are often accompanied by greater uncertainties. Since statistical standard methods often do not consider the complexity of data series from the QDT method, the so-called bootstrapping method (BS) is used here, which allows a more realistic analysis of the parameter quality. On the basis of the residuals between the metrologically determined and calculated collector power determined during the first parameterization, a large number of new data sets are created by resampling. For this purpose, randomly selected data blocks of residuals from the original data are used. This creates a newly sampled noise on the measurement data derived from the original residuals between measurement and calculation. By parameterizing these newly created measurement data multiple times, a large number of parameter sets are produced for the same collector, the scattering and co-variances of which can then be analyzed. The confidence intervals determined with BS are not based on as many and often simplifying assumptions as standard statistical methods, and are therefore more suitable for the use on time series data in particular. Like the DT method, the BS method has already been verified and used with great success in the measurement of concentrating collectors (Zirkel-Hofer et al., 2018).

3. Results

3.1 Laboratory measurements

For the comparative evaluation of the laboratory measurement with QDT and DT, the identical data basis was used.

For the QDT evaluation, a conditioning interval of 15 minutes and an averaging interval of 5 minutes were used, as well as a permissible fluctuation of the inlet temperature of 1K and the mass flow of 1%. Although an average time of 5 minutes has not been required in the standard since 2013, comparative evaluations with a shorter interval of 30 seconds in the laboratory and the sensitivity analysis in the field described below suggest that shorter intervals can have a significant influence on the parameters and are not advisable, especially for field measurements.

For the DT evaluation, no restrictions were specified with regard to the permissible fluctuations and the measurement data were evaluated in their 5s resolution.

Both evaluations lead to almost identical parameters except for a slight deviation in the incidence angle modifier (IAM). Figure 2 and Figure 3 show the efficiency curve and the IAM curve for both evaluations in comparison. Because absolute values cannot be disclosed, Table 1 shows the deviations of the parameters of the DT evaluation in comparison to the QDT. The comparison shows that the DT method is very well suited to also evaluate non-concentrating collectors and leads to almost identical results with respect to the QDT method.

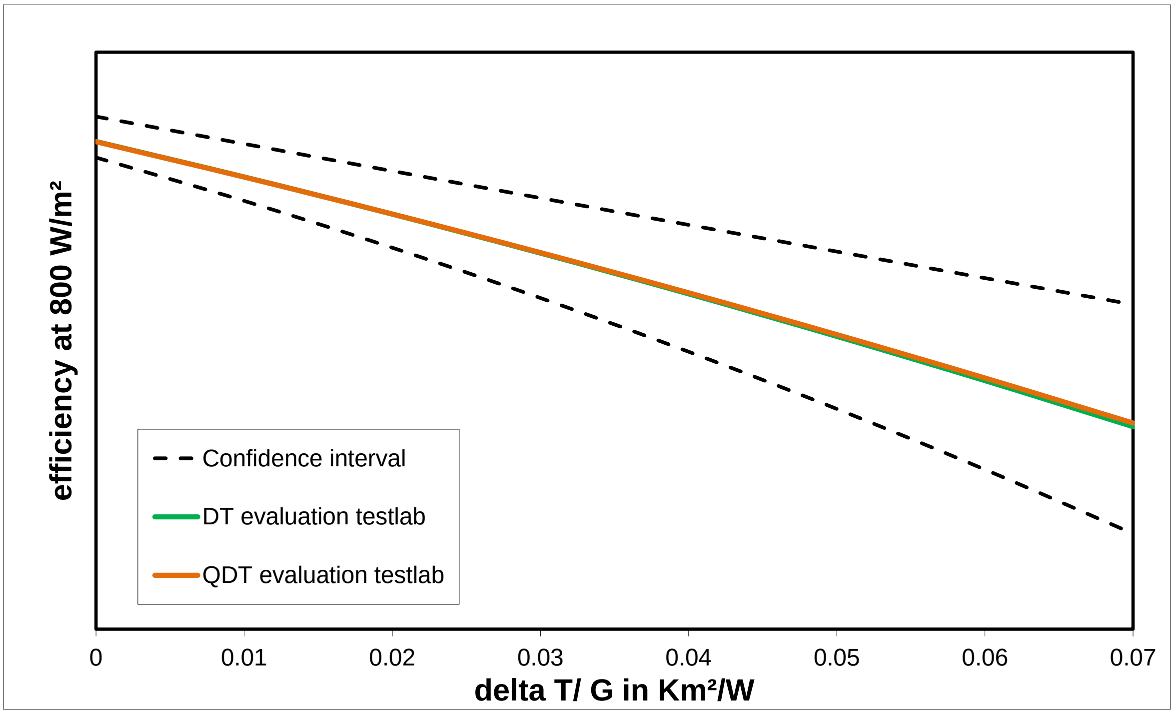

Figure 2: Efficiency curves with QDT and DT from the laboratory

Table 1: Deviations of the evaluation with DT compared to QDT in the laboratory

$\eta_{0,b}$ [-]	a_1 [W/m²K]	a_2 [W/m²K²]	$K_{b(50)}$ [-]	K_d [-]
0.001	0.00	0.001	0.013	0.00

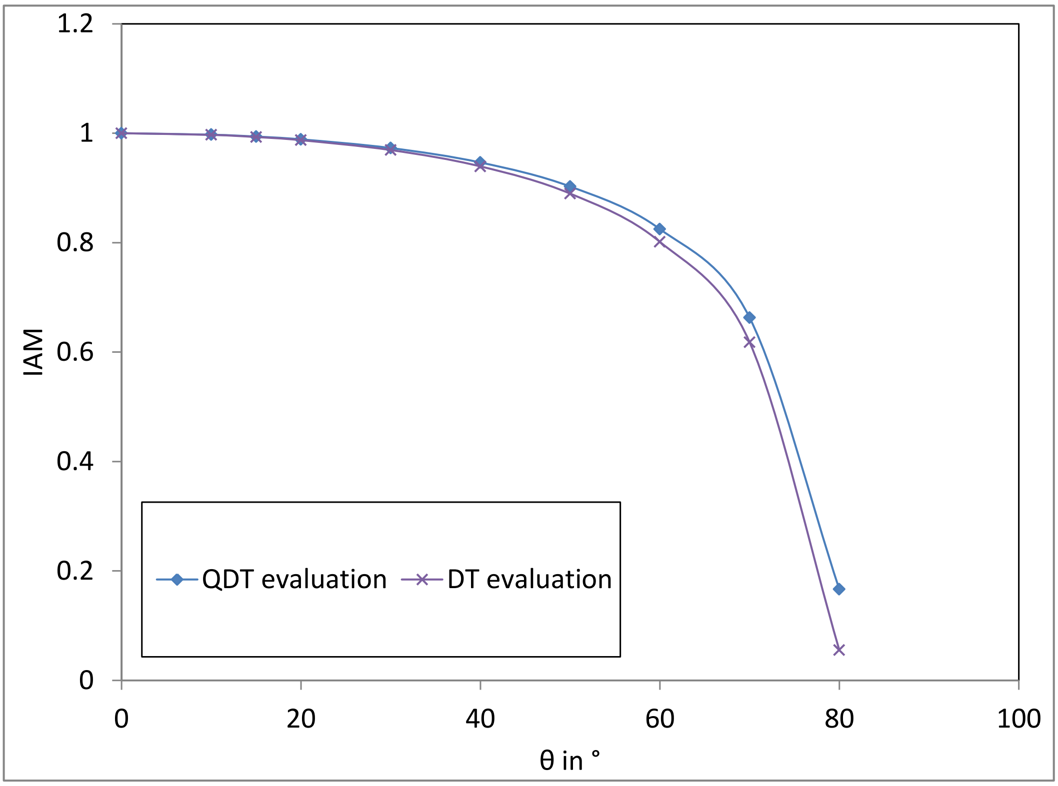

Figure 3: IAM curves determined with QDT and DT in the laboratory

In order to analyze the quality of the parameter sets in detail and to determine their confidence intervals, the bootstrapping procedure described above was used. For the parameters from the QDT method 500 runs were performed, creating the same number of parameter sets. The scattering of the parameters and the co-variances among each other were evaluated and graphically illustrated. Figure 4 shows the scattering for $\eta_{0,b}$ of the laboratory measurement according to QDT. The orange line represents the average of all BS values. The blue lines mark the lowest and the highest 2.5% of the results and enclose the 95% confidence interval. This may results in asymmetric confidence intervals if the scattering is not normally distributed. The confidence intervals on the basis of the BS results for the efficiency curve as a whole are shown in Figure 2.

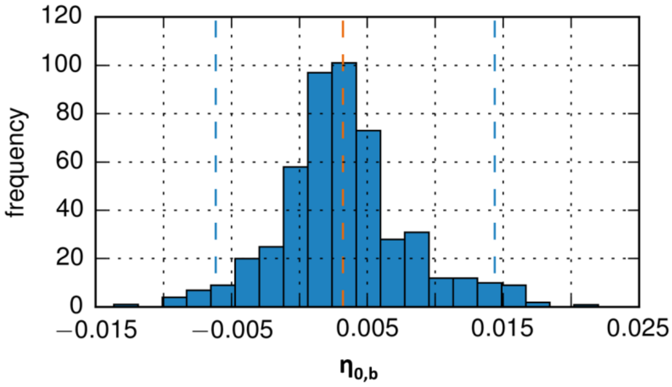

Figure 4: Histogram for the scattering of $\eta_{0,b}$ of the laboratory measurement according to QDT (normalized)

When analyzing the parameters, particular attention was paid to the IAM, as this shows the greatest difference in the comparison of QDT and DT results. It was found that the bootstrapping for the QDT results shows a much greater co-variance of the IAM parameter with the value for $\eta_{0,b}$ than is the case for the DT results. While for the QDT higher IAM values clearly correlate with lower values for $\eta_{0,b}$ (Figure 5, left), no obvious interdependence can be detected for the DT results (Figure 5, right).

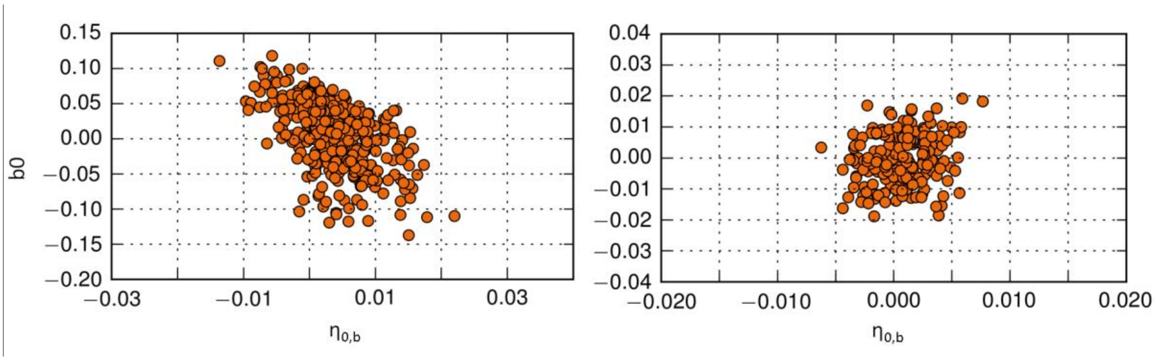

Figure 5: Co-Variance between IAM and $\eta_{0,b}$ for evaluation with QDT (left) and DT (right), both normalized

The further analysis of the existing measurement points and residuals showed that the DT method included significantly more measurement points at large angles of incidence than the QDT for the same data basis, due to the lack of limits in the permissible boundary conditions. Due to this small (and very limited) number of measuring points with large angles of incidence, the angular influence on the collector power in the QDT was apparently underestimated.

The histogram for the IAM parameter from the BS analysis of the QDT could have been an indication of this undervaluation even without direct comparison to the DT method. The scatter in Figure 6 does not show a normal distribution but a clear tendency towards higher IAM values.

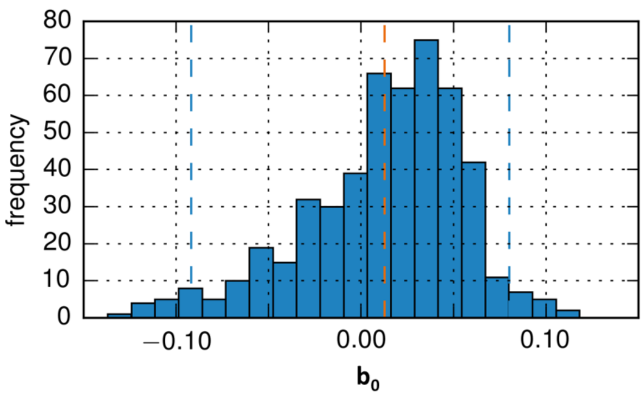

Figure 6: Scattering of the IAM parameter of the QDT evaluation (normalized)

The bootstrapping method has therefore proved to be extremely helpful in determining confidence intervals and analyzing the interrelationship between the parameters. Strictly normative measurements are always more or less error-prone and BS allows an in-depth analysis that helps to identify deficits.

Due to the detailed parameter analysis and the validation with almost identical results by the two evaluation methods, the results of the laboratory measurement can be used as a solid reference for the evaluation of the field measurements.

3.2 In situ measurements

The declared aim of the project is to test the suitability of the QDT for the evaluation of field measurement data which are recorded under regular operating conditions, that is, without specific operating states being brought about. This implies that the relative strict stability limits of the standard, especially with regard to inlet temperature and mass flow, cannot generally be complied with. Therefore, the core of the present study consisted in a sensitivity analysis to check the influence of different boundary conditions on the measurement results. For this purpose, the underlying measurement data, which cover a period of approximately three months, were parameterized multiple times under systematic variation of the permissible boundary conditions. At the same time, the first and last collector of the row as well as the combination of both individual collectors and the entire row were used to examine different energy balance areas. **Fehler! Verweisquelle konnte nicht gefunden werden.** lists the variants for all boundary conditions considered in the sensitivity analysis.

Table 2: Variations of the boundary conditions during sensitivity analysis

Criterion	Variants
Balance area	First collector, last collector, combination of both individual collectors, complete row
Conditioning interval	3 min, 5 min, 10 min, 15 min, 20 min
Averaging interval	15s, 30s, 5 min, 10 min, 15 min
Min. temperature lift	0.01K, 0.1K, 0.25K, 0.5K, 1K
Max. variation input temperature	1K, 2K, 3.5K
Max. fluctuation mass flow	1%, 2%, 3%, 5%, 15%, 40%

A total of approx. 1500 different evaluations of the same data basis were carried out from which then those parameter sets were filtered from which all values lie within the confidence interval of the laboratory measurement. By analyzing the conditions under which the remaining 34 parameter sets were identified, clear tendencies can be determined:

- All but one of the parameter sets originate from the first collector in the series
- All except one parameter set are based on a minimum temperature lift of 0.5K
- All are based on an average interval of 5 min
- The conditioning intervals of 3 min, 5 min, and 15 min occur in approximately equal parts
- The 3 different filter limits for the input temperature occur in equal parts
- With the filter limit for the mass flow there is a clear tendency to the higher values, about 2/3 of the parameter sets are based in equal parts on 15% and 40% fluctuation limit, the remaining third is distributed among the other 3 variations

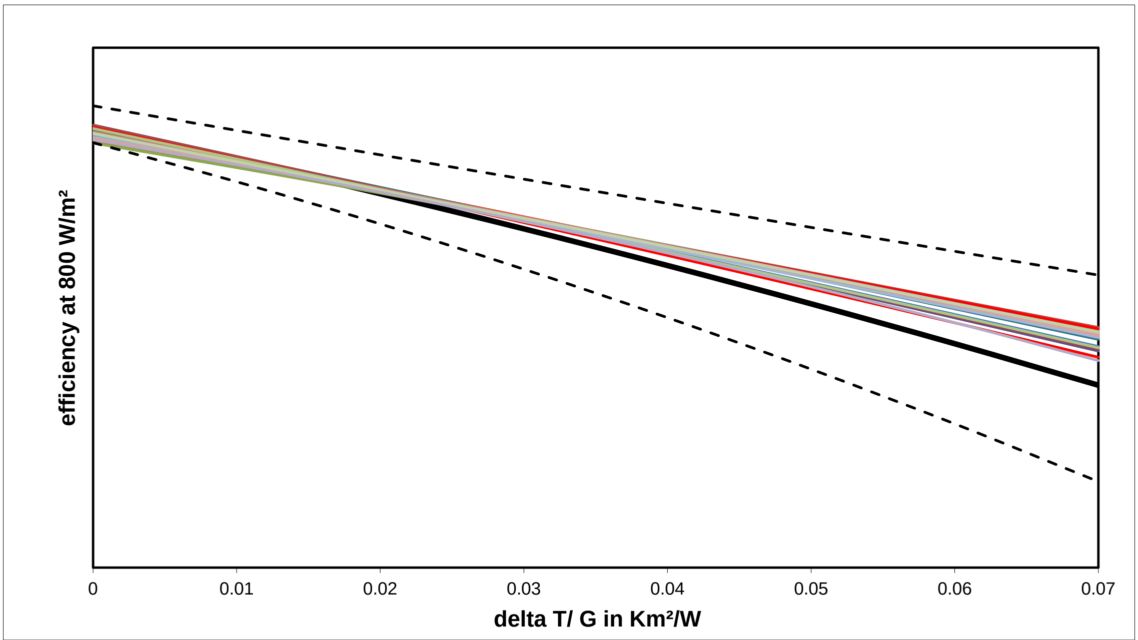

Figure 7: Selected efficiency curves from the field in the confidence interval (Intermediate results at time of publication)

Figure 7 depicts the efficiency curves for all the mentioned 34 cases and shows that all filtered parameter sets have similar characteristics. Compared to the reference measurement (black line) they show a very good agreement regarding $\eta_{0,b}$, but all imply slightly lower heat losses. Why the heat losses in those cases are consistently lower, is the subject of ongoing investigations; a first explanatory approach is the dominance of measured values at a lower temperature level at the first collector in the series. The definite integral in the measuring range (up to T_{mean}-T_{amb}/G=0.07 Km²/W) is used as a criterion to select the data set which is closest to the reference measurement. This is used for the subsequent comparisons with the DT method and is shown again in Figure 9 in comparison with the reference and the DT result.

If the same filter criteria as above are used, but only the results based on a combination of the first and last collectors in the series are considered, the result gives a completely different picture (see Figure 8). Here, measuring points of higher temperature levels are significantly more dominant and lead to a tilting of the efficiency curves in comparison to the reference measurement: The values for $\eta_{0,b}$ tend to be significantly higher than in the reference measurement (black line), but the heat loss coefficients are also higher. However, most of these parameter sets are outside the confidence interval of the reference measurement.

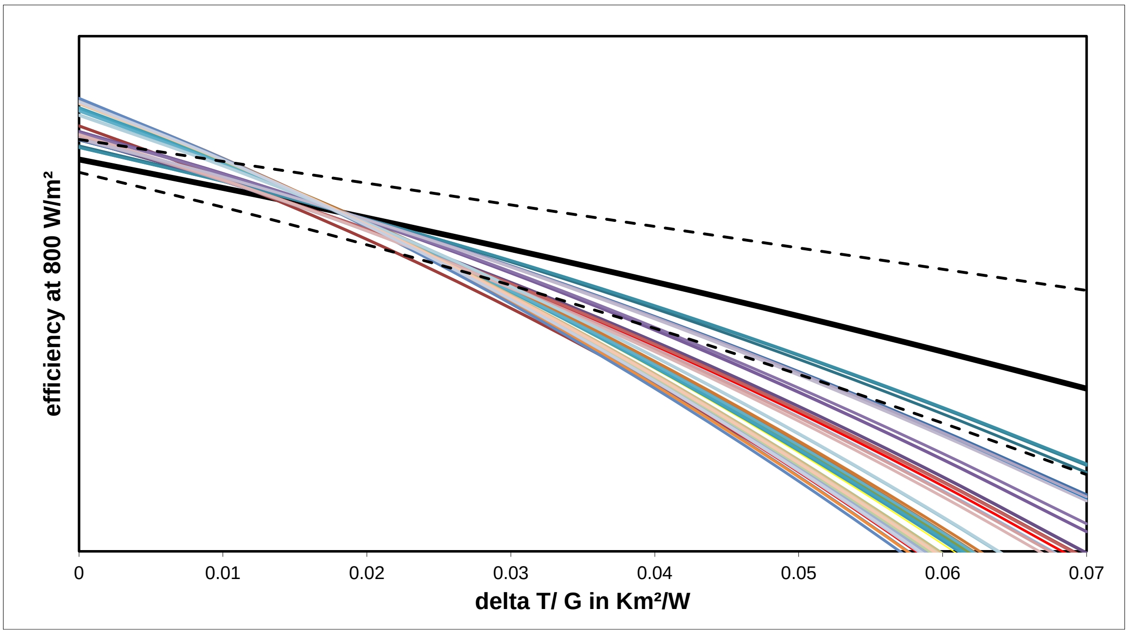

Figure 8: Efficiency characteristics for the combined evaluation of the first and last collector of the series (Intermediate results at time of publication)

If only parameter sets are considered which are based only on measured values of the last collector of the series, where low temperature levels hardly occur, results are completely and far above the confidence interval of the reference measurement. As they are not plausible they are not presented here.

In connection with the results of the sensitivity analysis listed above, the following keys are drawn:

- The QDT reaches its limits in very dynamic processes, a sufficiently long averaging interval should therefore be used. In this case, 5 minutes turned out to be the optimal interval.
- If sufficient conditioning and averaging intervals are given, the normative limits for the maximum permissible fluctuation of input temperature and mass flow are almost superfluous. They could be exceeded many times over without significantly changing the characteristic curve.
- In principle, the importance of the widest possible variance of all relevant boundary conditions cannot be overestimated for QDT. With regard to the operating temperatures covered, reaching temperatures close to the ambient temperature seems to be even more important than covering the uppermost temperature range.
- The QDT has the potential to be used in the field without active intervention in plant operation even under more varying process conditions, provided there is sufficient variance of all relevant boundary conditions.

The DT method is particularly suitable for the use in field measurements because it does not impose any limitations on the permissible boundary conditions. The collector was therefore also evaluated with this method, again using both, the individual collectors and the entire collector series as a balance room. The only restrictions made here were a minimum of three minutes preceding pump activity and minimum temperature lift of 0.1K. It should be noted at this point that the evaluation with DT does not refer to the exact same period as the QDT evaluations, but rather to a somewhat more extensive data set due to its subsequent use.

The results of the DT method also differ from the reference measurement depending on the balance area under consideration. Strikingly, the largest deviations result for the first collector in the series and are far outside the confidence interval (Figure 9, brown line), while this produced the best results for the QDT. The reasons for this are the subject of ongoing investigations.

Looking at the last collector in the series and the series as a whole, however, Figure 9 shows good agreement with the reference measurement with regard to optical efficiency.

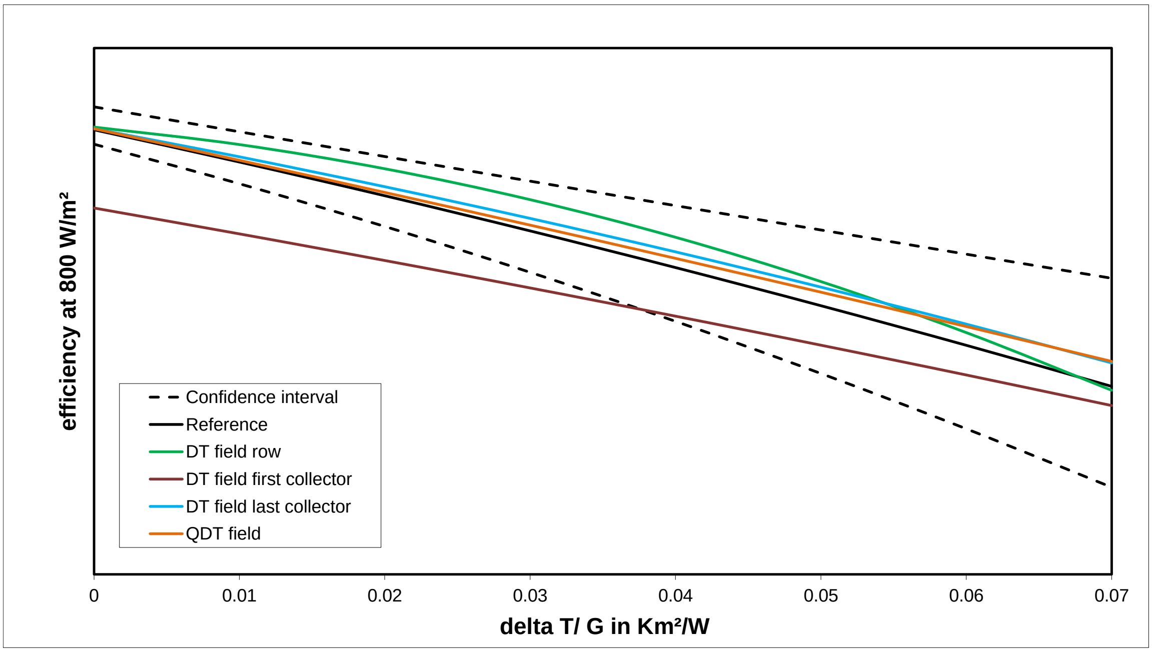

Figure 9: Efficiency lines from the field for DT (different balance areas) and QDT (selected data set) in comparison to laboratory measurement (Intermediate results at time of publication)

As with QDT, the thermal losses are slightly lower than in laboratory measurements. For the last single collector of the series, however, this cannot be explained by a lack of representation of measuring points at a high temperature level. The significantly greater curvature of the efficiency curve when evaluating the entire series may be attributed to the lack of correction of heat losses at the collector connections. It is obvious that these are less influential in the first part of the collector row at a low temperature level than at the high temperatures at the end of the row. In a next step, these connectors will be supplemented in the simulation model to verify this hypothesis. As already shown above, the angular dependence in the reference measurement has apparently been underestimated. This may also explain the somewhat larger differences between the IAM values from field and laboratory. **Fehler! Verweisquelle konnte nicht gefunden werden.** summarizes the deviations between the reference measurement and different evaluations in the field.

Table 3: Deviations of the selected field measurements from the reference measurement

	$\eta_{0,b}$ [-]	a_1 [W/m²K]	a_2 [W/m²K²]	$K_{b(50)}$ [-]	K_d [-]
QDT (selected parameter set)	0,000	-0,17	-0,004	-0,035	-0,046
DT Last collector	0,001	-0,365	0,002	0,005	0,031
DT complete row	0,002	-1,484	0,023	-0,020	-0,001

Looking at the BS results for the selected QDT measurement in the field, it can be seen that the confidence intervals of the parameters are in the same order of magnitude as in the laboratory and even tend to be smaller. This can be attributed to the far greater number of measurement points collected during the three-month field measurement than was the case during the laboratory measurement, which lasted only a few days. Also, the confidence intervals in the field are rather normally distributed. Figure 10 shows an example of the distribution for $\eta_{0,b}$. Compared to the representation for the laboratory measurement in Figure 4, it can be seen that the variance is slightly lower and more even around the mean value here as well.

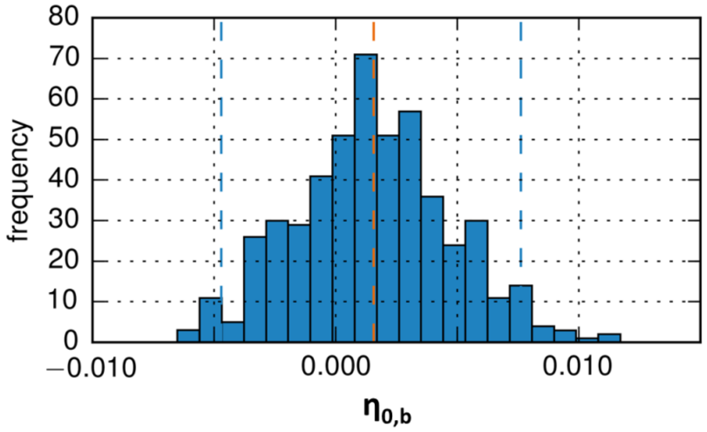

Figure 10: Histogram for the scattering of $\eta_{0,b}$ for the selected field parameter set from QDT (normalized)

Fehler! Verweisquelle konnte nicht gefunden werden. shows the confidence intervals of all parameters of the selected field measurement and the laboratory measurement relative to their parameter values.

Table 4: Upper and lower limits of the confidence intervals relative to the parameter value

	QDT laboratory measurement		QDT select field measurement	
	Lower limit	**Upper limit**	**Lower limit**	**Upper limit**
$\eta_{0,b}$[-]	-0,009	0,011	-0,006	0,006
b_0 [-]	-0,105	0,068	-0,017	0,016
K_d [-]	-0,055	0,043	-0,025	0,027
a_1 [W/m²K]	-0,541	0,571	-0,457	0,436
a_2[W/m²K²]	-0,008	0,006	-0,007	0,007

The covariances between the optical parameters are also lower for the field measurement, which is also attributed to a better variance of the underlying data. Covariances between the optical parameters are still present in the field, but also smaller than in laboratory measurements. As an example, Figure 11 shows the dependence between $\eta_{0,b}$ and the IAM parameter b_0 in the laboratory (left) and in the field (right).

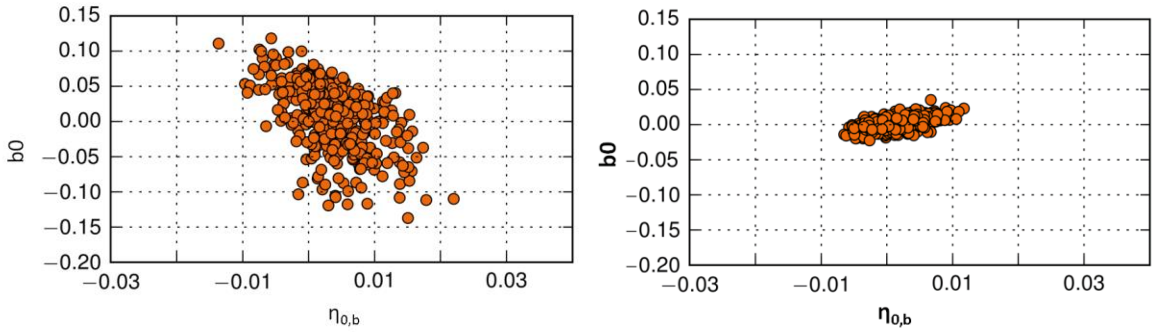

Figure 11: Co-Variance between b_0 and $\eta_{0,b}$ for evaluation with QDT in the laboratory (left) and in the field (right), both normalized

4. Summary

Based on the comparative evaluation of the same data basis from a laboratory measurement, it was shown, that the DT method is absolutely suitable for flat plate collectors and delivers almost identical results as the QDT method from the testing standard. It was additionally proven that the BS method can provide very useful additional information in order to assess the quality and independence of parameters. It can thus help to detect deficits in parameter sets that can occur even in strictly normative measurements.

On the basis of a sensitivity analysis, the influence of different filter criteria on the results of a QDT measurement was investigated in order to test their suitability for the evaluation of field measurement data. It turned out that the QDT reached its limits with very dynamic data and only worked well with longer averaging and conditioning times. If these averaging times were given, however, larger than the normative fluctuations of the input temperature and the mass flow could also be permitted in order to measure collectors in the field without interference with their regular operating conditions. A broad coverage of all relevant boundary conditions proved once more to be essential, in particular the sufficient consideration and weighting of input temperatures close to the ambient temperature. Under these premises, the QDT was able to generate results in the field within the confidence interval of the laboratory measurement. The remaining differences, especially in the heat losses, will continue to be investigated.

Results were also achieved with the DT method, which are largely within this confidence interval, but differ depending on the balance area considered. Although some deviations still exist which cannot yet be explained correctly, the method was able to demonstrate its general function and its great potential for application in the field testing. The consideration of losses at collector connections promises still improvement possibilities.

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